

# REINHOLD ENVIRONMENTAL®



## **2024 Reinhold/PCUG Round Table Presentation**

Hosted by LG&E/KU and Co-hosted by Southern Co. and TVA  
in The Marriott Resort Lexington Griffin Gate Hotel, Lexington,  
KY on June 24-25, 2024

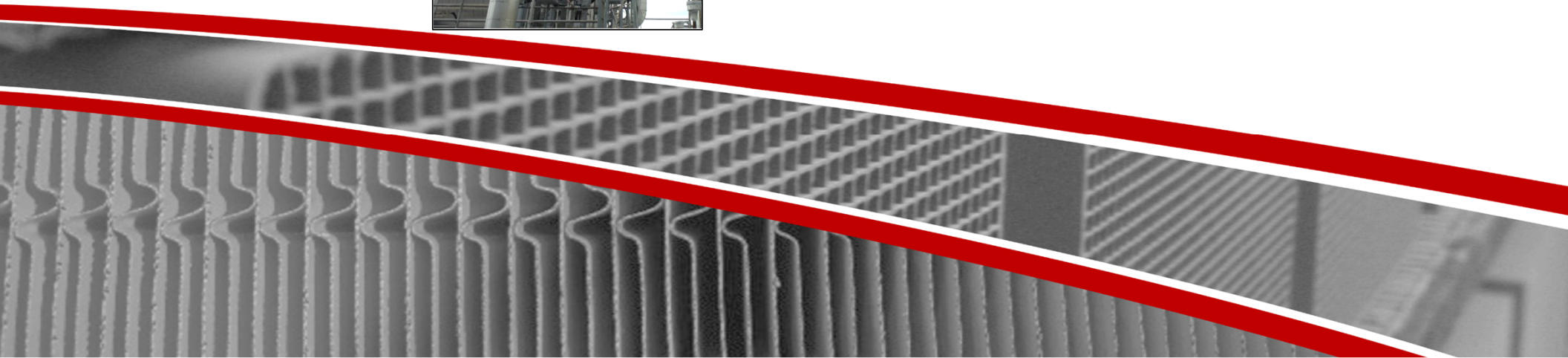
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2024 Reinhold Environmental Round Table



## Getting the Most Value out of Catalyst Testing

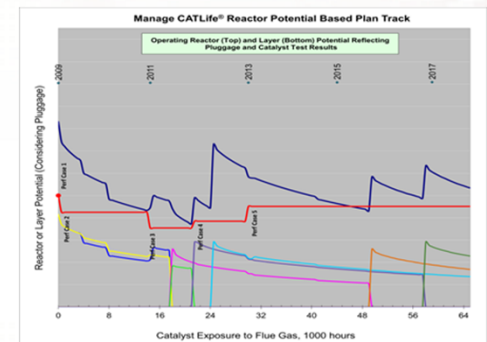
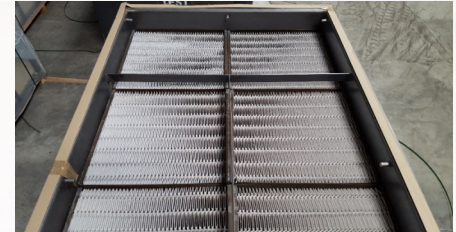
Presented by  
Noel Rosha (CERAM)  
June 26, 2024



# Introduction

Accurate laboratory testing is one critical component to proper analysis of your overall SCR system performance. Ensure that your laboratory results are accurate and meaningful, and know the challenges associated with interpreting and applying the results to the full scale SCR system.

- Presentation Road Map
  - CERAM Background
  - Catalyst Testing Theory and Limitations
  - Applying Test Results
  - Questions and Answers



# CERAM Background

## Ceram Austria, GmbH

- Catalyst Production Since 1985
- Plate and Honeycomb
- Laboratory Established for New and Used Catalyst Testing
- >2,000 Activity Tests Annually

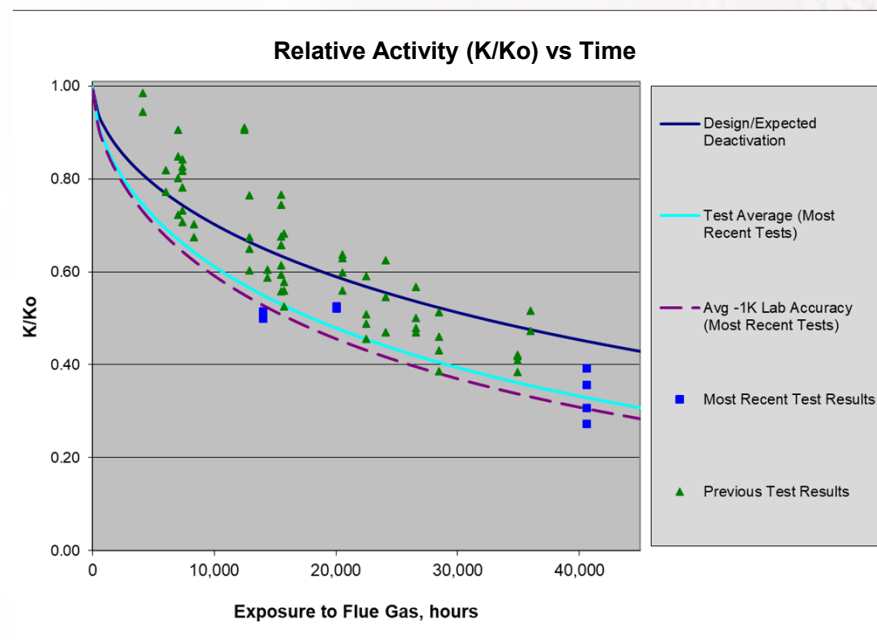
## Ceram USA, Inc.

- Established 2000, CATLife® Services Established 2002
- Catalyst Management, Inspections, AIG Tunings, Low Load Studies, etc.
- Aged Catalyst Testing for Wide Range of Applications



# Goals of Catalyst Testing

- Is my New Catalyst Meeting Design?
- How is my Aged Catalyst Performing?
- When do I Replace Catalyst?
- Has Anything Changed?
- What is the Deactivation Rate?
  - What is Causing Deactivation?
  - Are we doing Something Operationally?
  - Can Deactivation be Remedied?
  - What are the Operational Risks?



**Standardized Laboratory Activity Assessment (K-value) Addresses Questions on a Host of Fronts**

# Common SCR Catalyst Analytical Tests

## Catalyst Activity (K, Nm<sup>3</sup>/m<sup>2</sup>-h)

- DeNO<sub>x</sub> Capabilities for Each Layer
- Helps Define Deactivation Applicable to Every Layer
- Bench, Semi-Bench

## SO<sub>2</sub> to SO<sub>3</sub> Conversion Rate

- Lab Setting Result Useful as a Comparative Tool
- Not a Direct Gauge of Field Performance
- Bench, Semi Bench

## Chemical Composition

- XRF Analysis (Bulk, Surface)
- Useful as Context for Activity

## Specific Surface Area (BET, m<sup>2</sup>/g)

- Pore Structure Condition (Sintering, Blinding)
- Useful as a Comparison to Fresh Sample
- Useful in Determining Cause of Deactivation, but not a Direct Correlation to Activity Measurement



Semi-Bench

Small Sample, Syn Gas, may not Match Linear Velocity

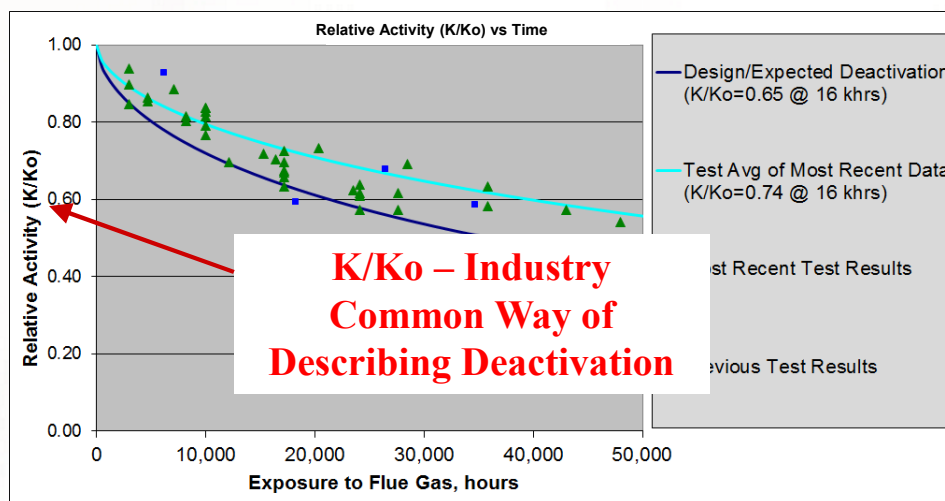


Bench

Standard HC Element Dimensions or Typical 1 Plate Length, Fired Gas, Match Linear Velocity

# Catalyst Activity

- Catalyst Activity (K)- *the ability of Catalyst to Perform the DeNO<sub>x</sub> Reaction at a Given Set of Process Conditions*
- Catalyst will Deactivate (lose DeNO<sub>x</sub> ability) Over Time
  - Catalyst Poisoning, Masking/Blinding, Sintering, Damage, etc.



# How is Catalyst Activity Measured?

Activity (K) is not Measured - It is Calculated from Measurements

New or Aged Sample Tested in a Recreated SCR Scenario

NOx Reduction Measured in Bench or Semi Bench Reactor

$$K = -Av * \ln(1 - \eta)$$

## Area Velocity

Depends on:

- Flow
- Catalyst Geometry

## Measured NOx Reduction %

Depends on:

- NOx Inlet & NOx Outlet
- Molar Ratio (1.0 for bench)
- Flow and Temperature
- H<sub>2</sub>O%, O<sub>2</sub>%, Gas Composition

# Area Velocity

$$Av = Q/A_{tot}$$
$$= Q/(V_{tot} \times SSA)$$

Area Velocity, Function of Reactor Flow and Catalyst Geometry

**Q** Flue Gas Flow Rate, Nm<sup>3</sup>/h

**A<sub>tot</sub>** Total Catalyst Geometric Surface Area, m<sup>2</sup>

**V<sub>tot</sub>** Total Reactive Catalyst Volume Available, m<sup>3</sup>

**SSA** Catalyst Specific Surface Area m<sup>3</sup>/m<sup>2</sup>

# Standardized Test Procedures

- VGB Test Protocol (Vereinigung der Großkraftwerksbetreiber)

- Developed in Germany 1987
- Bench-Scale Testing
- Replicate Operating Conditions
  - NO<sub>x</sub>, SO<sub>2</sub>, Velocity, Temp, O<sub>2</sub>%, H<sub>2</sub>O%
    - Except: No ash, NH<sub>3</sub>:NO<sub>x</sub> ratio 1.0

- EPRI Test Protocol

- Published in 2006
- Most recently revised in 2018
- Very similar to VGB

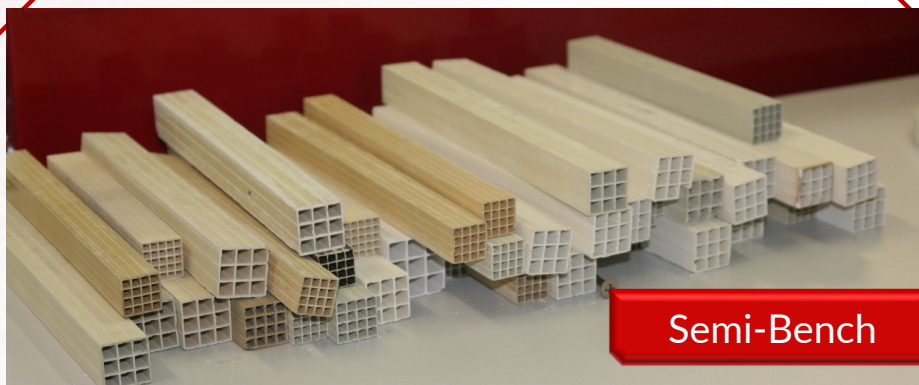
Requires End-User Definition

Table 3-1  
Activity Test Conditions

Parameter	Target	Allowed Deviation from Target	Required Measurement Accuracy	Maximum Drift During Testing
Temperature	Representative field condition	± 5°F (±2.8°C)	± 3°F (±1.7°C)	± 5°F (±2.8°C)
Linear Velocity	Representative field condition	± 10%	± 2% of value	± 5% of value
O <sub>2</sub>	Representative field condition	± 0.2% absolute	± 0.1% absolute	± 0.1% absolute
H <sub>2</sub> O	Representative field condition or as-generated	NA	± 1% absolute	± 1% absolute
CO <sub>2</sub>	As-generated	NA	NA	NA
NO <sub>x</sub> (inlet)	Representative field condition	± 10%	± 1% of value	± 1% of value
NO <sub>x</sub> (outlet)	NA	NA	± 1% of value	NA <sup>24</sup>
SO <sub>2</sub>	Representative field condition	± 1%	± 1% of value	± 0.5% of value
SO <sub>3</sub>	None added	NA	NA	NA
NH <sub>3</sub> /NO <sub>x</sub> ratio	1.01	±0.01 absolute	±0.01 absolute	±0.01 absolute
N <sub>2</sub>	Balance	NA	NA	NA

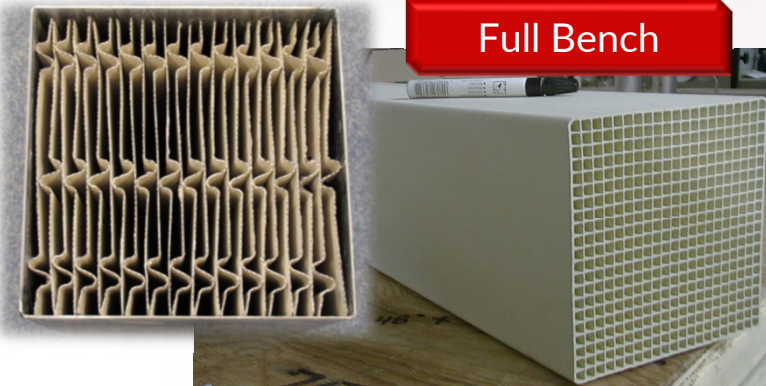
Table 3-1 from EPRI Laboratory Testing Protocol for Coal-Fired SCR Catalyst: 3<sup>rd</sup> Edition. Nov. 2018

# Bench vs Semi-Bench



Semi-Bench

- Smaller Samples
- Demands Consistent Geometry
  - CERAM only does HC in semi-bench accordingly
  - Scaling Results to Bench Takes Experience
- Quicker, Less Expensive
- Syn Gas Based Measurements
  - Tighter 'Flue gas' Variable Control



Full Bench

- Nominal 6" x 6" Facial Dimensions
- Better Captures Plate Geometry (sinusoids)
- 'Fired' Reactor- More Difficult Process Control
  - Lower Measurement Precision
- Correcting as-fired Data Takes Experience

$$K = -A_v * \ln(1 - \eta)$$

# Using Activity Test Data

## Testing Standardization

- Results Should be Comparable Between Labs (Same Language, K)
- Consistency, Repeatability
- Catalyst Management Depends on Accurate, Consistent Data
- Comparing Catalyst Proposals Requires Consistent Conditions

## EPRI, VGB Guidelines

- Benchmarking is Critical
- Remember these are GUIDELINES
  - Conditions and Protocols are End-User Driven

# Good Catalyst Sample

Representative of Full-Scale Catalyst!

Clean, Free of Pluggage

- For All Catalyst Types
- Account for Pluggage Elsewhere in Catalyst Management Evaluation
- Plugged Samples Result in Artificially High Activity

Free of Mechanical Damage

- Including Removal Damage
- Remove Extra Plates



# Catalyst Testing Key Consideration

Laboratory Sample Should be Representative of Full-Scale Catalyst!

Uniformity Ensures Operating Reactor Potential

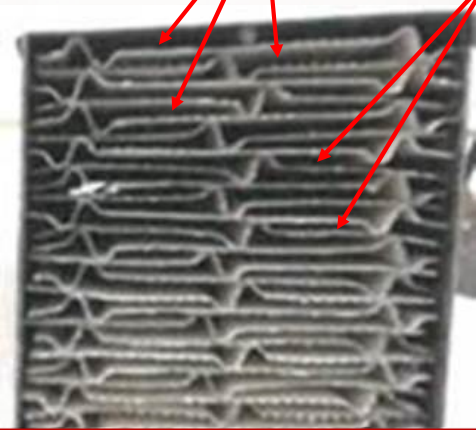
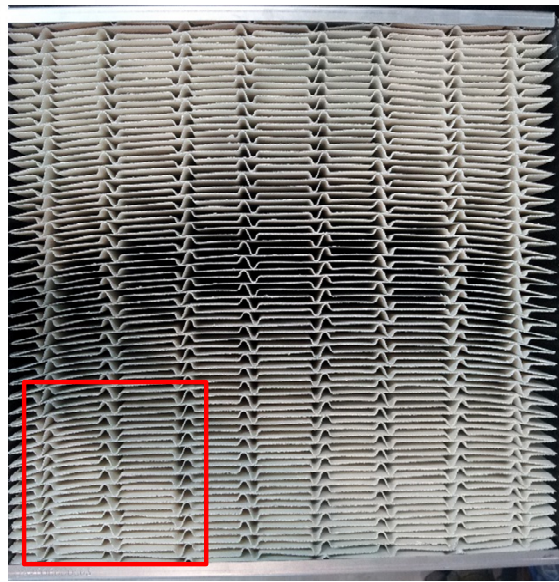
Geometric Uniformity Influences Laboratory Results

Large Flow Areas

Small Flow Areas



Properly Packed Laboratory Sample



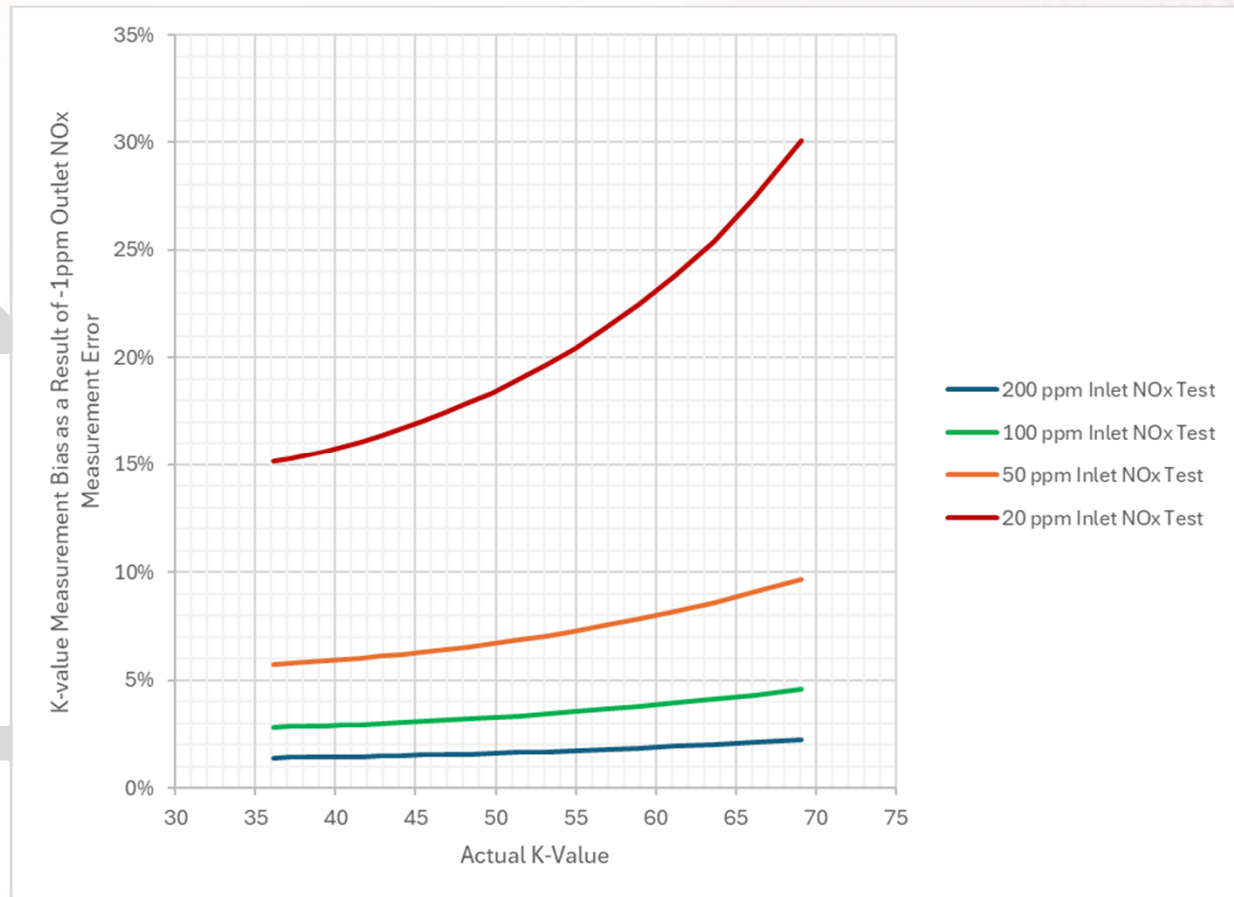
Sample Packing Not Representative of Full Scale (reversing sine waves) or Proper Laboratory Procedure!

# Instrumentation Tolerances - NOx Example

$$K = -A_v * \ln(1 - \eta)$$

Measured NOx Reduction %

- Severity of Error Propagation
  - Depends on Inlet NOx
  - Depends on Activity
  - Fired vs. Syn Gas
  - H<sub>2</sub>O, O<sub>2</sub>, ...



## Testing Takes Time (EPRI Standards Example)

### New Catalyst Activity

- Minimum 8-hours Sample Conditioning
- Active Site Seasoning

### Used Catalyst Activity

- Minimum 2.5-hours Sample Conditioning

### All Activity Measurements

- Minimum Four Tests Showing No Trends After Conditioning
- One Hour Intervals

### Quality is more Significant than Volume of Lab Tests (e.g., Quality vs Quantity)

- 'Rapid-fire' Multiple Test Conditions, Temperatures, etc.
- Establishing Activity and Applying Appropriate Corrections is more Useful
- Corrections to Field Conditions are Always Needed
- Operating Life is Defined by the Ability to Match Critical Operating Circumstance

## Why Catalyst Activity?

- *Why not just report the NOx reduction percentage?*
- Activity Provides Standard Measurement Capabilities at a Specific Area Velocity
  - Life Analysis can Readily be Adapted to Changing Conditions Based on Established Science (Much less Extrapolation)
  - Correlating Lab Performance to Field Conditions is Critical
  - All Lab Results Need to be Subject to Corrections
- *Why not just report overall Relative Potential?*
  - Reporting Performance of Individual Layers Provides the End User with Best Determination of Replacement Layer
  - Reporting Performance of Individual Layers Provides More Flexibility in Test History Analysis
  - Third-Party Analysis More Complicated for “Apples to Apples” Comparison

# Why Catalyst Activity?

- Better Describes the Trend in Deactivation (e.g., Relative Activity ( $K_{\text{measured}}/K_0$ ))
- Test Results are not only a Snapshot of Performance (e.g., Examine Test History)
  - Tool to Describe Performance at Varying Operating Conditions
  - Many Operating Conditions can not be Described Directly in the Lab!
    - *Or Change over Time*

Most Recent Test Data

Catalyst Type	Reactor Level	Hours of Catalyst Exposure to Flue Gas	Activity (K-bench at 410 C), m/h	K/Ko	Std Deactivation K/Ko @ 16khr	-1K/-2K Based K/Ko @ 16khr
2021 Plate	1	10,233	38.0	0.760	0.700	0.677 / 0.653
Original	2	42,003	19.4	0.436	0.623	0.604 / 0.586
Original	3	42,003	19.7	0.443	0.628	0.61 / 0.591

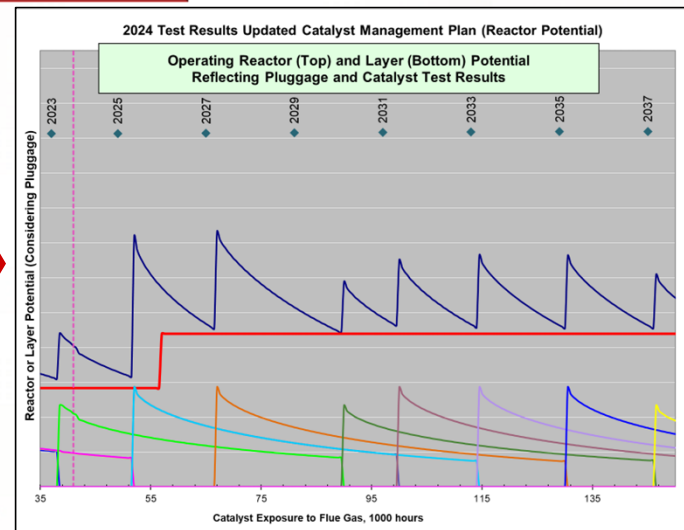
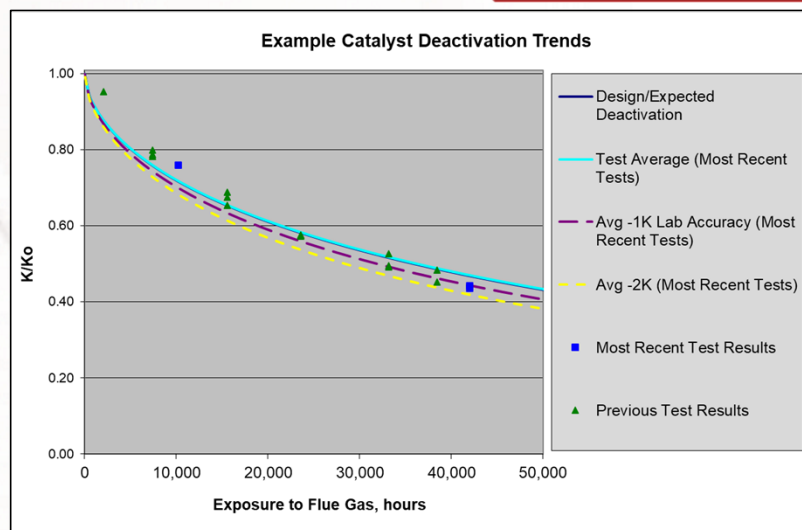
- Consistent Activity Definition
- Ability to Compare Normalized Deactivation Data
- More Tangible Error Analysis

# Why Catalyst Activity?

Most Recent Test Data

Catalyst Type	Reactor Level	Hours of Catalyst Exposure to Flue Gas	Activity (K-bench at 410 C), m/h	K/Ko	Std Deactivation K/Ko @ 16khr	-1K/-2K Based K/Ko @ 16khr
2021 Plate	1	10,233	38.0	0.760	0.700	0.677 / 0.653
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Consistent Analysis Provides Better Context to All Test Data

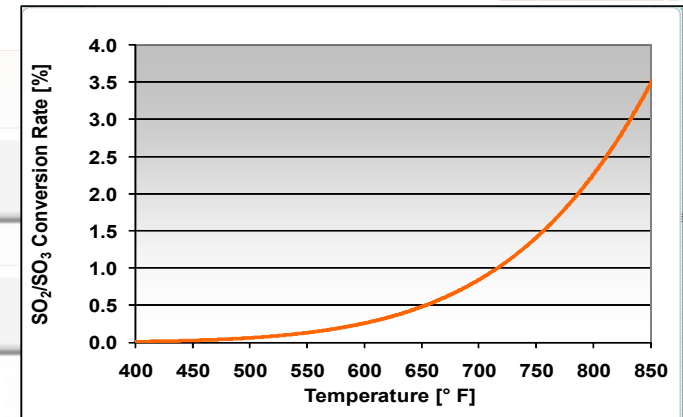


# SO<sub>2</sub> to SO<sub>3</sub> Conversion Rate

Temperature is Critical

Lab Measurement ≠ Field Performance

- Conversion Rate Chemistry is Sensitive
- Particulate, NH<sub>3</sub>, H<sub>2</sub>O, Inlet SO<sub>3</sub> all Inhibit Conversion Rate
- Dissimilar Test Conditions are Significant when Comparing Results
- Correlating Dissimilar Test Conditions more Difficult when Comparing Test Results
- Understand what Results mean to your Application

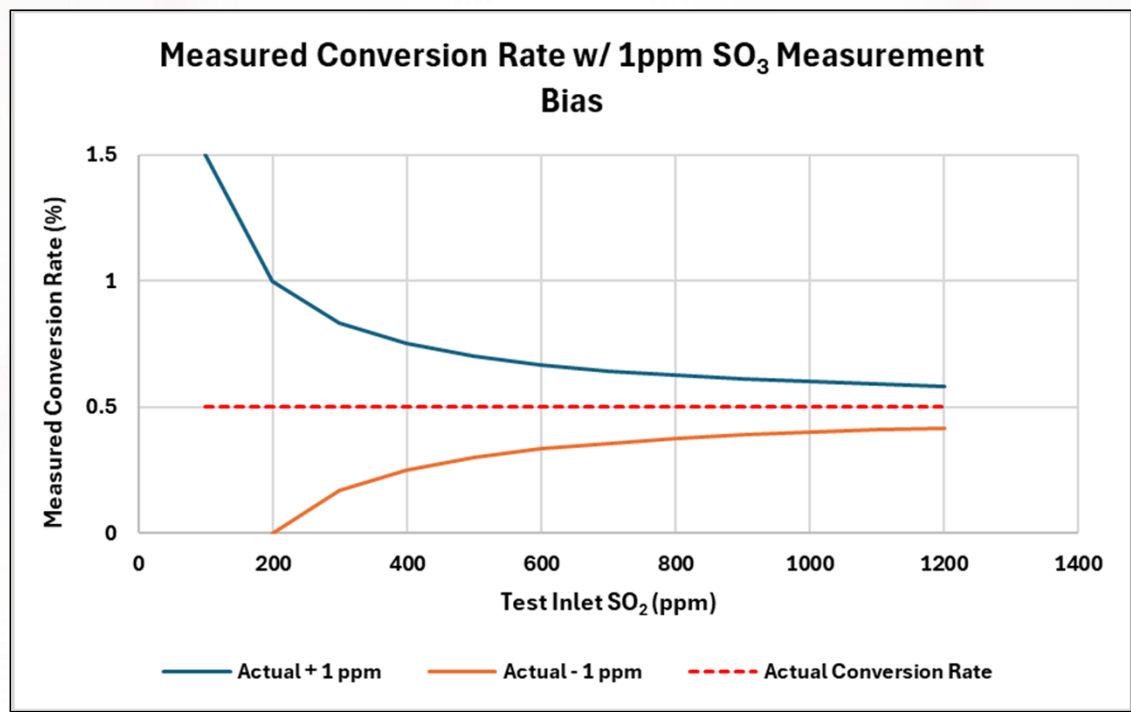


Lab results will be conservative to field (e.g., doubling plate samples)

# SO<sub>2</sub> to SO<sub>3</sub> Conversion Rate

Effects of ±1 ppm SO<sub>3</sub> Error Analysis (at 0 ppm Inlet SO<sub>3</sub>)

- Low Inlet SO<sub>2</sub> Subject to High Error



# Using Test Results

The Temptation is to Oversimplify Results- “Do we need Catalyst or Not?”

- Testing is about the Long Game
- Missing or Low-Quality Analysis Impacts Future Analysis

To be Universally Useful, Test Data should Include:

- Measured K-value for Each Layer
- Test Conditions (AV, Temp, H<sub>2</sub>O, O<sub>2</sub>, NO<sub>x</sub>, Molar Ratio)
  - Consistent with Industry Standards
- Initial K-value (as available)
- Operating Time for each Layer
- Sufficient Information for the Same Analysis by Third Party

# DeNOx Demand and Reactor Potential

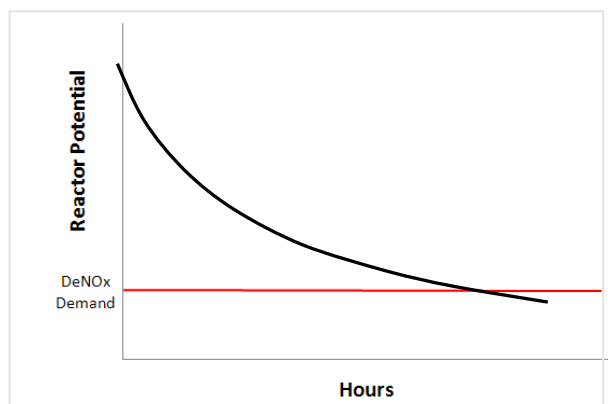
## Reactor Potential

- The Current NOx Reduction Capabilities of the Catalyst
- Takes K and trends in K and Applies Results over Field Geometry
- Dependent on Operating and Mechanical Conditions (temperature, distributions, pluggage, etc.)
- Catalyst Management Depends on Accurate Assessment for Each Layer
- Established (Accurate) Test History → More Accurate Deactivation

$$P = K / Av$$

## DeNOx Demand

- The Reactor Potential Required to Meet NOx Removal and NH<sub>3</sub> Slip Requirements
- Function of SCR System Demand, not a Function of the Catalyst Installed



$$DeNOx\ Demand = P_{req} = K_{req} / Av_{actual}$$

# Operating Reactor Potential

$$P_o = \sum K_i / AV_i$$

Operating Reactor Potential, Amount of SCR System Performance Possible (DeNOx & Ammonia Slip Control)

Describing Overall SCR Performance as a Sum of Individual Layer Performance

$K_i$

Operating Catalyst Activity (layer based), Nm<sup>3</sup>/m<sup>2</sup>h (based on catalyst and operating conditions)

$AV_i$

Area Velocity (layer based), Nm/h (normal gas flow, Nm<sup>3</sup>/h divided by total catalyst surface area in service (e.g. pluggage affected), m<sup>2</sup>)

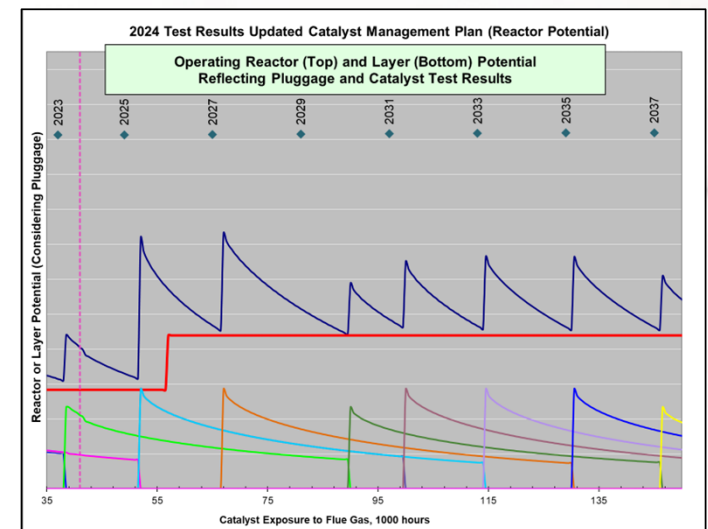
# Operating Reactor Potential

$$P_o = \sum K_i / Av_i$$

Catalyst Testing Should Support this Catalyst Management Philosophy

- Test Layers Individually at Consistent Conditions
- Report Performance of Individual Layers
- Assessment of Deactivation
- Correlate Lab Performance to Field Performance
- Assessment of Overall Reactor Potential

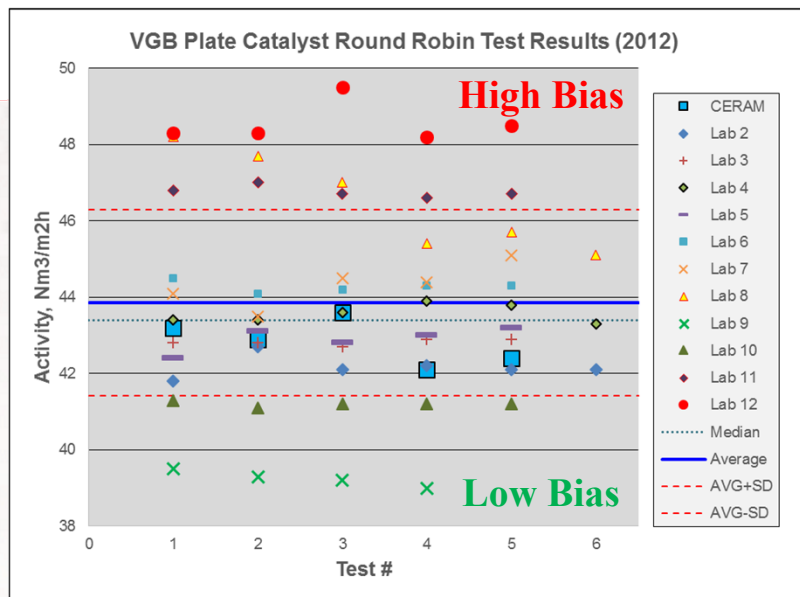
Note that Error Propagation is Still a Critical Consideration



# Accurate Testing Takes Practice!

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

\*VGB Round Robin: Element With Unknown Activity Circulated to Participating 3<sup>rd</sup> Party and Manufacturer SCR Catalyst Test Laboratories

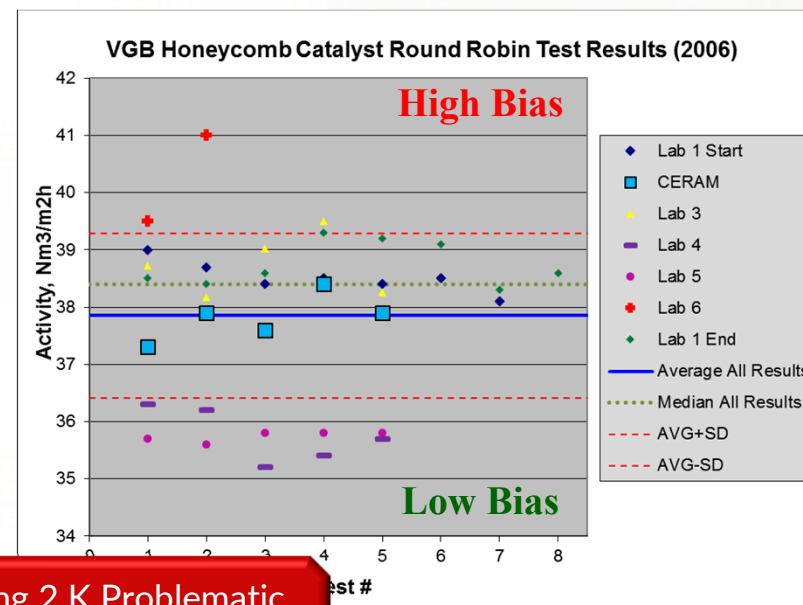


### Low Bias

Premature Catalyst Replacement  
(increased catalyst cost)

### High Bias

Late Catalyst Replacement  
(increased NH3 use and operating risk)



Laboratory Bias Exceeding 2 K Problematic for Catalyst Management

# Implications of Biased K Measurements

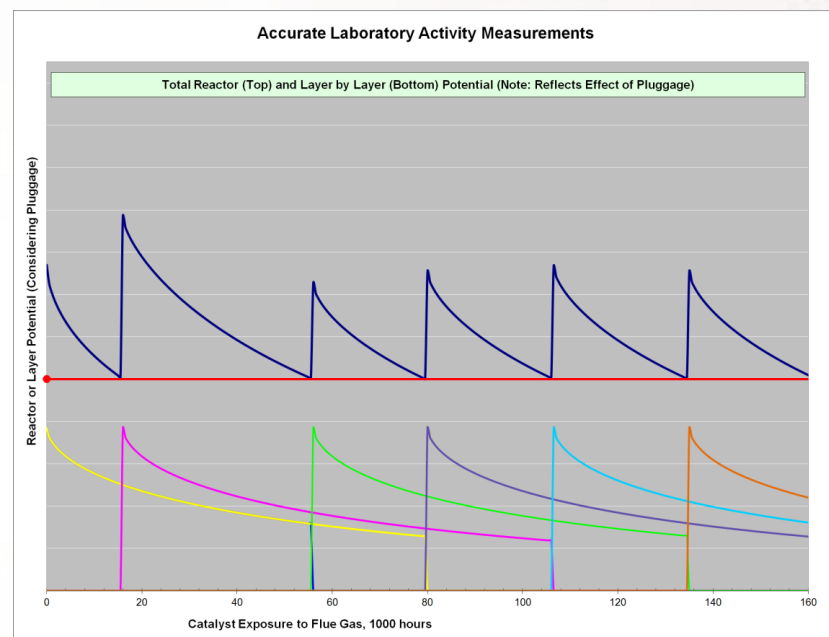
## Example 500 MW Unit With 2+1 Reactor

### Operating Conditions

- 80% NO<sub>x</sub> Reduction
- 2 ppm NH<sub>3</sub> Slip
- Original 16khr Design Life

### Assumed Unbiased Activity Measurement:

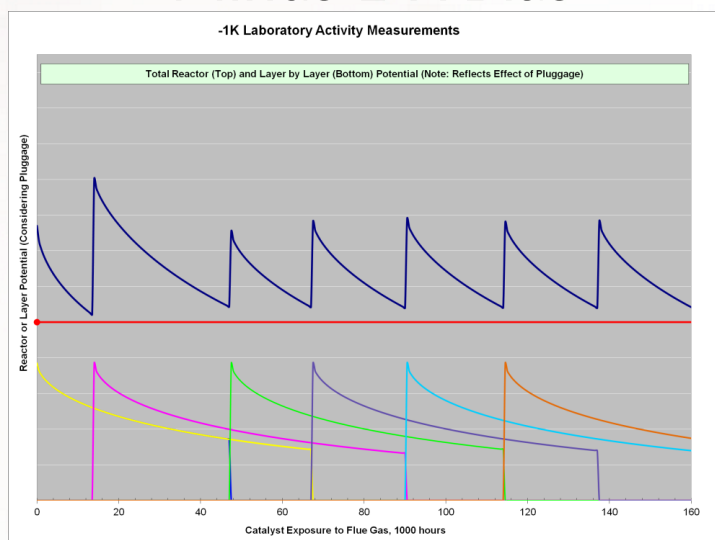
- 20 Year Capital Cost Projection
- \$11M in Catalyst Costs
- 5 Catalyst Events



# Low Bias Lab Activity Result:

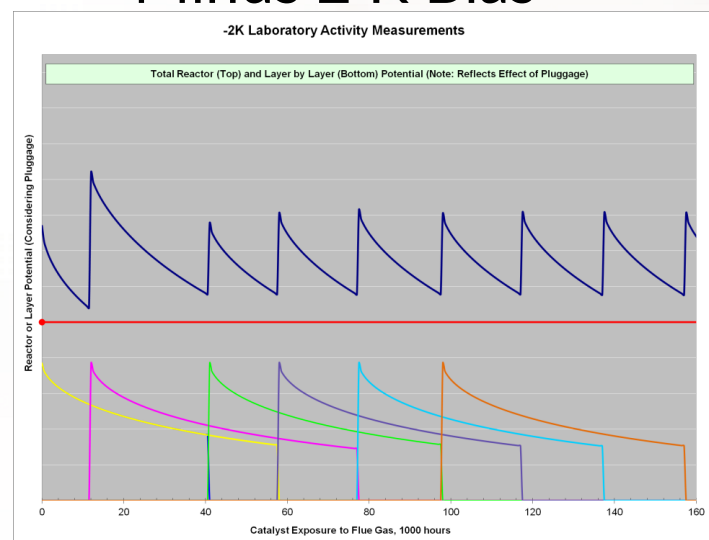
## Wasted Activity and Increased Catalyst Costs

### Minus 1 K Bias



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

### Minus 2 K Bias

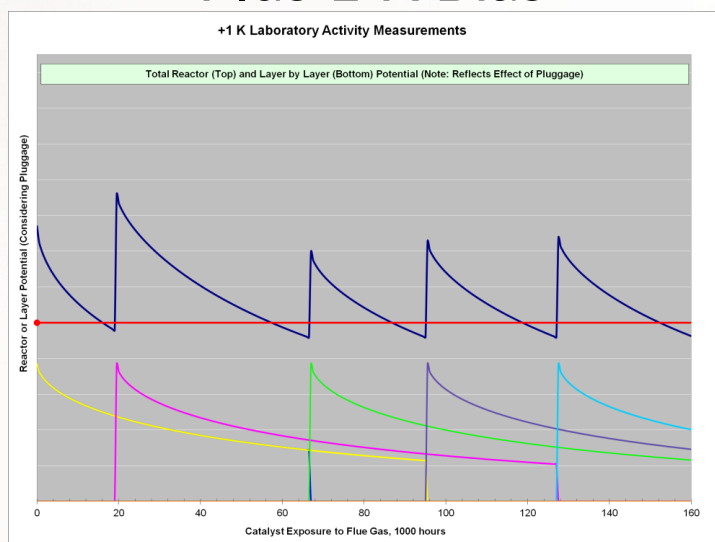


\$3.6 M (33%) more catalyst  
8 Events (+3 to Unbiased)

# High Bias Lab Activity Result:

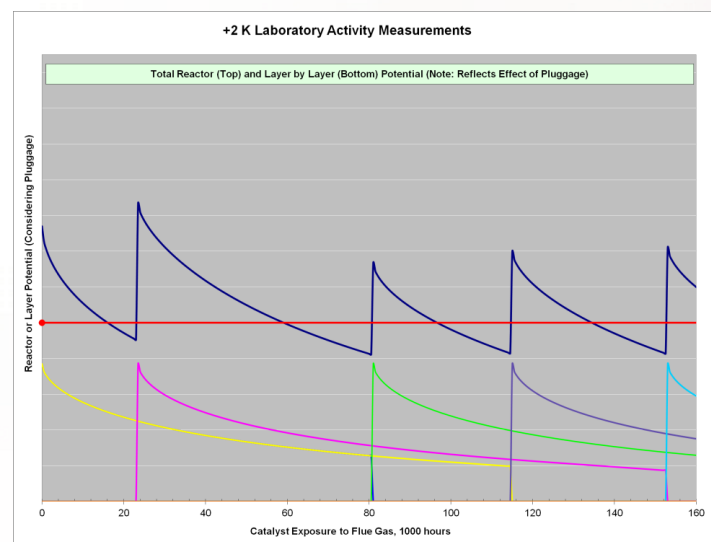
## Deficient Performance

### Plus 1 K Bias



3.5 ppm NH3 slip  
 Surprise Catalyst Needs (+\$),  
 Ammonia Costs (+\$), etc.  
 Compliance Issues (+\$\$\$)

### Plus 2 K Bias



6 ppm NH3 slip  
 Surprise Catalyst Needs (+\$), Ammonia Costs  
 (+\$), Ammonia System Limits, etc.)  
 Compliance Issues (+\$\$\$)

# Conclusions

- Standardized, per-layer, Laboratory Activity Assessment (K) Addresses Questions on a Host of Fronts for Proper Catalyst Management
  - Still Use Sum of Individual Layer Performance for Catalyst Management
  - *Confirms the Best Layer to Replace, Regenerate, or Move*
- Evaluate DeNO<sub>x</sub> Capabilities “Universally” From Lab-to-Lab
  - Test Histories and Results should be Universal
  - Helps in Procurement and Correlating Third Party Measurements
- Correlate Test Data to Varying/Changing Field Conditions
  - Exception of SO<sub>2</sub> Conversion (No Ash or Ammonia in Lab)
- Be Cognizant of Error and Error Propagation
  - Know How Measurement Bias Affects Results
    - ❖ Quality Testing is much more Important than Volume of Test Conditions
    - ❖ Sensitivity Analysis - Timing of Catalyst Event Based on -1K, -2K, etc.
    - ❖ Linear & Area Velocities Matched, Lab H<sub>2</sub>O, O<sub>2</sub>, etc. vs Field, ...