REINHOLD ENVIRONMENTAL Ltd.

2018 NOx-Combustion Round Table & Expo Presentation

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

2018 NOX-COMBUSTION-CCR/PCUG CONFERENCE
Marriott St. Louis Airport Hotel
St. Louis, MO

EPRI LABORATORY COMPARISON STUDIES
(SCR CATALYST DENOx ACTIVITY AND SO_2 CONVERSION; MERCURY OXIDATION)

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Agenda

- **Value of Laboratory Testing**
- **Key EPRI Documents**
- **2017 Multi-Lab Comparison Tests for K and SO_2 Conversion**
  - Test Plan
  - Sample Characteristics (plate, honeycomb)
  - Results and Discussion
- **2017 Multi-Lab Comparison Tests for Hg Oxidation**
  - Test Plan
  - Sample Characteristics (honeycomb)
  - Results and Discussion

Value of Laboratory Testing

- **Lab tests are generally used for:**
  - SCR catalyst performance tracking and end-of-life forecasting
    - *DeNOx activity (K), SO_2 conversion, Hg oxidation*
  - Guarantee verification
  - Troubleshooting
- **Testing protocols:**
  - DeNOx activity (K) and SO_2 conversion: EPRI (2007) and VGB (1998)
  - Hg oxidation: EPRI (2015 guideline)
- **Purpose of "round-robin", multi-lab comparisons:**
  - Evaluate industry consistency; quantify inter-lab uncertainty
  - Provide information for updating/improving testing protocols
  - Cautions for the current study:
    - Lab instrument accuracies not evaluated or verified
    - Results do not serve as an audit or certification (no "gold standard" for comparison)

Key EPRI Documents

- **Lab Testing for DeNOx Activity (K) and SO_2 Conversion**
  - *Protocol for Laboratory Testing of SCR Catalyst: 2nd Edition*, 2007, EPRI Report #1014256
  - *Bench-Scale Laboratory Comparative Testing of DeNOx and SO_2 Conversion: Test Plan and Procedure*, 2016, EPRI Report #3002008310
  - *Laboratory Comparative SCR Catalyst Testing for DeNOx Activity and SO_2 Conversion: 2017 Testing Results*, February 2018, EPRI Report #3002010384

- **Lab Testing for Hg Oxidation**
  - *SCR Catalyst Mercury Oxidation Laboratory Testing Guideline – Industry Version*, 2015, EPRI Report #3002005087
  - *Laboratory Comparative SCR Catalyst Testing for Mercury Oxidation: Test Plan and Procedure*, 2016, EPRI Report #3002009279
  - *Laboratory Comparative SCR Catalyst Testing for Mercury Oxidation: 2017 Testing Results*, 2017, EPRI Report #3002011761

2017 Multi-Lab Comparison Tests for K and SO_2 Conversion

"Bench-Scale Round Robin"

EPRI 2017 Multi-Lab Comparison Study
Participants (Activity and SO_2 Conversion)

American Electric Power
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Groveport, OH 43125
USA

IBIDEN Porzellanfabrik Frauenthal GmbH
Gamserstraße 38 - 8523 Frauental
Austria

Cormetech, Inc. (formerly **STEAG SCR-Tech, Inc.***)
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Charlotte, NC 28273
USA

Cormetech, Inc.
5000 International Drive
Durham, NC 27712
USA

Innovative Combustion Technologies, Inc.
10 Commerce Drive / P.O. Box 1029
Pelham, AL, 35124
USA

Mitsubishi Hitachi Power Systems Ltd. (MHPS)
Akitsu Works
3300 Kazahaya, Akitsu-cho, Higashi Hiroshima-shi,
Hiroshima-ken, 739-2403
Japan

STEAG Energy Services GmbH
Forellstraße 100
44629 Herne
Germany

** At the time of testing, this lab was not affiliated with Cormetech*

EPRI 2017 Multi-Lab Comparison Test Plan (K and SO_2 conversion)

Industry Collaboration (coal-fired systems)

EPRI Report #3002008310

Bench-Scale Laboratory Comparative Testing of DeNOx and SO_2 Conversion

Test Plan and Procedure

Table 3-1
DeNOx Test Conditions

Parameter	Target Value	Accuracy[11]	Maximum Drift[12]
Temperature (°F)	700	± 4.5°F (±2.5°C)	5° F
Flow Rate (m^3/hr, at 0°C and 1 atm.)	138 to 146 Exact flow rate TBD	± 5 % of target	± 2% of target
O_2 (%,dry basis)	3.4	± 1% of target	± 0.5% of target
H_2O (%, at actual O_2)	9.0 or as-generated	NA	NA
CO_2 (%, at actual O_2)	16.0 or as-generated	NA	NA
NOx (ppmvd, at actual O_2)	300	± 1% of target	1 ppm
SO_2 (ppmvd, at actual O_2)	1500	± 1% of target	± 0.5% of target
SO_3	None Added		
NH_3/NOx ratio	1.0	−0.02[13]	+0.02[14]
N_2	Balance	NA	NA

Table 2-1
SO_2 Conversion Test Conditions

Parameter	Target Value	Accuracy[4]	Maximum Drift[5]
Temperature (°F)	700	± 4.5°F (±2.5°C)	5°F
Flow Rate (m^3/hr, at 0°C and 1 atm.)	138 to 146 Exact flow rate TBD	± 5 % of target	± 2% of target
O_2 (%,dry basis)	3.4	± 1% of target	± 0.5% of target
H_2O (%, at actual O_2)	9.0 or as-generated	NA	NA
CO_2 (%, at actual O_2)	16.0 or as-generated	NA	NA
NOx (ppmvd, at actual O_2)	300	± 1% of target	1 ppm
SO_2 (ppmvd, at actual O_2)	1500	± 1% of target	± 0.5% of target
SO_3	None added		
NH_3/NOx ratio	No NH_3 added		
N_2	Balance	NA	NA

Hinton & Associates Research & Consulting Engineers

EPRI ELECTRIC POWER RESEARCH INSTITUTE

2017 Tests: SCR Catalyst Sample and Flow Characteristics

Test Sample Description					Flow and AV	
Sample ID	Description	Length (mm)	Width (mm)	Sample Surface Area (m^2)	Flow Rate (m^3/hr 0 °C)	AV (m/hr, 0 °C)
PT1	OEM Plate (25 plates)	623	147	4.58	151.1	33.0
PT2	OEM Plate (25 plates)	623	147	4.58	151.1	33.0
HC1	OEM HC (7.4 mm pitch, 18X18 cells)	1,152	145	9.54	138.3	14.5
HC2	OEM HC (7.4 mm pitch, 18X18 cells)	1,152	145	9.54	138.3	14.5

For a given catalyst type, both samples were from the same manufacturer and batch

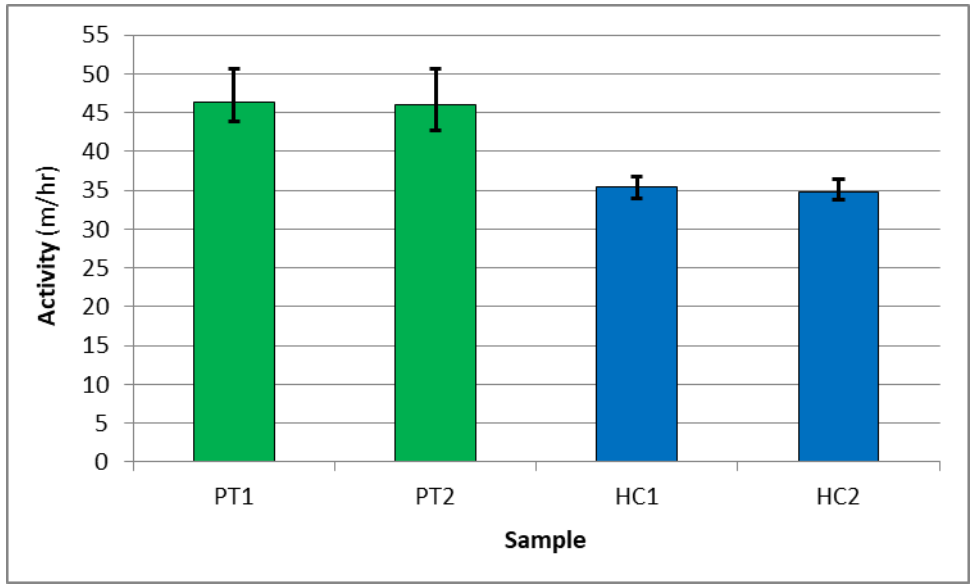
Plate Sample

Honeycomb Sample

Multi-Lab Comparison Results

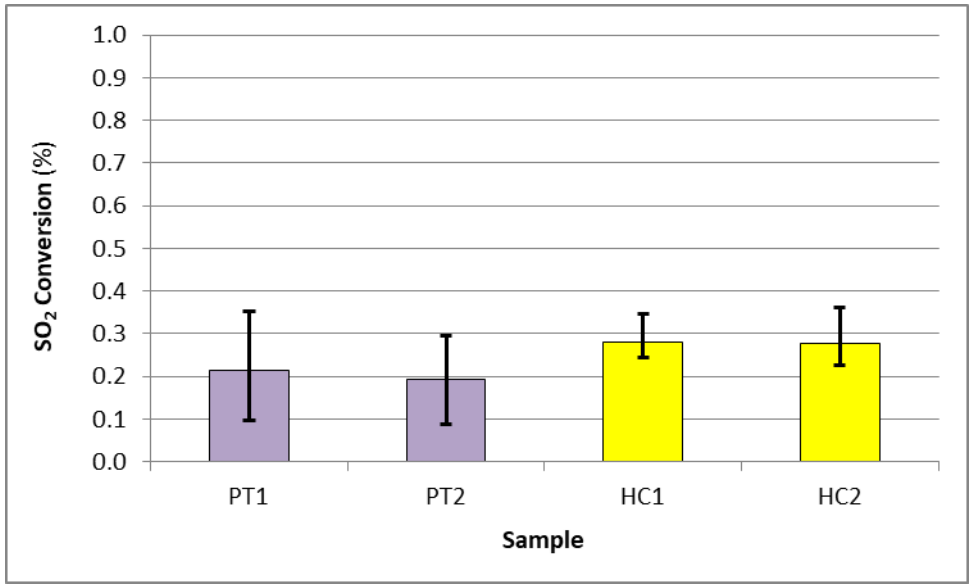
Results Summary

DeNOx Activity, K (m/hr) = -AV*ln(1-deNOx Eff.)



Parameter	Plate	Honeycomb
DeNOx	75.4%	91.0%
Average Activity	46.3 m/hr	35.1 m/hr
Average Absolute Deviation	±3.66 m/hr	±1.37 m/hr
Average Relative Deviation	±7.92%	±3.90%
Average Absolute Standard Deviation	2.69 m/hr	1.03 m/hr
Average Relative Standard Deviation	5.8%	2.9%

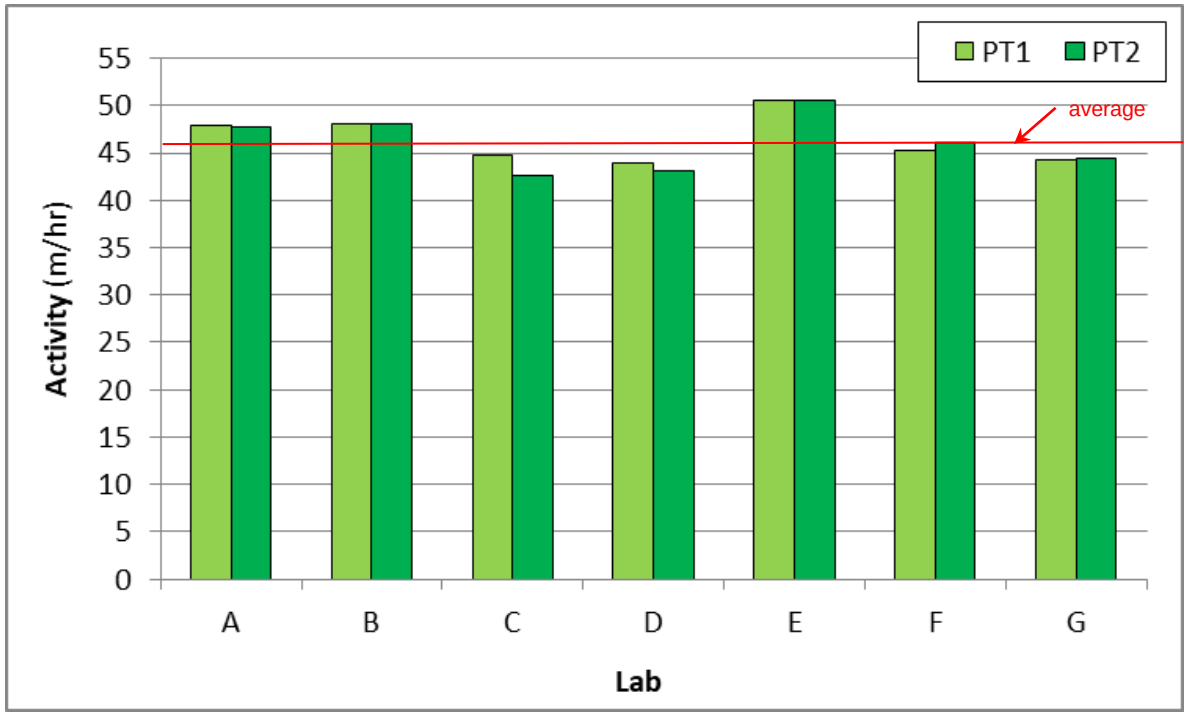
SO_2 Conversion (%) = $(SO_{3\text{-out}} – SO_{3\text{-in}})/(SO_{2\text{-in}}) * 100\%$



Parameter	Plate	Honeycomb
Average SO_2 Conversion	0.20%	0.28%
Average Absolute Deviation	±0.12%	±0.06%
Average Relative Deviation	±56.78%	±21.20%
Average Absolute Standard Deviation	0.07%	0.04%
Average Relative Standard Deviation	34%	16%

Multi-Lab Comparison Results (DeNOx Activity, K)

Plate Samples

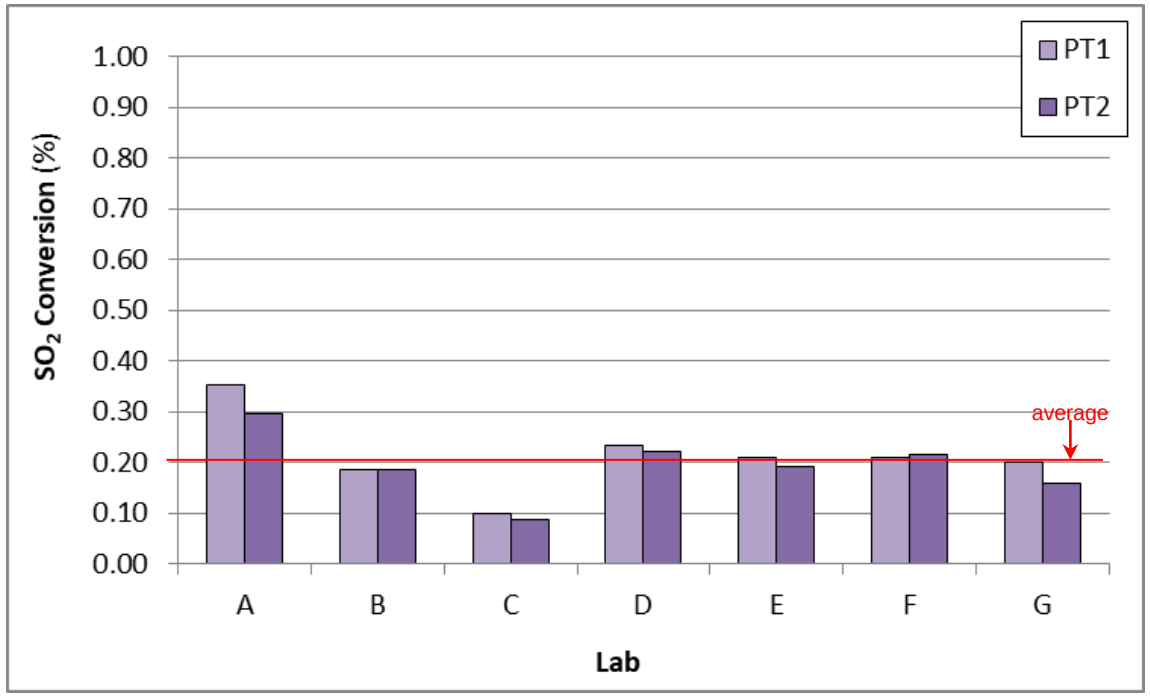


Parameter	Units	PT1	PT2
Average DeNOx		75.5%	75.2%
Average Activity	m/hr	46.4	46.1
Absolute Range -High	m/hr	50.6	50.6
Absolute Range -Low	m/hr	43.9	42.7
Absolute Deviation from Average - High	m/hr	+4.2	+4.5
Absolute Deviation from Average - Low	m/hr	-2.5	-3.4
Relative Deviation from Average - High		+9.1%	+9.8%
Relative Deviation from Average - Low		-5.3%	-7.5%
Absolute Standard Deviation	m/hr	2.49	2.89
Relative Standard Deviation		5.4%	6.3%

- *Plot does not represent chronological testing order*
- *Pre- and post-round robin tests performed by the initiating lab provided similar results (within 1 m/hr)*

Multi-Lab Comparison Results (SO_2 Conversion)

Plate Samples



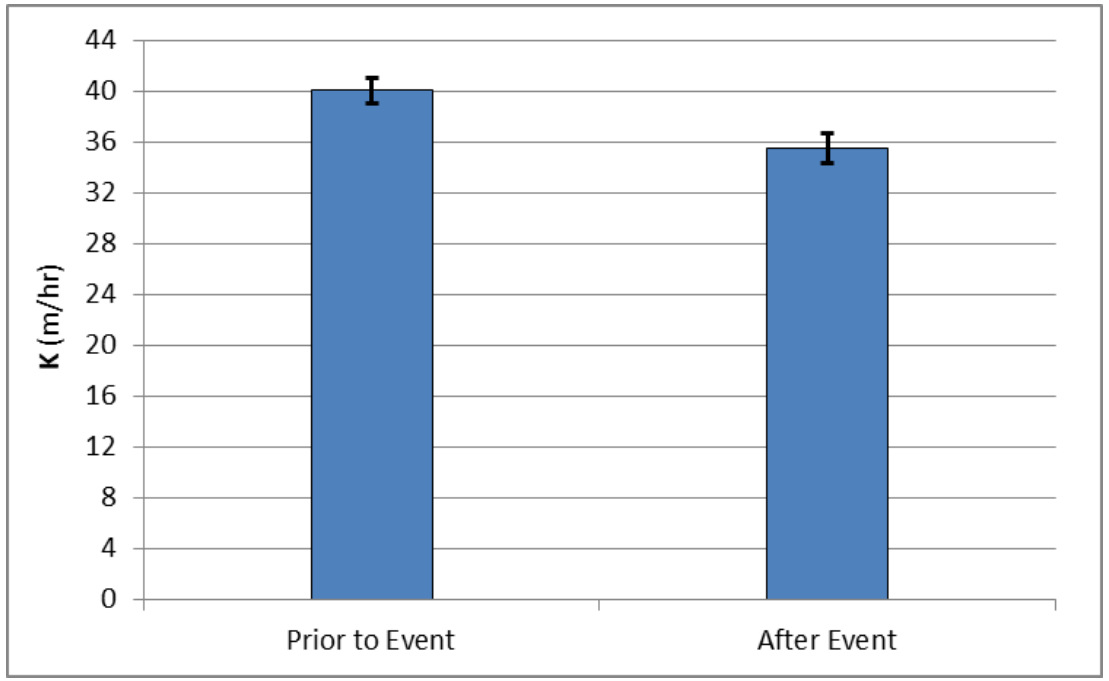
- *Plot does not represent chronological testing order*
- *Pre- and post-round robin tests performed by the initiating lab provided similar results (within 0.01%)*

Parameter	Units	PT1	PT2
Average SO_2 Conversion	%	0.21	0.19
Absolute Range -High	%	0.35	0.30
Absolute Range -Low	%	0.10	0.09
Absolute Deviation from Average - High	%	+0.14	+0.10
Absolute Deviation from Average - Low	%	-0.12	-0.11
Relative Deviation from Average - High		+65.7%	+52.3%
Relative Deviation from Average - Low		-54.2%	-55.0%
Absolute Standard Deviation	%	0.08	0.06
Relative Standard Deviation		35.4%	32.7%

Multi-Lab Comparison Results (DeNOx Activity, K)

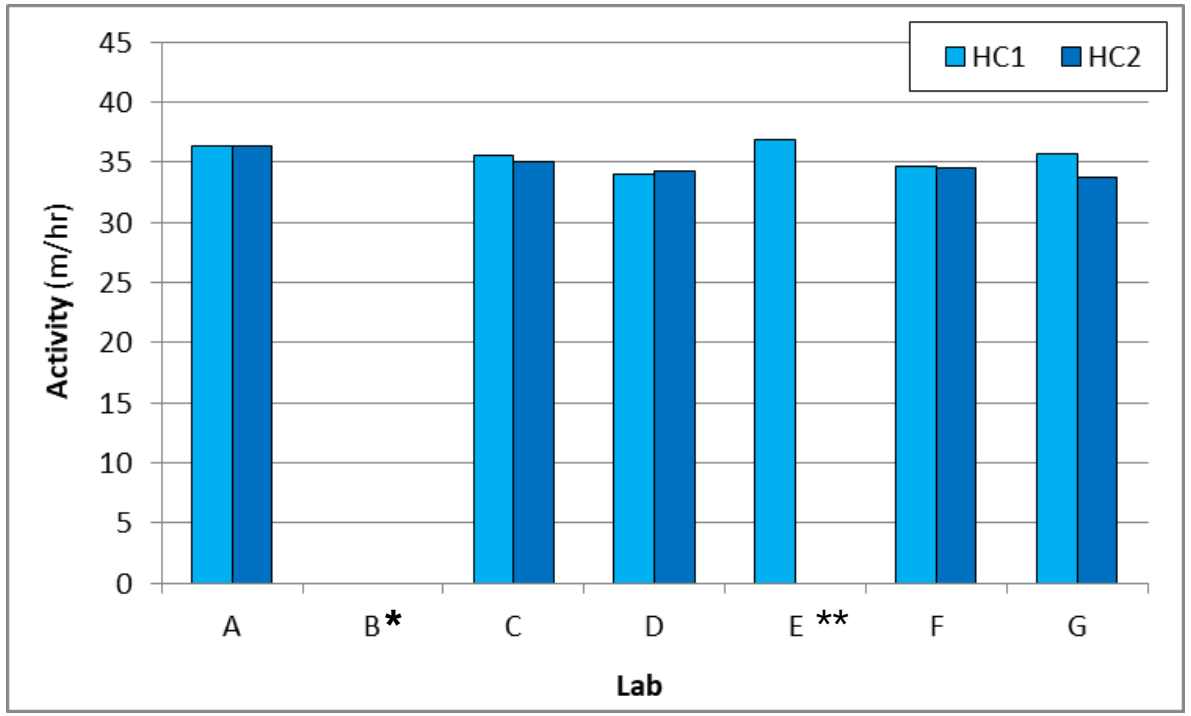
Honeycomb Sample Deactivation

- **Pre- and post-round robin activity tests indicated possible deactivation of <u>both</u> honeycomb samples**
- **XRF tests confirmed sodium poisoning consistent with moisture exposure**
- **Repeat activity tests performed with deactivated samples**



Multi-Lab Comparison Results (DeNOx Activity, K)

Deactivated Honeycomb Samples



Plot does not represent chronological testing order

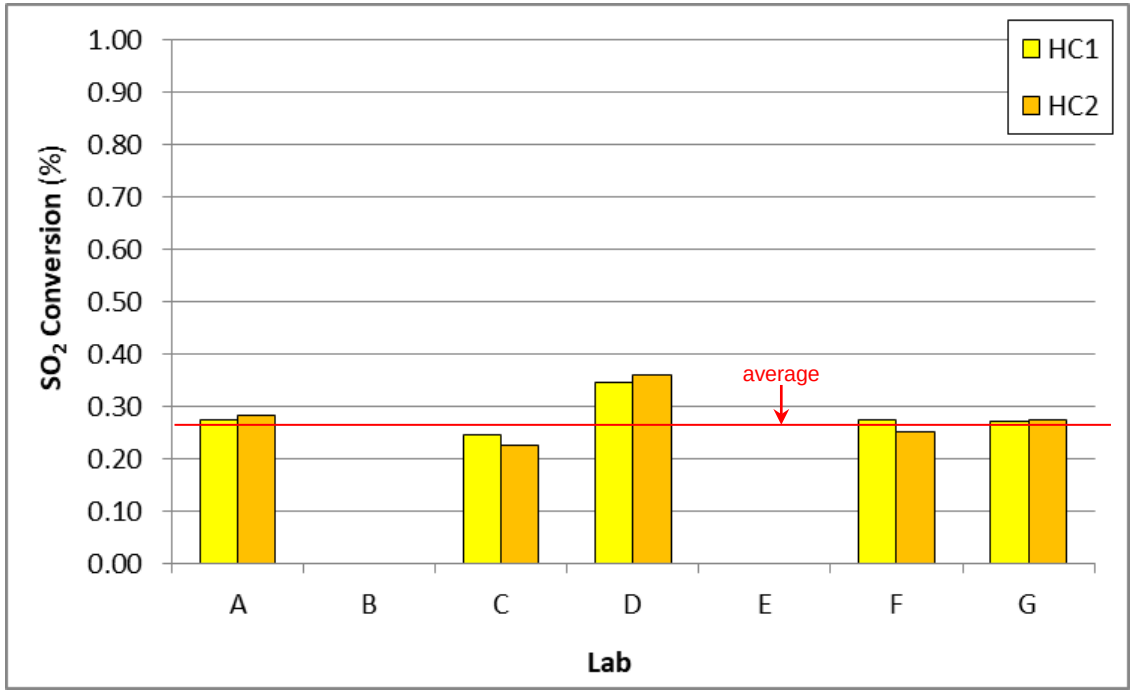
Parameter	Units	HC1	HC2
DeNOx		91.2%	90.8%
Average Activity	m/hr	35.5	34.8
Absolute Range -High	m/hr	36.8	36.4
Absolute Range -Low	m/hr	34.0	33.7
Absolute Deviation from Average - High	m/hr	+1.3	+1.6
Absolute Deviation from Average - Low	m/hr	-1.5	-1.1
Relative Deviation from Average - High		+3.7%	+4.6%
Relative Deviation from Average - Low		-4.2%	-3.0%
Absolute Standard Deviation	m/hr	1.04	1.02
Relative Standard Deviation		2.9%	2.9%

* Lab B did not participate in the honeycomb sample round-robin study

** Lab E only tested sample HC1

Multi-Lab Comparison Results (SO_2 Conversion)

Deactivated Honeycomb Samples



Plot does not represent chronological testing order

Parameter	Units	HC1	HC2
Average SO_2 Conversion	%	0.28	0.28
Absolute Range -High	%	0.35	0.36
Absolute Range -Low	%	0.25	0.23
Absolute Deviation from Average - High	%	+0.06	+0.08
Absolute Deviation from Average - Low	%	-0.04	-0.05
Relative Deviation from Average - High		+23.0%	+29.6%
Relative Deviation from Average - Low		-13.0%	-19.2%
Absolute Standard Deviation	%	0.04	0.05
Relative Standard Deviation		13.6%	18.4%

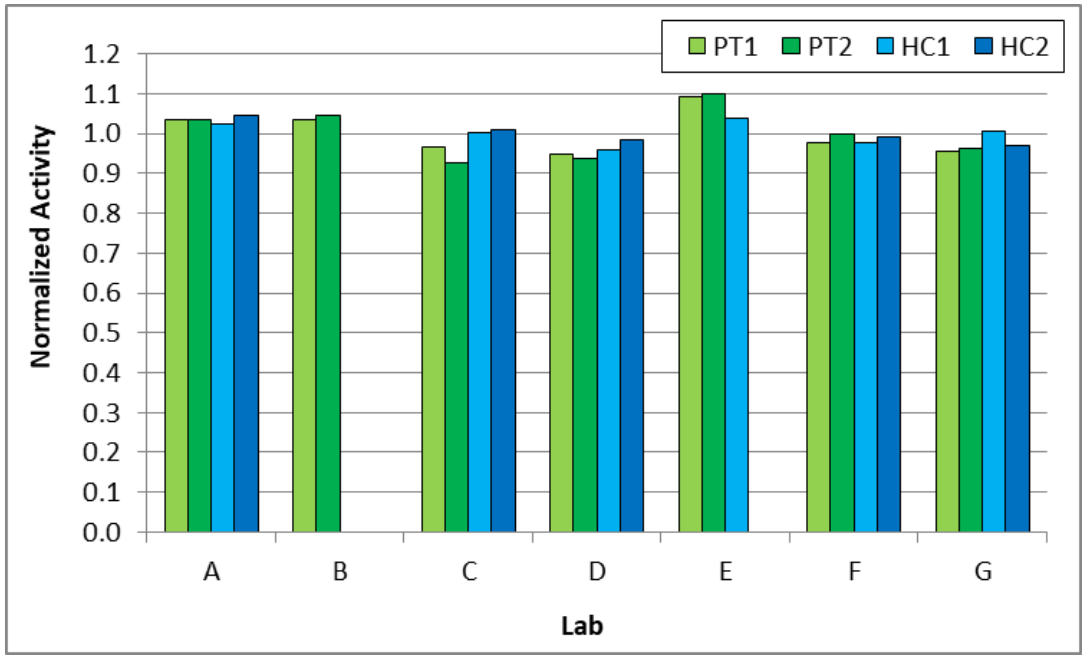
* Lab B did not participate in the honeycomb sample round-robin study

** Lab E did not perform SO_2 conversion tests on the honeycomb samples

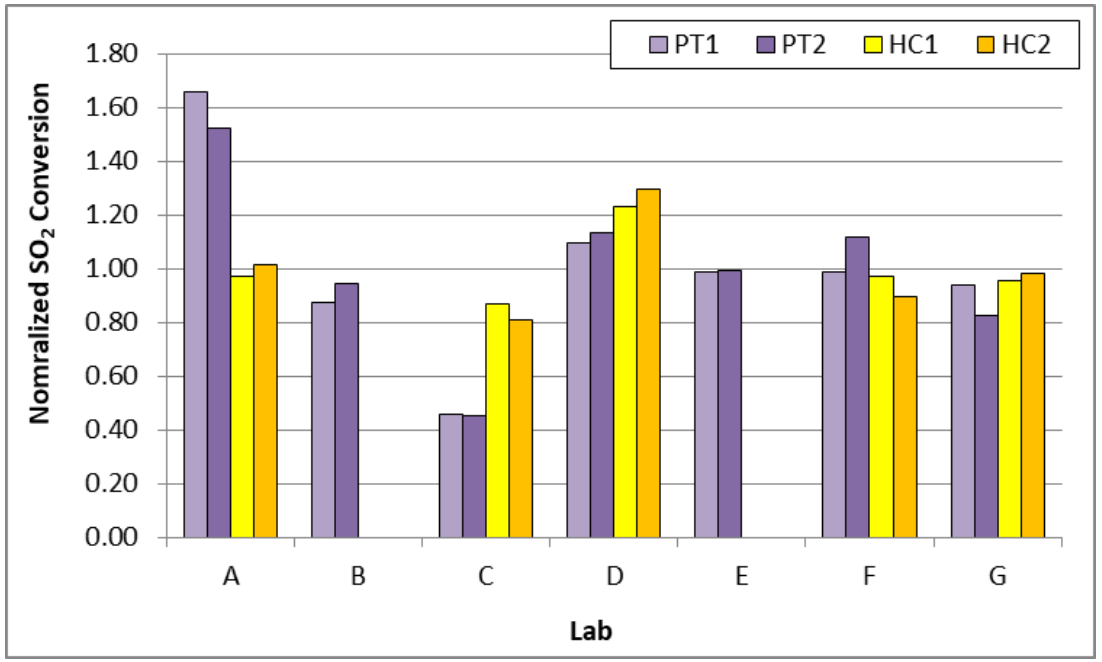
Multi-Lab Comparison Results (Activity and SO_2 Conversion)

Comparing Catalyst Types

Normalized Activity



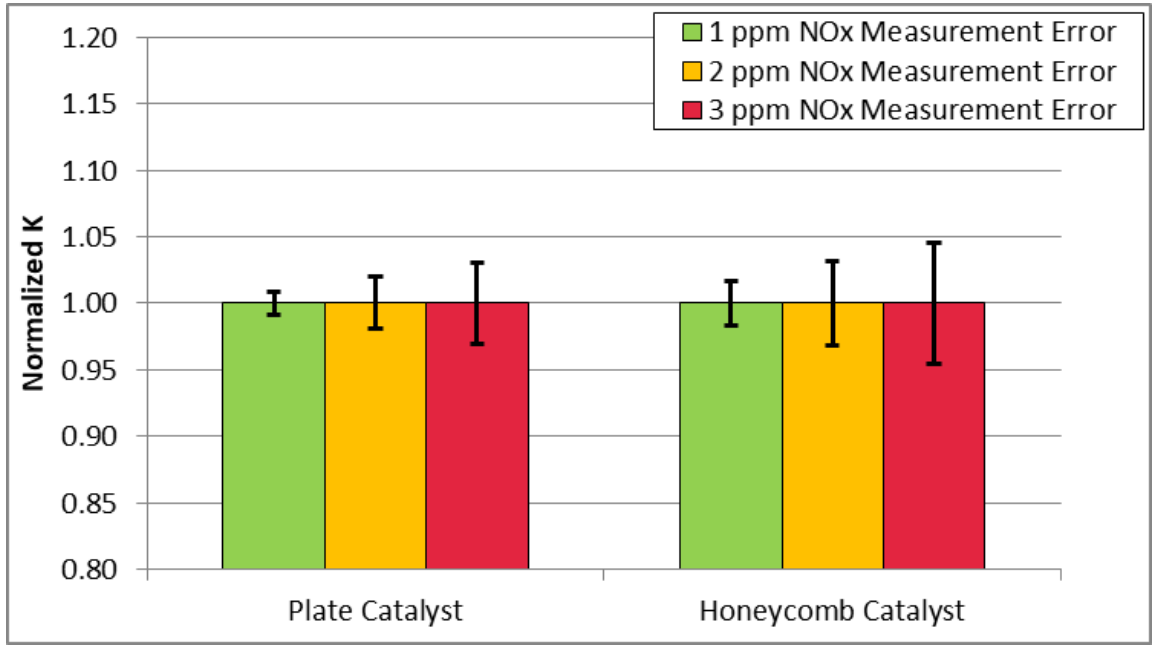
Normalized SO_2 Conversion



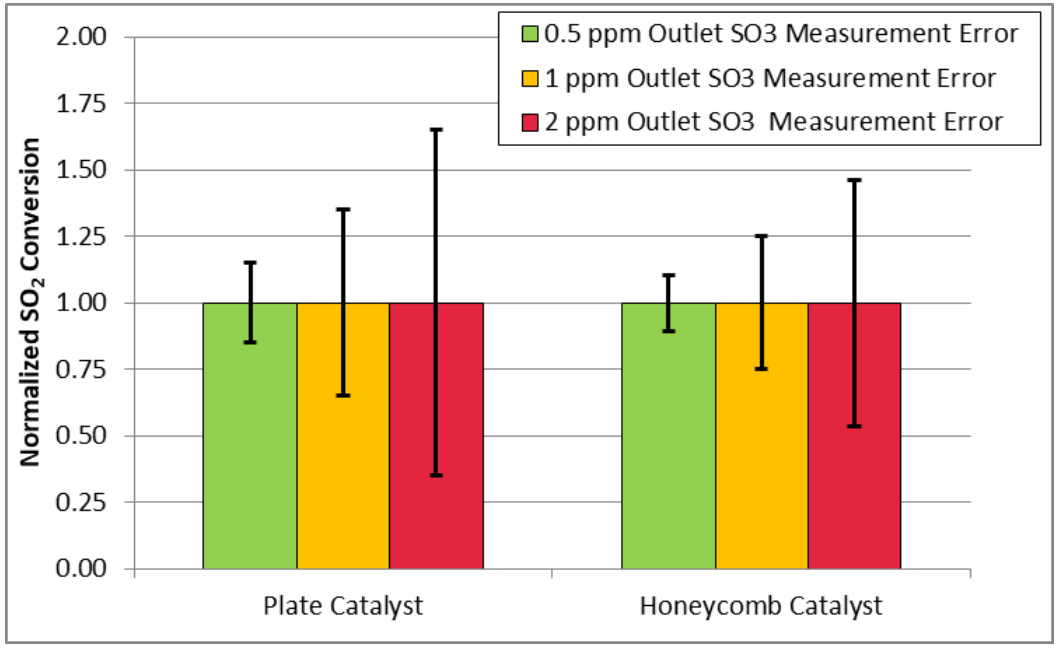
Multi-Lab Comparison Results (Activity and SO2 Conversion)

Measurement Error Discussion

Impact of Outlet NOx Measurement Error on Activity



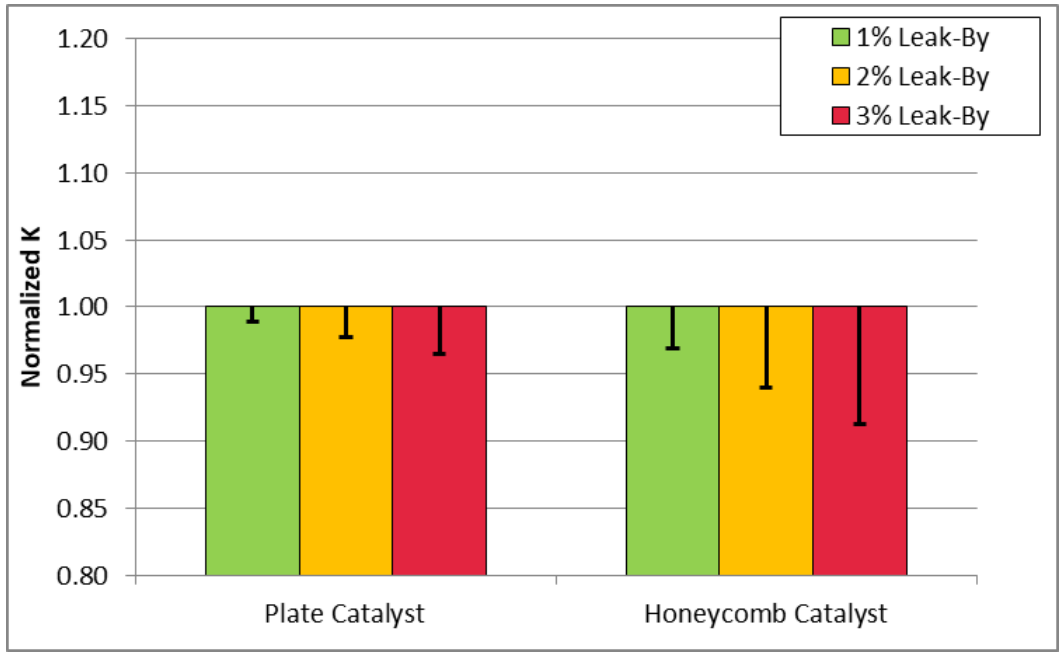
Impact of Outlet SO_3 Measurement Error on SO_2 Conversion



Multi-Lab Comparison Results (Activity and SO2 Conversion)

Flue Gas Bypass Discussion

Impact of Flue Gas Bypass on Activity



Impact of Flue Gas Bypass on SO_2 Conversion

At small flue gas bypass levels, there is no significant impact on SO_2 conversion

Conclusions

Multi-Lab Comparison: DeNOx Activity and SO_2 Conversion

- **Results provide a glimpse of current inter-lab uncertainty bounds**
- **DeNOx Activity Results Summary**

Parameter	Plate	Honeycomb
Relative Standard Deviation	5.8%	2.9%
Max. Relative Deviation from Average	9.8%	4.6%

- **SO_2 Conversion Results Summary**

Parameter	Plate	Honeycomb
Relative Standard Deviation	34%	16%
Max. Relative Deviation from Average	66%	30%

Conclusions (cont'd)

Multi-Lab Comparison: DeNOx Activity and SO_2 Conversion

- **Normalized results show systematic lab trends relative to other labs**
- **Accuracy of lab instrumentation not verified – sources of variability not investigated yet**
- **Results not to be used for auditing or certification purposes (no "gold standard" used for comparison)**

Next Steps

DeNOx Activity and SO_2 Conversion

- **Update EPRI testing protocol**
  - **Continue industry collaboration**
  - **Uncertainty analysis to guide recommendations for lab instrument accuracies**
  - **Lab study to evaluate sensitivities and develop best practices:**
    - Improving plate catalyst sample consistency (e.g., minimizing variations in pitch)
    - Minimizing flue gas bypass

2017 Multi-Lab Comparison Tests for Hg Oxidation

“Mercury Oxidation Testing Round Robin”

EPRI 2017 Multi-Lab Comparison Study
Participants (Hg Oxidation)

AECOM
9400 Amberglen Blvd.
Austin, Texas 78729
USA

Cormetech, Inc.
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Durham, NC 27712
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Mitsubishi Hitachi Power Systems Ltd. (MHPS)
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Japan

Johnson Matthey
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Reading RG4 9NH
United Kingdom

STEAG Energy Services GmbH
Forellstraße 100
Herne 44629
Germany

2017 EPRI Multi-Lab Comparison Test Plan (Hg Oxidation)

Industry Collaboration (coal-fired systems)

EPRI Report #3002009279

Laboratory Comparative SCR Catalyst Testing for Mercury Oxidation

Table 2-1
Mercury Oxidation Test Conditions

Parameter	Reference Test Condition Target Value	Allowable Deviation from Target[2]	Allowable Drift[3]
Temperature	700°F	± 10°F	± 5°F
Flow Rate	TBD (0°C, 1 atm.)	± 2% relative	± 2% relative
O_2	3.0% (dry)	± 0.1%, absolute	± 0.1%, absolute
H_2O	8.0% (actual O_2)	± 1%, absolute	± 0.5%, absolute
CO_2	0.0% or as-generated	--	--
NOx	0.0 ppmvd (3% O_2)	± 5% of value	± 2% of value
α (NH_3/NOx ratio)	0.00 (i.e., no NH_3)	± 0.02 absolute	± 0.01 absolute
SO_2	1,000 ppmv (dry, 3% O_2)	± 5% of value	± 2% of value
HCl	75 ppmv (dry, 3% O_2)	3 ppmv absolute	2 ppmv absolute
Hg^0	20-100 µg/m³ (dry, 3% O_2, 32°F, 1 atm.)	--	± 5% of value
N_2	balance	--	--

Table 2-2
Approximate Equilibrium Times and Recommended Frequency of Mercury Measurements

Sample/Test Type	Approximate Time to Establish Equilibrium	Recommended Frequency of Mercury Measurements	Number of Measurements Recommended to Show Established Equilibrium[4]	Allowable Loss/Gain in Total Mercury across Catalyst	Allowable Deviation in Elemental Mercury Oxidation Rate across Catalyst
New or freshly regenerated catalyst, initial conditioning and lab testing	72-168 hours	One (1) set of inlet/outlet measurements every 4-8 hours	Minimum of six (6) sets of inlet/outlet measurements spaced evenly across minimum 24-hour period	≤5% of inlet value, no trending[5]	AVG[6] ± 5% (absolute), no trending
Aged catalyst,[7] initial lab testing or after lab system SD/SU [8]	48-72 hours	One (1) set of inlet/outlet measurements every 4-8 hours	Minimum of six (6) sets of inlet/outlet measurements spaced evenly across minimum 24-hour period	≤5% of inlet value, no trending	AVG ± 5% (absolute), no trending
Aged catalyst, change in lab test conditions, not including lab system SD/SU	12-24 hours	One (1) set of inlet/outlet measurements every 2-4 hours	Minimum of three (3) sets of inlet/outlet measurements spaced evenly across minimum 8-hour period	≤5% of inlet value, no trending	AVG ± 5% (absolute), no trending

2017 Multi-Lab Hg Oxidation Tests: EPRI Report #3002011761

SCR Catalyst Sample Characteristics

Table 1-1
Parent Element Geometry

Parameter	Value
Catalyst Type	Honeycomb
Pitch	7.1 mm
Wall Thickness	0.8 mm
Cross Section	150 mm x 150 mm
Specific Surface Area	502 m^2/m^3

Table 1-2
Sample Dimensions

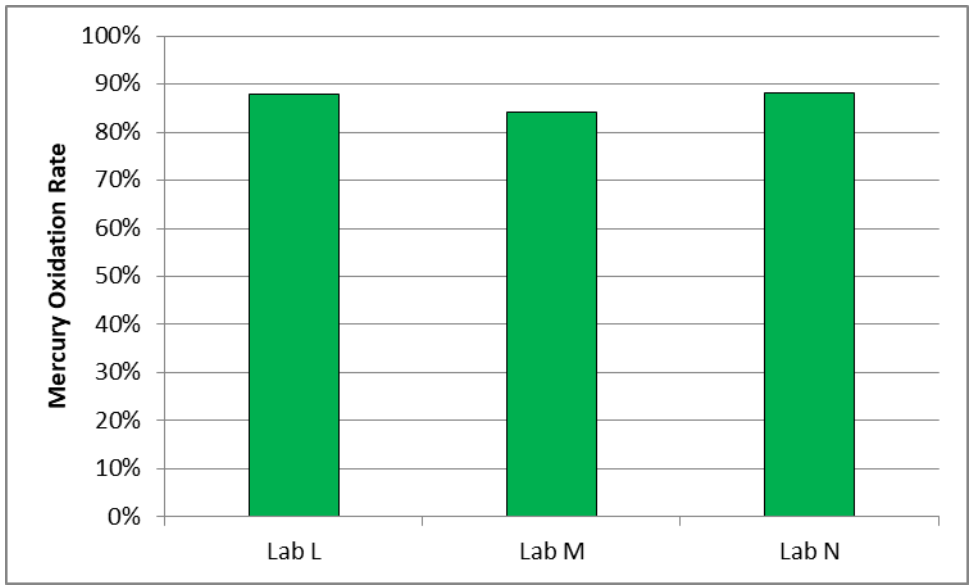
Parameter	Micro		Semi-Bench[4]
Cell Configuration	2x2	3x3	4x4
Cross Section	15.0 mm x 15.0 mm	22.1 mm x 22.1 mm	29.2 mm x 29.2 mm
Length	151 mm	151 mm	649 mm
Sample Surface Area	0.0154 m^2	0.0346 m^2	0.264 m^2

[3] Note that the 2x2 micro sample was broken after its initial testing. A replicate sample was cut from the same honeycomb element, and all other labs tested this replicate sample.

[4] The semi-bench sample was cut into two roughly equal lengths, and assembled in the test reactor end to end for testing.

Multi-Lab Comparison Results (Hg Oxidation)

Micro-Scale Tests



Parameter	Test Plan	Lab L	Lab M	Lab N
Sample Size	2x2	2x2	2x2	2x2
Temperature (°F)	700	700	700	700
Flow Rate (m^3/hr @ 0 °C)	0.198	0.198	0.198	0.198
O_2 (2.9%, dry)	2.9	3.0	2.9	2.9
H_2O (%, actual O_2)	8.0	8.0	8.0	8.0
SO_2 (ppmv, dry, 3% O_2)	1,000	1,014	1,000	1,032
HCl (ppmv, dry, 3% O_2)	25	25.9	25.0	25.0
Hg^0 (dry, 3% O_2, 0 °C, 1 atm.)	20-100	50.2	73.8	23.9
Mercury Oxidation Rate		88.0%	84.1%	88.2%

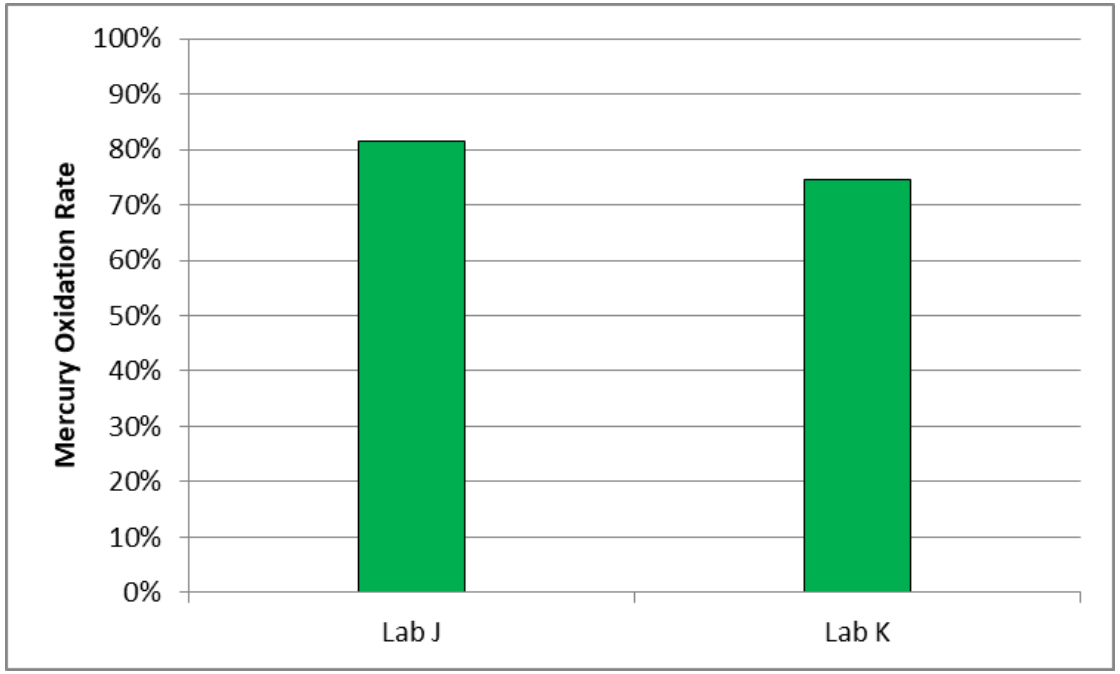
Parameter	Value
Average	86.8%
High	88.2%
Low	84.1%
Absolute Deviation from Mean Above	+1.4%
Absolute Deviation from Mean Below	-2.7%
Relative Deviation from Mean Above	+1.7%
Relative Deviation from Mean Below	-3.1%
Standard Deviation	2.3%
Relative Standard Deviation	2.7%

Multi-Lab Comparison Results (Hg Oxidation)

Semi-Bench Tests

Parameter	Test Plan	Lab J	Lab K
Sample Size	4x4	4x4	4x4
Temperature (°F)	700	700	701
Flow Rate (m^3/hr @ 0 °C)	5.01	4.99	5.02
O_2 (2.9%, dry)	2.9	2.7	3.1
H_2O (%, actual O_2)	8.0	7.1	7.9
SO_2 (ppmv, dry, 3% O_2)	1,000	1,084	961
HCl (ppmv, dry, 3% O_2)	75	71.2	73.9
Hg^0 (dry, 3% O_2, 0 °C, 1 atm.)	20-100	29.9	11.1
Mercury Oxidation Rate		**81.6%**	**74.6%**

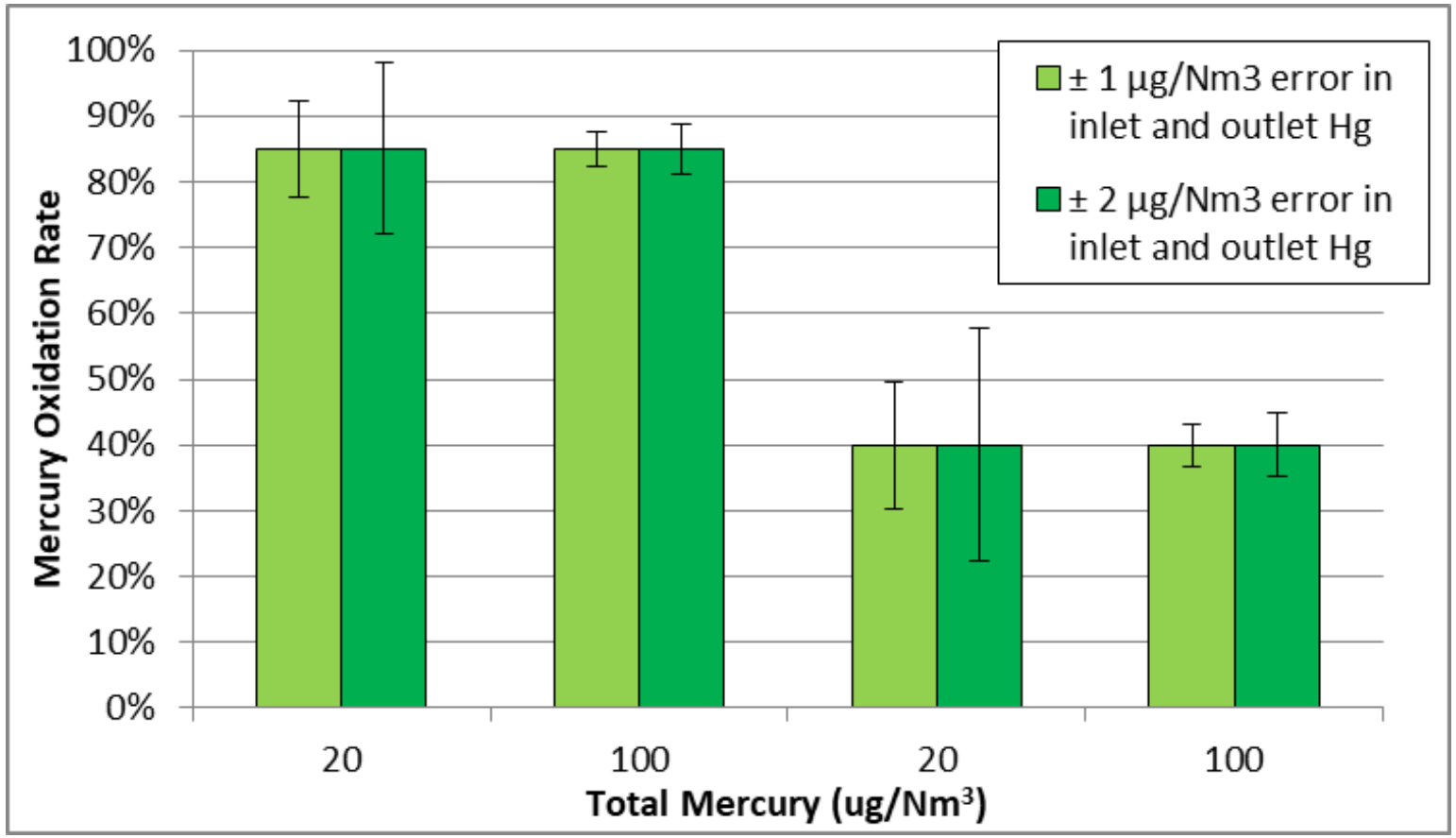
Parameter	Value
Average	78.1%
Absolute Deviation from Mean	±3.5%
Relative Deviation from Mean	±4.5%



Multi-Lab Comparison Results (Hg Oxidation)

Measurement Error Discussion

Impact of Hg Measurement Error



Conclusions

Multi-Lab Comparison: Hg Oxidation

- **Results provide a glimpse of current inter-lab uncertainty bounds**
- **Micro-Scale Tests (3 labs):**
  - Relative standard deviation: 2.7%
- **Semi-Bench Tests (2 labs):**
  - Mercury oxidation results: 81.6% vs 74.6%
- **Accuracy of lab instrumentation not verified**
- **Results not to be used for auditing or certification purposes (no “gold standard” used for comparison)**

Next Steps

Hg Oxidation

- **Update EPRI testing protocol?**
  - **Variations in ammonia and halogen levels**