

REINHOLD ENVIRONMENTAL Ltd.



2016 NO_x-Combustion-CCR Round Table Presentation

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

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Catalyst Testing: Beyond EPRI and VGB

Nick Pollack – STEAG SCR-TECH
Ken Jeffers – Southern Research



EPRI/VGB – Just One Piece of the Testing Puzzle



System Design Considerations

Pre Test QA/QC Procedures

Procedures for Conversion and Activity Measurements

Reporting



EPRI/VGB

Measuring catalyst geometry
General activity and conversion procedures
Conditioning
Specifies test conditions

Design Considerations

Flow Distribution Analysis



Initial design

- SO2 Injection location 1
- No Mixing at reactor entrance

SO2 Uniformity - Baseline

Variation through Catalyst Channels

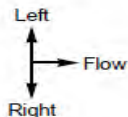
% Deviation Relative to Average:

6.3	1.8	1.8	2.5	3.6	5.0	6.6	8.5	10.5	12.6	14.8	16.9	18.9	20.8	22.6	24.1
3.2	-2.7	-2.9	-2.3	-1.2	0.3	2.2	4.4	7.0	9.7	12.5	15.2	17.8	20.2	22.3	24.3
2.6	-5.3	-6.3	-6.2	-5.5	-4.1	-2.2	0.3	3.3	6.6	10.1	13.4	16.6	19.5	22.2	24.5
1.6	-7.5	-9.1	-9.5	-9.1	-8.0	-6.2	-3.7	-0.4	3.4	7.5	11.6	15.5	18.9	22.0	24.7
0.6	-9.4	-11.4	-12.1	-12.0	-11.2	-9.6	-7.1	-3.9	0.2	4.9	9.7	14.3	18.3	21.8	24.8
0.2	-11.1	-13.3	-14.2	-14.3	-13.6	-12.2	-9.9	-6.7	-2.6	2.2	7.5	12.8	17.5	21.5	24.8
0.9	-12.3	-14.7	-15.7	-15.9	-15.4	-14.1	-11.9	-8.8	-4.7	0.0	5.3	11.1	16.5	21.0	24.5
2.5	-13.2	-15.7	-16.7	-17.0	-16.5	-15.3	-13.3	-10.2	-6.2	-1.5	3.7	9.5	15.3	20.2	24.0
3.6	-13.8	-16.3	-17.3	-17.6	-17.2	-16.1	-14.1	-11.2	-7.2	-2.6	2.5	8.2	14.1	19.2	23.2
3.4	-14.1	-16.6	-17.5	-17.7	-17.3	-16.3	-14.4	-11.6	-7.8	-3.3	1.7	7.3	13.0	18.0	22.2
2.8	-14.0	-16.4	-17.3	-17.4	-16.9	-15.9	-14.1	-11.4	-7.9	-3.6	1.3	6.6	11.9	16.7	20.9
3.3	-13.2	-15.8	-16.5	-16.5	-16.0	-14.8	-13.0	-10.5	-7.2	-3.2	1.3	6.1	10.8	15.4	19.6
4.7	-12.1	-14.7	-15.3	-15.1	-14.4	-13.1	-11.3	-8.9	-5.9	-2.4	1.6	5.8	10.0	14.2	18.3
5.3	-11.0	-13.3	-13.5	-13.1	-12.2	-10.8	-9.1	-6.8	-4.1	-1.0	2.4	6.0	9.6	13.2	17.0
3.5	-9.9	-11.4	-11.2	-10.4	-9.3	-7.9	-6.2	-4.1	-1.7	0.9	3.7	6.7	9.7	12.6	15.7
8.8	-3.5	-6.9	-7.2	-6.6	-5.5	-4.2	-2.7	-0.9	1.2	3.4	5.7	8.1	10.4	12.6	14.8

Average Concentration 3.35E-3 kg SO2 / kg Air
 RMS 12.4 %
 Channels within ±2.5% of Average 11.3 %
 Channels within ±5.0% of Average 24.6 %
 Maximum +24.8 %
 Minimum -17.7 %

Above +2.5%
 Below -2.5%

Table 3



Design Considerations

Flow Distribution Analysis



Revised design

- SO2 Injection location 2
- Mixing added at reactor entrance

SO2 Uniformity - Design 1

Variation through Catalyst Channels

% Deviation Relative to Average:

0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.4	0.4	0.4	0.5	0.5	0.6	0.6	0.6
0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.4	0.4	0.5	0.5	0.5	0.6
0.2	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.3	0.3	0.4	0.4	0.5	0.5	0.6
0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.3	0.3	0.4	0.4	0.5	0.5
0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.2	0.3	0.3	0.4	0.5	0.5
0.1	0.0	-0.1	-0.1	-0.1	-0.1	0.0	0.0	0.0	0.1	0.1	0.2	0.3	0.4	0.4	0.5
0.0	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	0.0	0.0	0.1	0.2	0.2	0.3	0.4	0.5	0.5
-0.1	-0.2	-0.2	-0.2	-0.2	-0.2	-0.1	-0.1	-0.1	0.0	0.1	0.2	0.3	0.4	0.4	0.5
-0.3	-0.3	-0.3	-0.3	-0.3	-0.2	-0.2	-0.2	-0.1	-0.1	0.0	0.1	0.1	0.2	0.3	0.4
-0.4	-0.4	-0.4	-0.3	-0.3	-0.3	-0.2	-0.2	-0.1	-0.1	0.0	0.0	0.1	0.2	0.3	0.3
-0.5	-0.5	-0.4	-0.4	-0.4	-0.3	-0.3	-0.2	-0.2	-0.1	-0.1	0.0	0.1	0.2	0.3	0.3
-0.6	-0.5	-0.5	-0.5	-0.4	-0.4	-0.3	-0.3	-0.2	-0.2	-0.1	0.0	0.1	0.1	0.2	0.3
-0.6	-0.5	-0.5	-0.5	-0.4	-0.4	-0.3	-0.3	-0.2	-0.2	-0.1	0.0	0.0	0.1	0.2	0.2
-0.6	-0.6	-0.5	-0.5	-0.5	-0.4	-0.4	-0.3	-0.3	-0.2	-0.1	-0.1	0.0	0.1	0.2	0.2
-0.6	-0.6	-0.5	-0.5	-0.5	-0.4	-0.4	-0.3	-0.3	-0.2	-0.1	-0.1	0.0	0.1	0.1	0.2
-0.6	-0.6	-0.5	-0.5	-0.5	-0.4	-0.4	-0.3	-0.2	-0.2	-0.1	0.0	0.0	0.1	0.1	0.2

Average Concentration 3.35E-3 kg SO2 / kg Air
 RMS 0.3 %
 Channels within ±2.5% of Average 100.0 %
 Channels within ±5.0% of Average 100.0 %
 Maximum +0.6 %
 Minimum -0.6 %

Above +2.5%
 Below -2.5%

Table 3

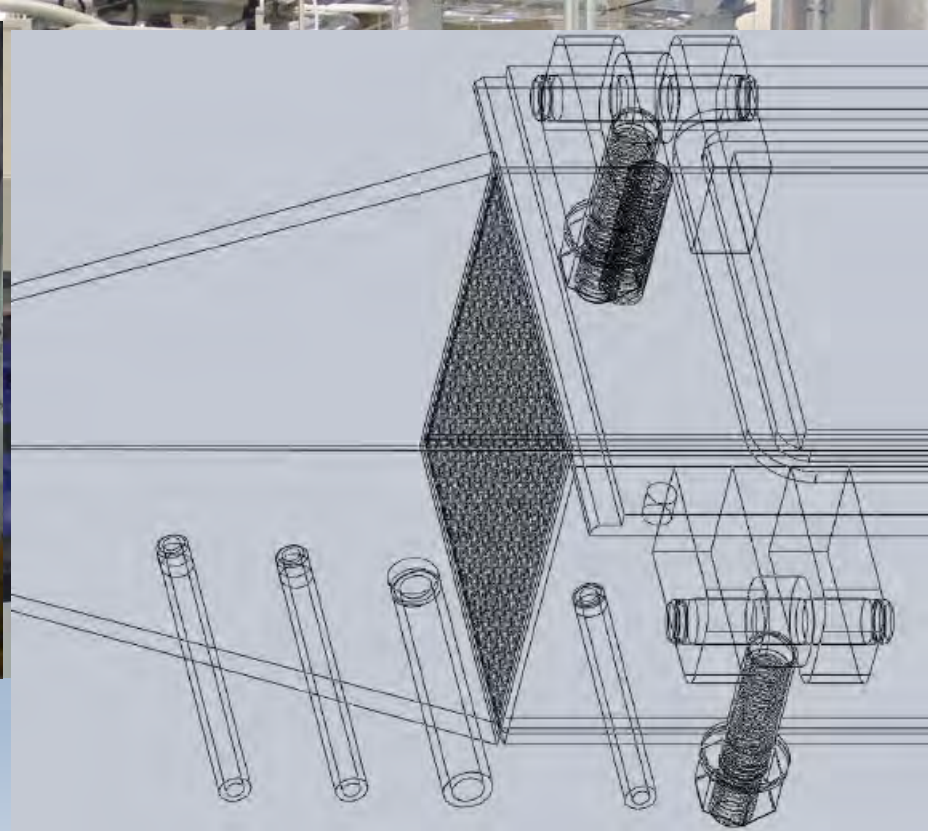


Design Considerations Analytical System

SOUTHERN
RESEARCH
1941-2016

75
YEARS

STEAG SCR-Tech
An Environmental Services Company



➤ Sample lines

- Located down stream of mixing devices
- Must be heated uniformly to eliminate ammonia reaction with SO₂

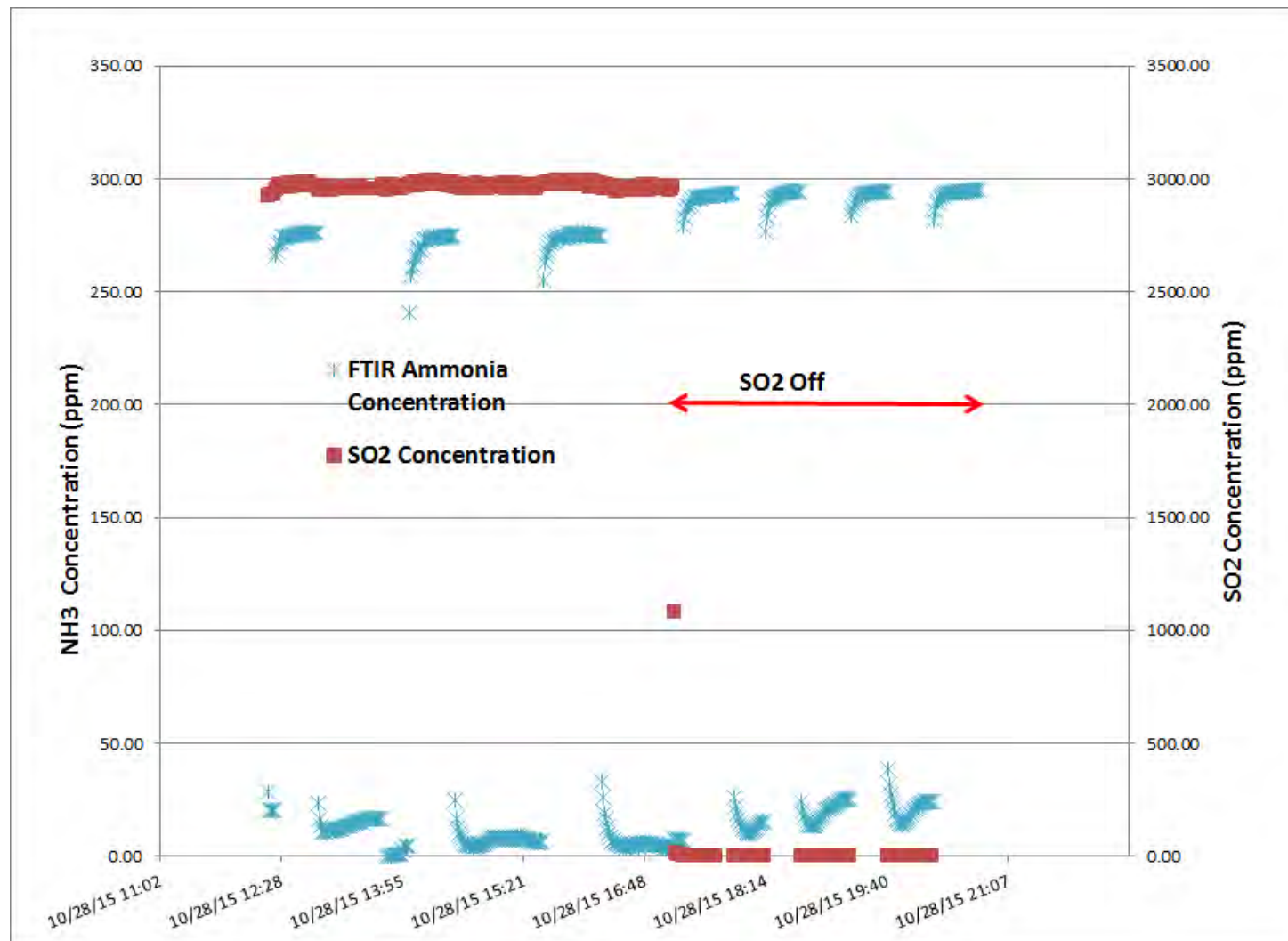
superior for ammonia measurement

Design Considerations Sample Train

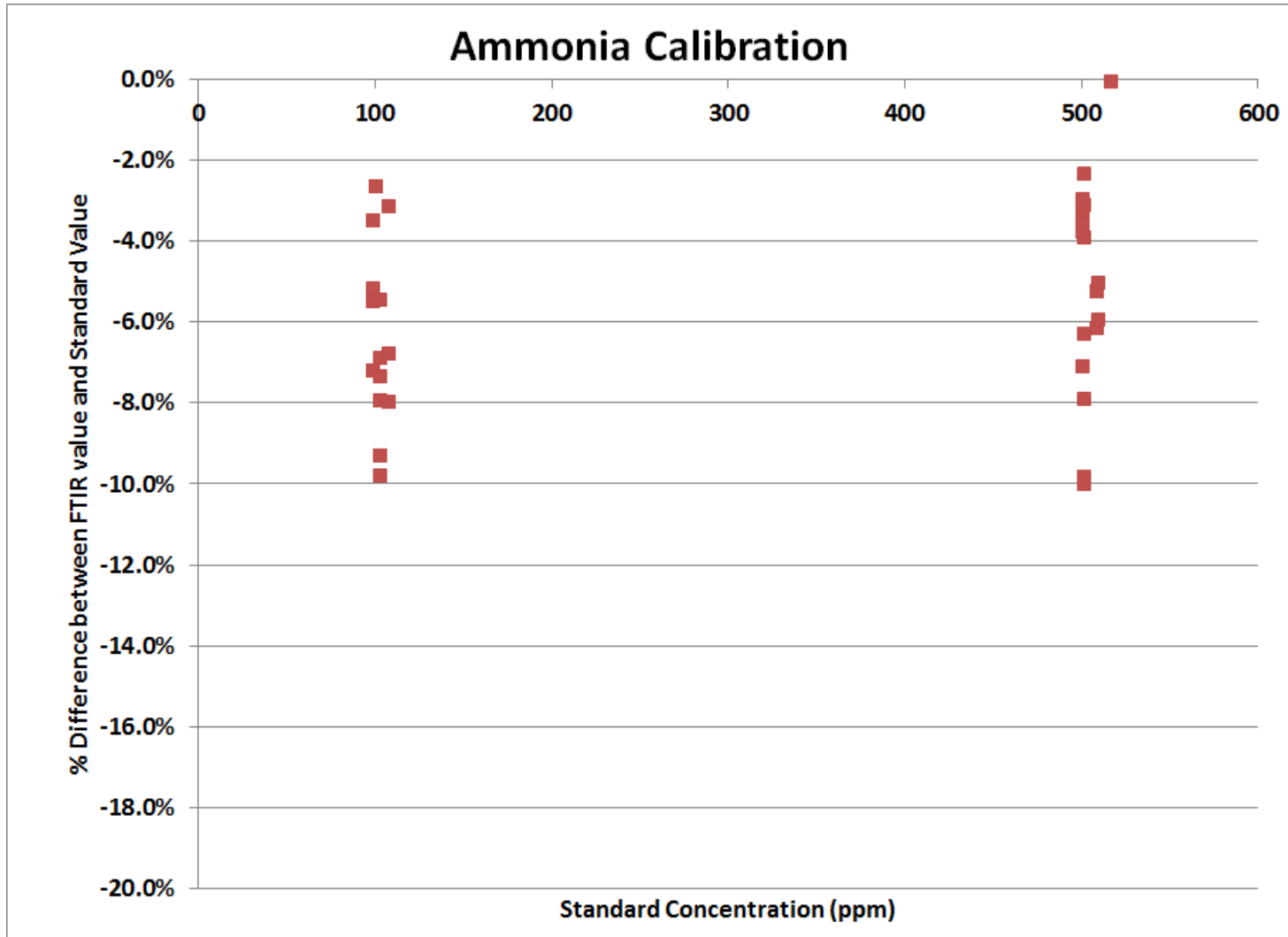
SOUTHERN
RESEARCH
1941-2016

75
YEARS

STEAG SCR-Tech
An Environmental Services Company



Daily Instrument Calibration



Pre Test QA/QC Measures



- Closing the mass balance – Mass injected -----> Concentration Measured
 - ✓ Total flow measurement
 - ✓ Mass flow controller
 - ✓ Analytical system
- SPC Charting – Is the process “in control”?
- Conducted prior to every test

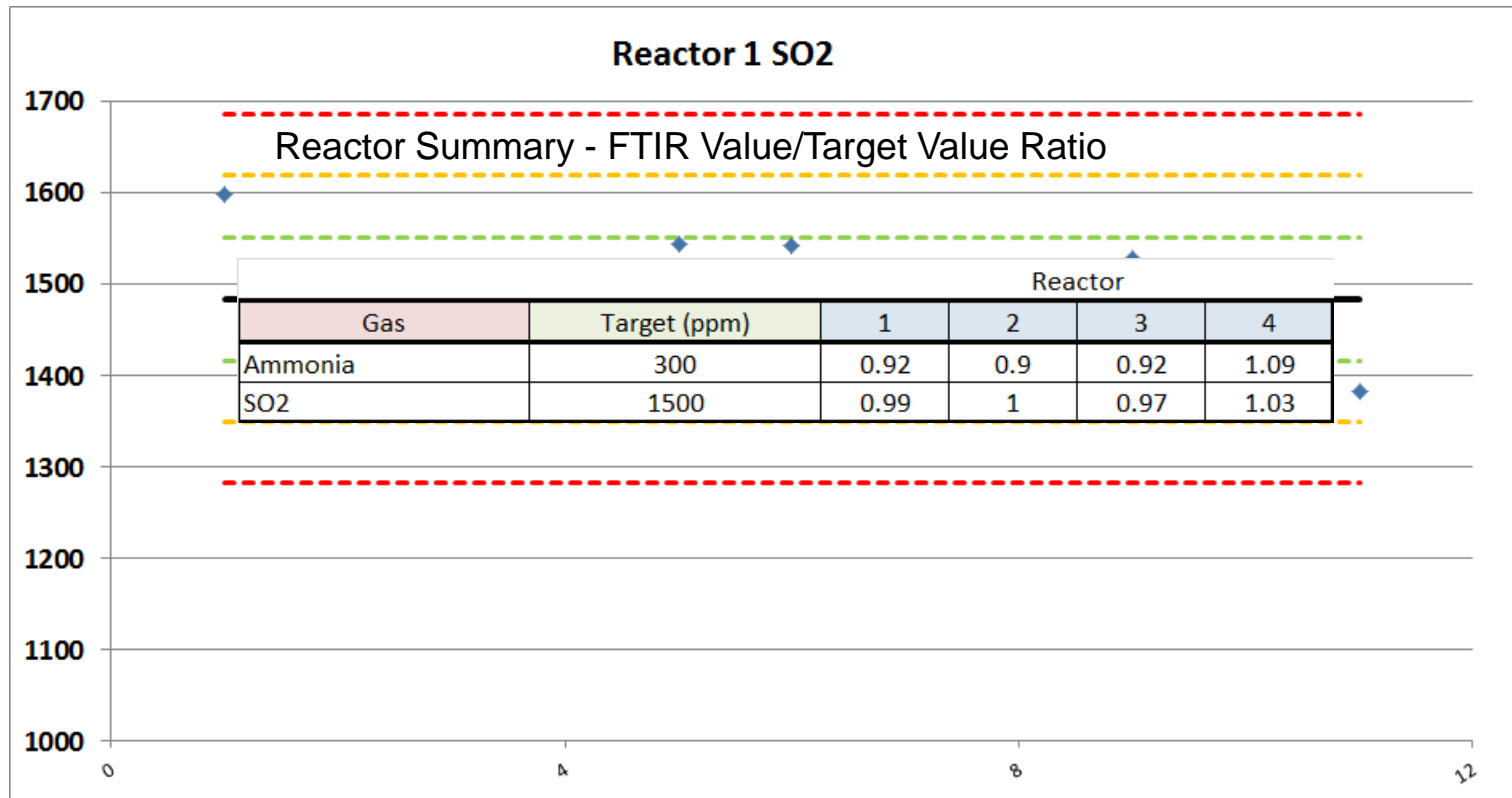


Plate Stacking is Critical



Well Stacked Plate Sample



Generally achievable with 2 pleats every 150 mm
5.7 mm plate and some 7 mm plates
Difficult when pleats are spaced > 150 mm

Plate Stacking is Critical

Inlet Initial Stacking

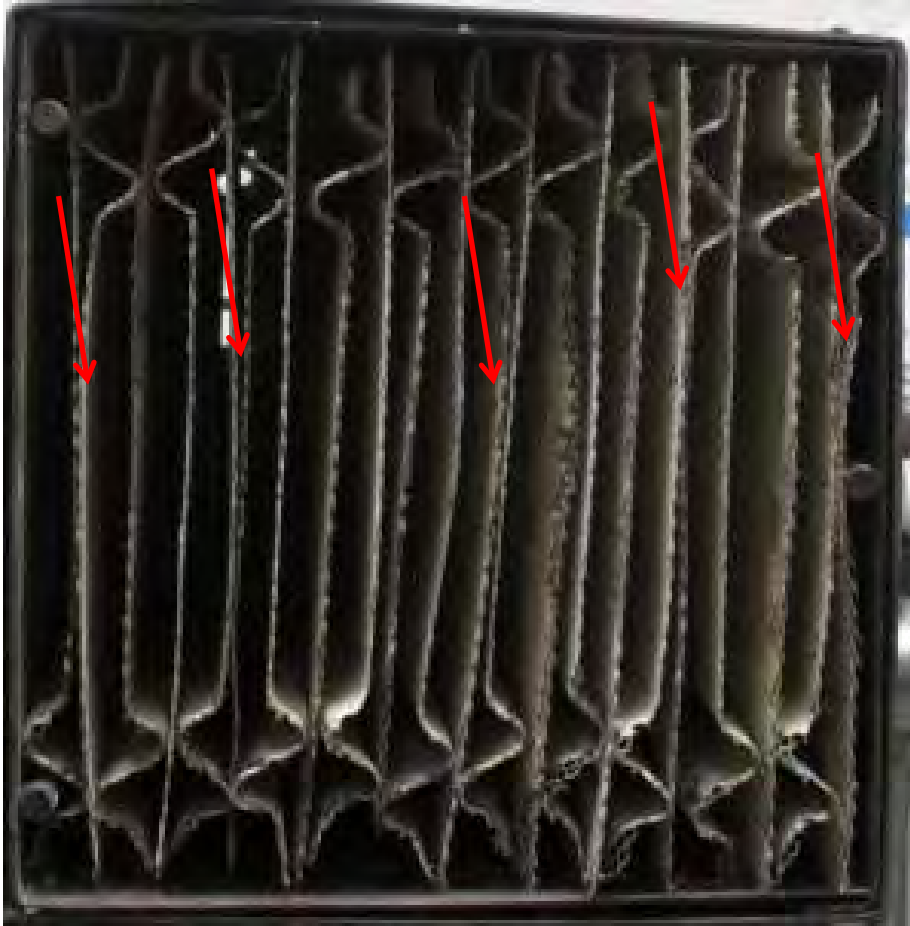


Inlet Restacked



Plate Stacking is Critical

Outlet Initial Stacking



Outlet Restacked



Plate Stacking is Critical



Date	Initial Stacking	Restacked
Activity	30.5	34.5
SO2 Conversion	0.50%	0.45%

Initial Stacking



Restacked



Honeycomb Plugging and Damage

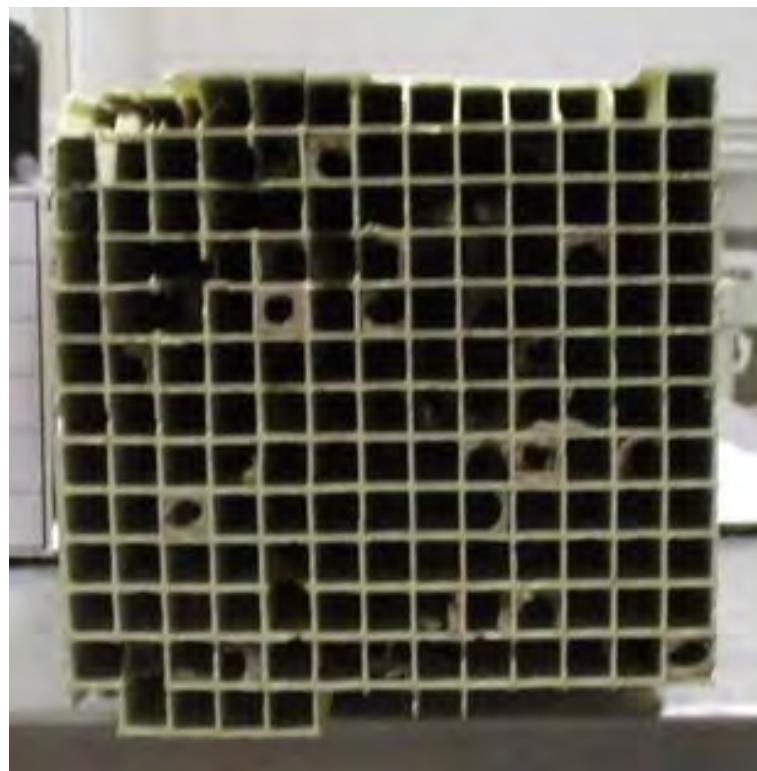
SOUTHERN
RESEARCH
1941-2016

75
YEARS

STEAG SCR-Tech
An Environmental Services Company

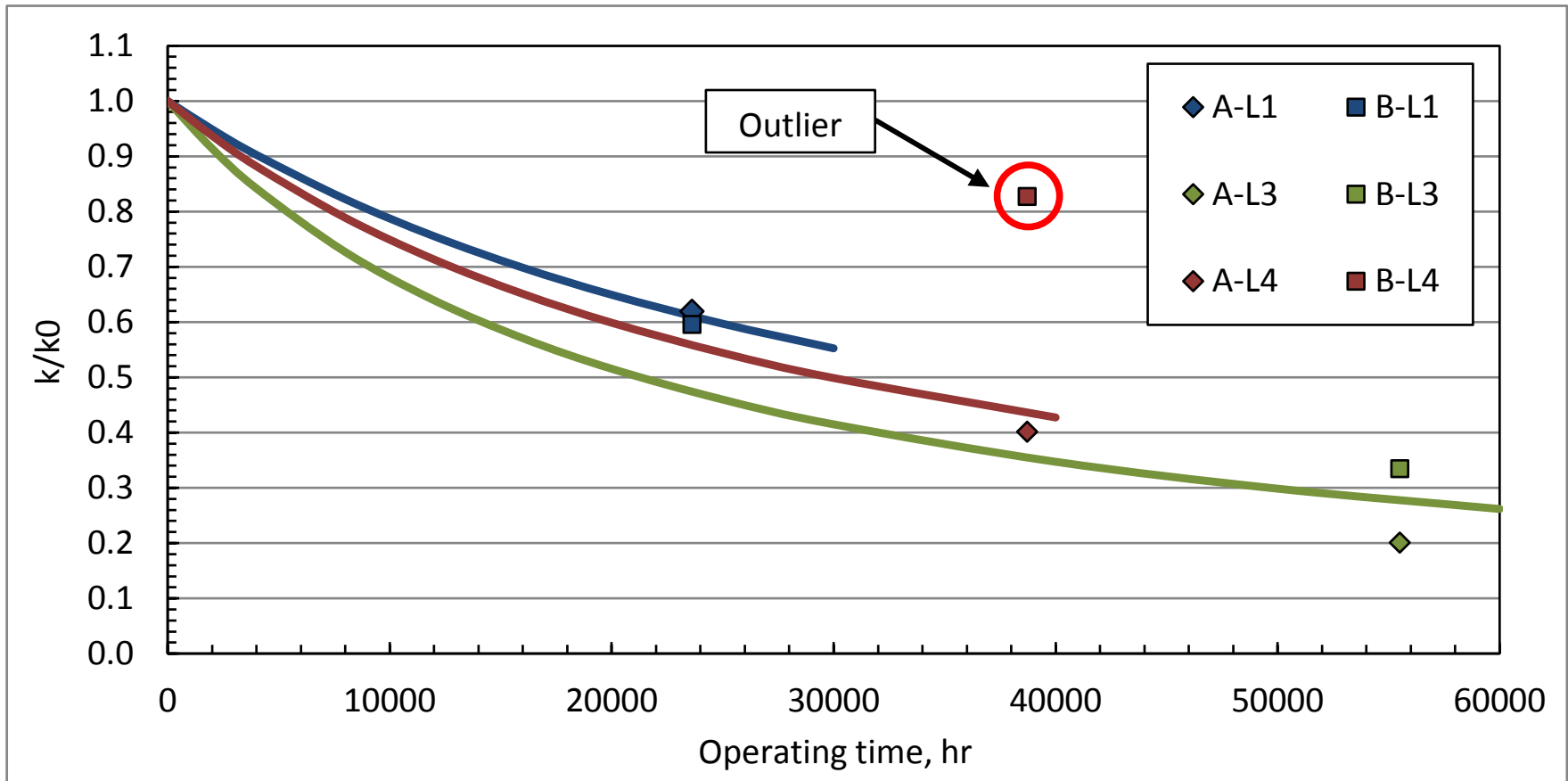


Inlet face as received, B-side Reactor



Inlet face after cleaning/repair

Activity Testing Results A-, B-side Comparison



Sample Plugging



Date	Sample ID	Activity, m/h	Arsenic Conc, ppm	Comments
10/16/2015	S15-1955	19.8	11338	6% Plugged
10/16/2015	S15-1968	27.5	3951	52% Plugged

Make flue gas → push through catalyst sample → performance tests

2 Tests:

#1 SO₂ – SO₃ Conversion (normally NH₃ = 0)

SO₃ determination at catalyst inlet and outlet by controlled condensation (EPA Method 8A)

SO₂ – SO₃ Conversion = (SO₃ increase / SO₂ in) * 100%

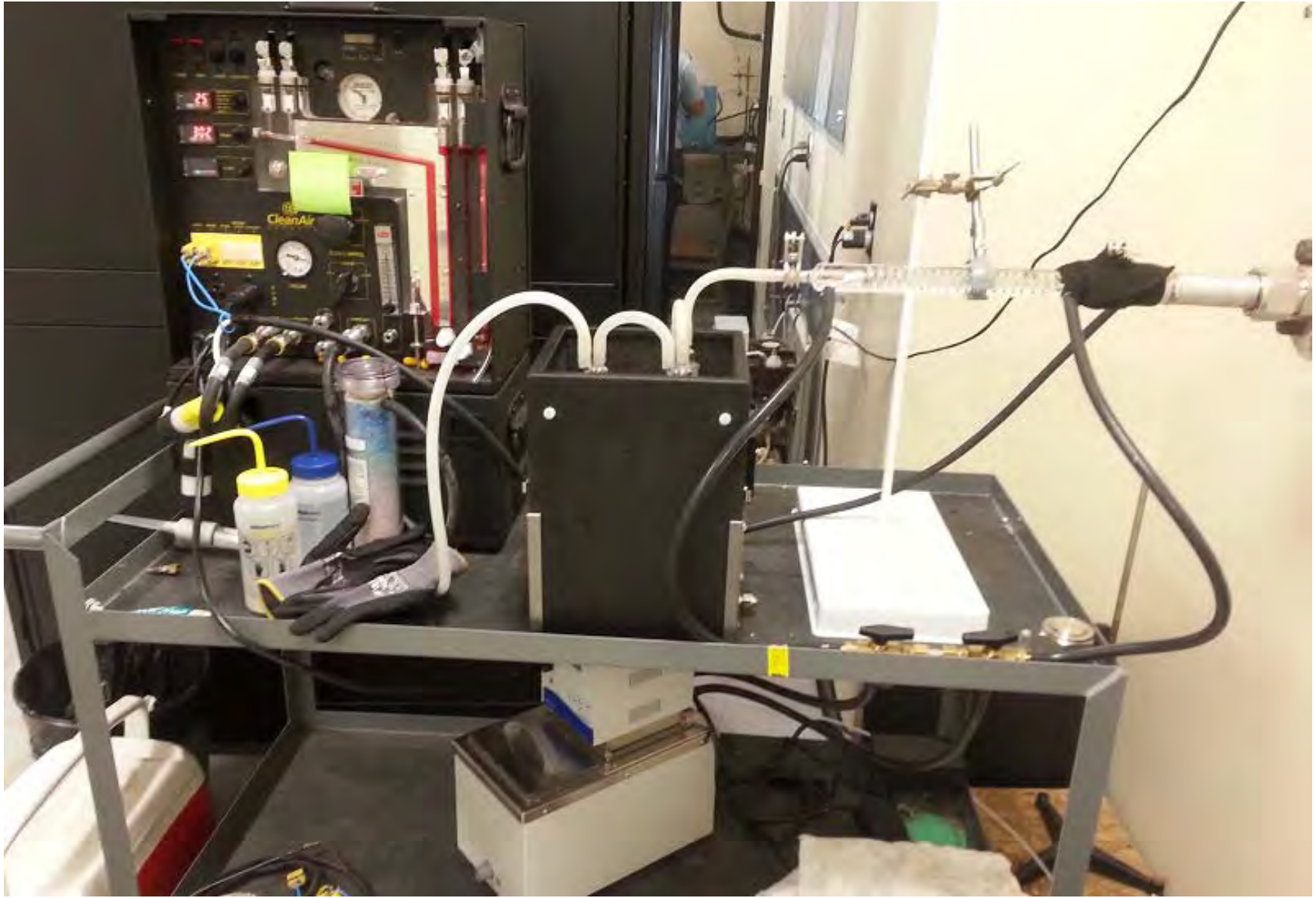
#2 deNO_x Activity, k

NO_x conversion = (NO_x in – NO_x out) / NO_x in

k = – AV ln (1 – NO_x conversion) valid for NH₃/NO_x = 1

AV = area velocity = Volumetric flow / catalyst surface area

SO3 – Contolled Condensation



SO₃ Determination Accuracy – Ba(ClO₄)₂ Titration



Variable	Units	Practical Error
Inlet SO ₂	ppmvd	+/- 2%
Barometric Pressure	in Hg	-
Titrant molarity	mol/L	+/- 1%
Titrant blank volume	mL	+/- 1%
Sampled flue gas volume	L (dry)	+/- 1 L
Temperature at Gas Meter	°C	+/- 1 °C
O ₂ at Gas Meter	vol% (dry)	+/- 0.1 vol%
Condenser Rinse Volume	mL	+/- 1 mL
Titrant Volume	mL	+/- 2%

Inlet Error: +/- 6% (~0.1 ppmvd)

Outlet Error +/- 3% (0.1 – 1.0 ppmvd)

SO₂ – SO₃ Conversion +/- 6 – 10%

SO3 Determination – IC vs Titration



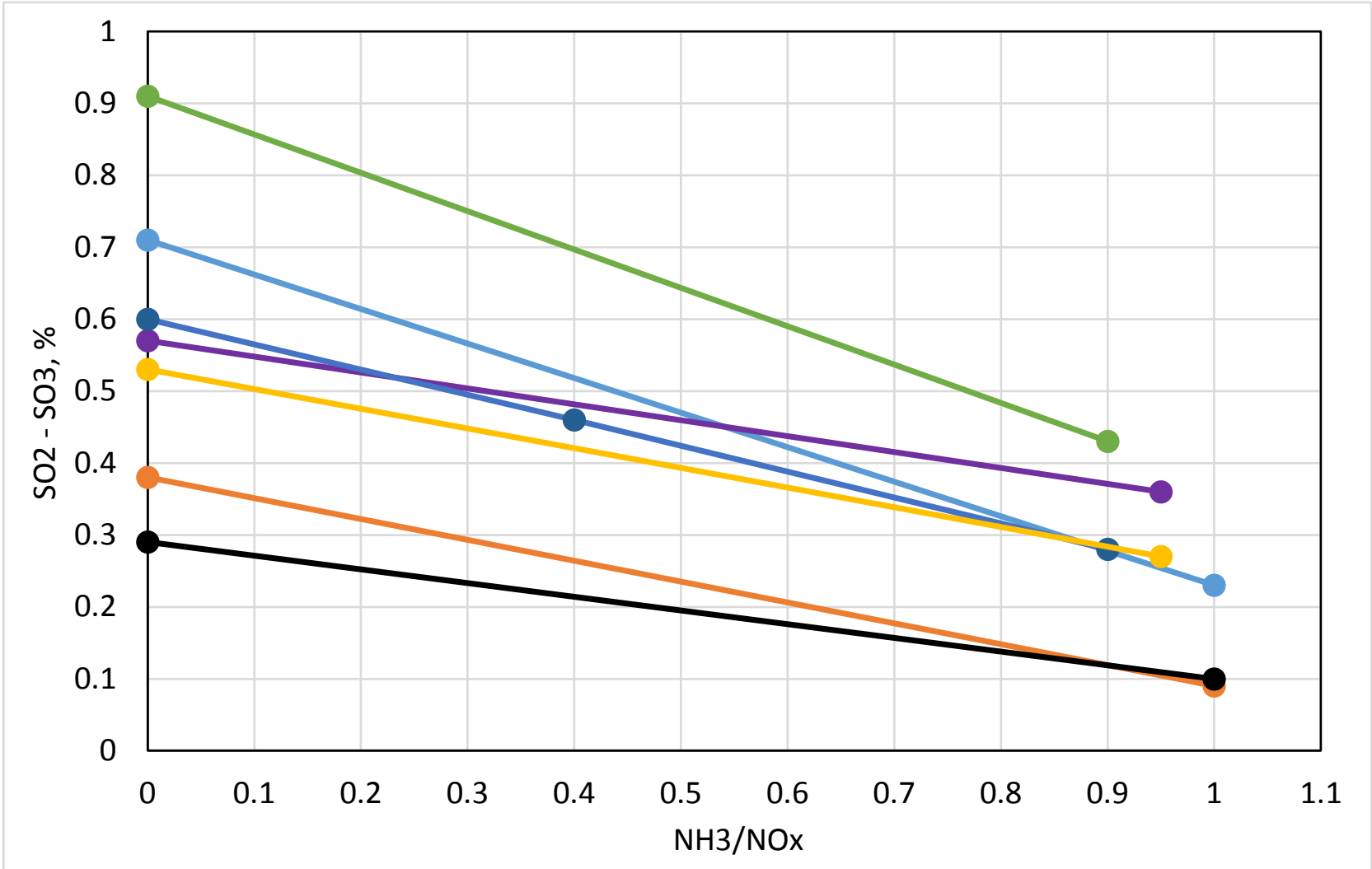
S15-1190

Sample	Inlet	Coil #1	Coil #2	Coil #3	Coil #4	Outlet Avg.	rel. mean diff. %
Coalogix measured [SO3] (ppmvd)	0.05	3.78	3.83	3.90	3.92	3.86	
Coalogix calc. Conv %	N/A	0.285	0.290	0.297	0.297	0.292	
SRI measured [SO3] (ppmvd)	0.073	3.590	3.597	3.688	3.568	3.61	
SRI calc. Conv %	N/A	0.269	0.271	0.279	0.268	0.272	
SRI measured [SO3] (ppmvd) input into Coalogix calc. method	N/A	0.270	0.273	0.280	0.270	0.273	

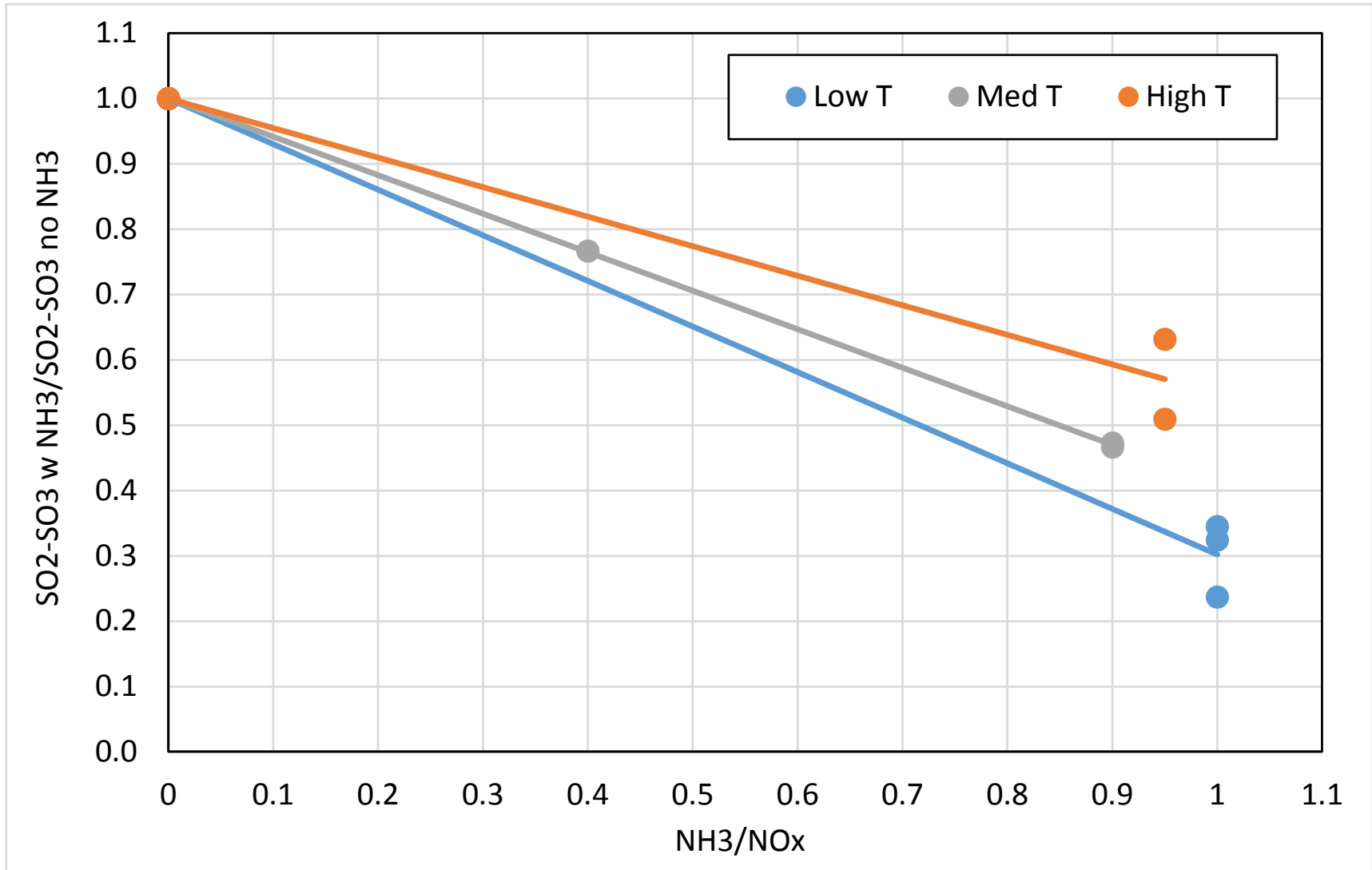
S15-1240

Sample	Inlet	Coil #1	Coil #2	Coil #3	Coil #4	Outlet Avg.	rel. mean diff. %
Coalogix measured [SO3] (ppmvd)	0.04	3.12	3.54	3.58	3.72	3.49	
Coalogix calc. Conv %	N/A	0.146	0.166	0.168	0.175	0.164	
SRI measured [SO3] (ppmvd)	0.034	2.955	3.358	3.368	3.543	3.31	
SRI calc. Conv %	N/A	0.139	0.159	0.159	0.167	0.156	
SRI measured [SO3] (ppmvd) input into Coalogix calc. method	N/A	0.138	0.158	0.158	0.166	0.155	

SO2 – SO3 with NH3



SO2 – SO3 with NH3



Impact of SO₂ on deNO_x Activity, k



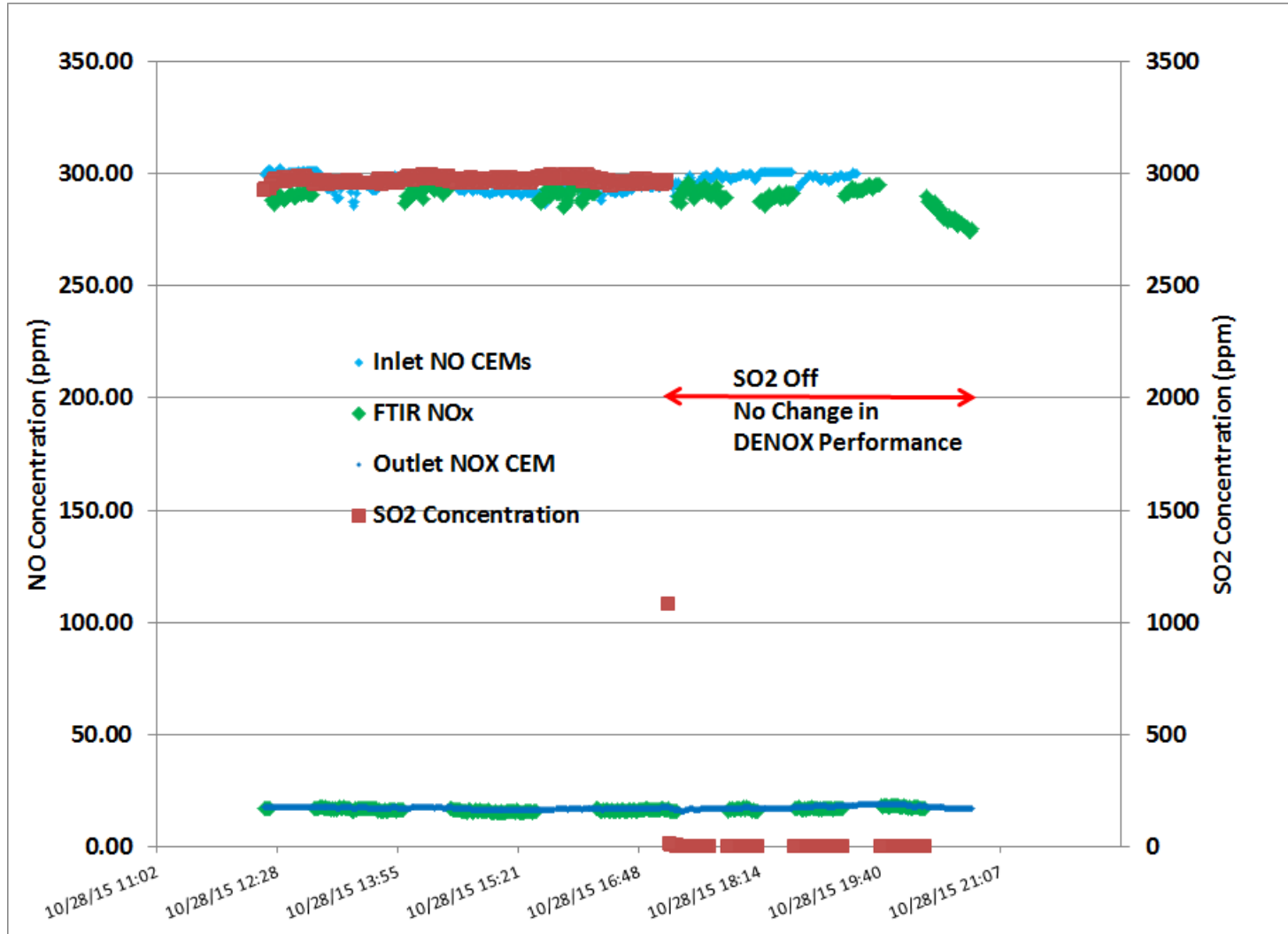
Fresh catalyst element, never exposed to flue gas

Test 1 – flue gas on ~12 hr, no SO₂, measure k

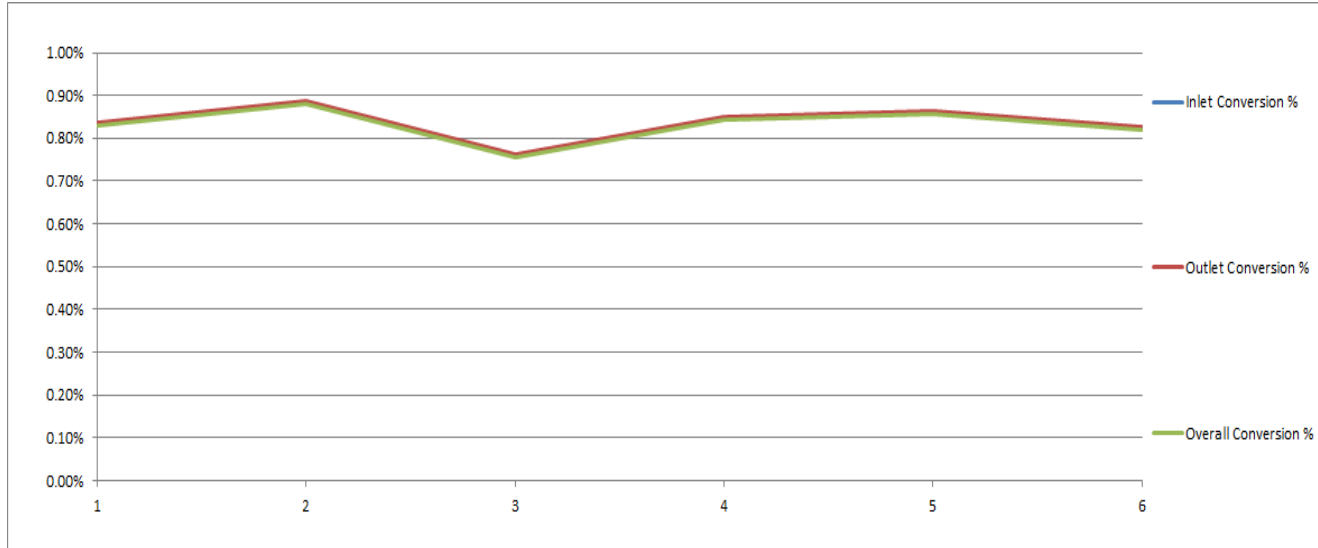
Test 2 – condition ~60 hr with 2000 ppmvd SO₂, measure k

Condition	Test 1	Test 2
Flue gas on, hr	12	60
Temperature, F	700	700
Flow, N m ³ /h	120	120
SO ₂ , ppmvd	0	2000
O ₂ , vol% dry	4	4
H ₂ O, vol%	8.1	8.2
NO _x , ppmvd	297	301
NH ₃ /NO _x	1.006	1.004
k, m/h	33.9	41.4

Impact of SO2 on Activity



Steady State Measurements – Statistical Verification



Period	Period Start	Period Stop	SO3 in (ppmvd)	SO3 Out (ppmvd)	SO3 Increase (ppmvd)	SO2 (ppmvd)	% Conversion
1	12/6/15 12:05	12/6/15 13:20	0.02	2.48	2.46	296.6	0.83%
2	12/6/15 13:25	12/6/15 13:50	0.02	2.64	2.62	297.1	0.88%
3	12/6/15 13:55	12/6/15 14:20	0.02	2.27	2.25	297.1	0.76%
4	12/6/15 14:25	12/6/15 15:24	0.02	2.53	2.51	297.7	0.84%
		Average	0.0	2.5	2.5	297.1	0.83%

$$1. \left(\left| \frac{m(\text{slope of conv.plot})}{\bar{x}(\text{avg.conv.})} \right| \right) \leq 2\%$$

$$2. \left(\frac{\text{std}(x)(\text{std.dev.conv.data points})}{\bar{x}(\text{avg.conv.})} \right) \leq 10\%$$

Sample Geometry Summary
 Comparison of Test Targets to Actual Conditions
 Conditioning time and conditions
 Proof of Steady State

DeNO_x Detailed Test Results

Period Start	Period Stop	NO in	NO out	%DeNO _x	Activity
12/6/15 18:08	12/6/15 18:45	634.4	30.2	95.29%	38.9
12/6/15 18:46	12/6/15 19:24	636.5	30.5	95.29%	38.8
12/6/15 19:27	12/6/15 20:01	634.0	30.1	95.31%	38.8
12/6/15 20:02	12/6/15 20:29	634.0	30.0	95.35%	38.9
Average		634.7	30.2	95.31%	38.8

SO₂ – SO₃ Conversion Results

Period Start	Period Stop	SO ₃ in (ppm)	SO ₃ Out (ppm)	SO ₃ Increase (ppm)	SO ₂ (ppm)	% Conversion
12/6/15 16:16	12/6/15 13:20	0.02	2.59	2.57	298.2	0.86%
12/6/15 14:25	12/6/15 15:24	0.02	2.53	2.51	297.7	0.84%
12/6/15 15:28	12/6/15 15:50	0.02	2.57	2.56	298.2	0.86%
12/6/15 15:55	12/6/15 16:14	0.02	2.46	2.45	298.2	0.82%
Average		0.02	2.54	2.52	298.1	0.85%

Pictures of the catalyst as received and as tested

Lab-to-Lab Comparison



Sample	S15-0302		S15-0700		S14-1516		S15-0819		S15-0978		S15-1950	
Catalyst Type	Plate		Plate		Plate		Honeycomb		Honeycomb		Plate	
Temperature	382		384		338		360		385		343	
Flow (Nm ³ /hr)	152		215		178		160		157		152	
NO _x (ppmvd)	322		365		353		358		300		295	
SO ₂ (ppmvd)	3376		888		712		2087		2800		2608	
H ₂ O (%)	9.4		11.8		8.8		8.3		9.5		9.5	
O ₂ (dry %)	3.5		3.5		3.0		3.3		3.2		3.4	
Lab	SCR-TECH	SR	SCR-TECH	SR	SCR-TECH	SR	SCR-TECH	SR	SCR-TECH	SR	SCR-TECH	SR
K	36.5	36.9	39.5	43.8	45.2	43.6	39.6	N/A	37.7	40.1	38.9	38.7
DeNO _x (%)	91.3	92.2	74.0	76.6	88.8	87.9	95.0	N/A	95.0	96.6	74.2	74.0
K ₂₋₃	0.65	0.70	0.57	0.59	0.49	0.71	0.25	0.34	0.31	0.28	0.73	0.68
SO ₃ Increase (ppmvd)	21.4	23.6	5.1	5.2	3.5	5.1	4.9	7.1	8.8	6.9	19.0	17.7

Differences

- K, 1.8 m/h
- SO₂ – SO₃, 0.08%
- SO₃ delta, 1.6 ppmvd

Summary



- VGB/EPRI Compliance does not ensure consistent and reliable results
- Far more detail is required
 - ✓ System design features
 - ✓ QA/QC procedures
- Testing laboratories should be completely transparent with procedures and test results.
- Cooperation between laboratories is in everyone's interest.