REINHOLD ENVIRONMENTAL ®

2026 Reinhold/PCUG Round Table Presentation

Hosted by TVA, Southern Company and Vistra

in the Sonesta Nashville Airport Hotel, Nashville, TN

on June 22-23, 2026

2026 Reinhold PCUG Conference – June 22nd & 23rd 2026

Dry Sorbent Injection (DSI) Basics & Best Practices

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Travis Reynolds

Overview

- Introductions
- Audience Questionnaire
- DSI Quick Overview
- Piping Challenges & Design Considerations
- Conveying Air Systems
- Storage & Feed Systems
- Dispersion & Lance Design
- Sorbent Selection & Performance
- Key Takeaways

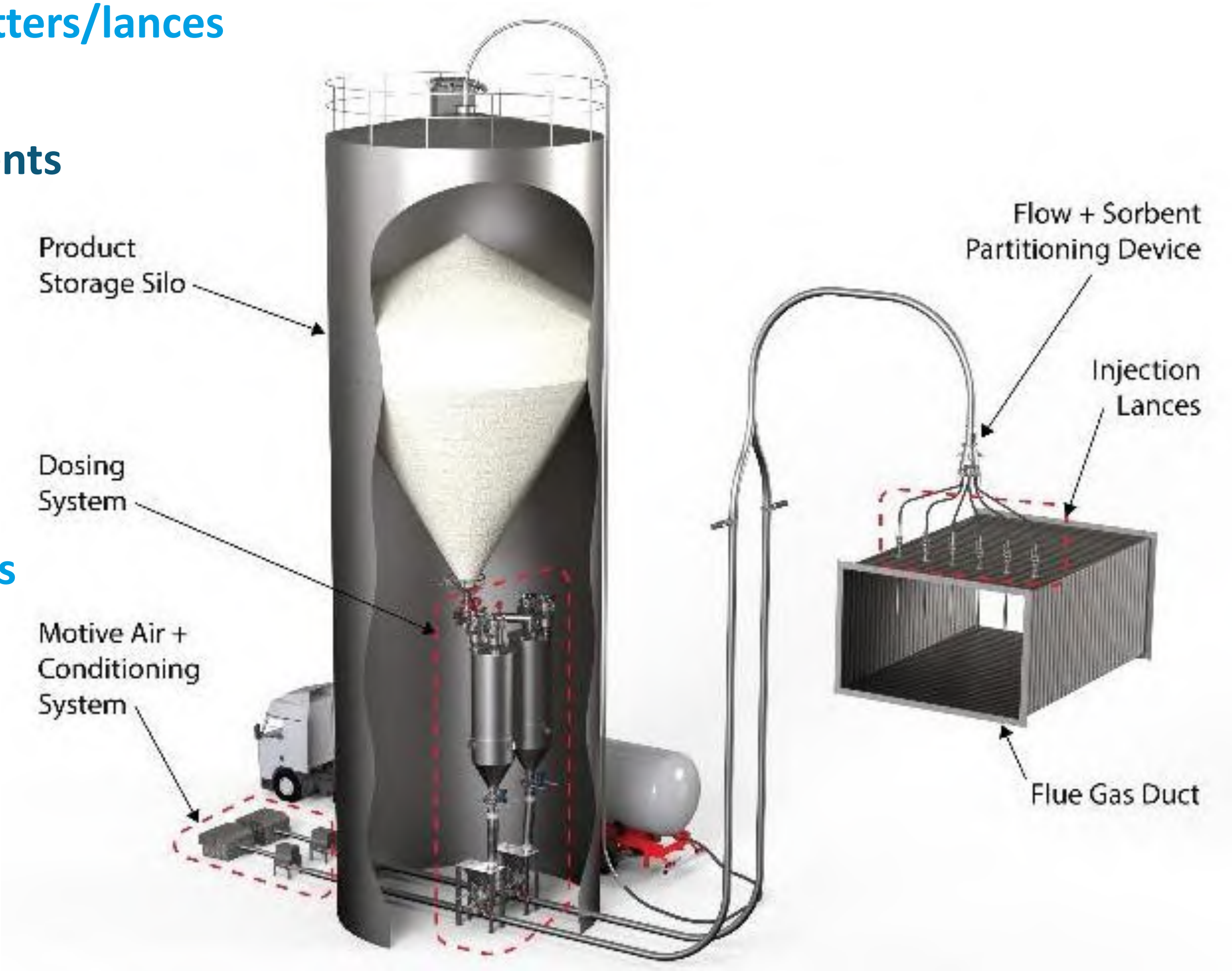
Audience Questionnaire

- **DSI experience?**
  - < 5 years
  - 5 to 10 years
  - > 10 years
- **Pain Points?**
  - Scaling and pipe plugging issues?
  - Conveying blowers or fans?
  - Feed system reliability (rotary air locks, loss-in-weight feeders, screw feeders, etc.)
  - Silos (filling, dusting, level indication, etc.)
  - Dispersion, injection lances, and mixing plates
- **DSI system optimization?**
- **Which sorbent are you using?**
  - Standard hydrated lime
  - Enhanced hydrated lime
  - Sodium based sorbent

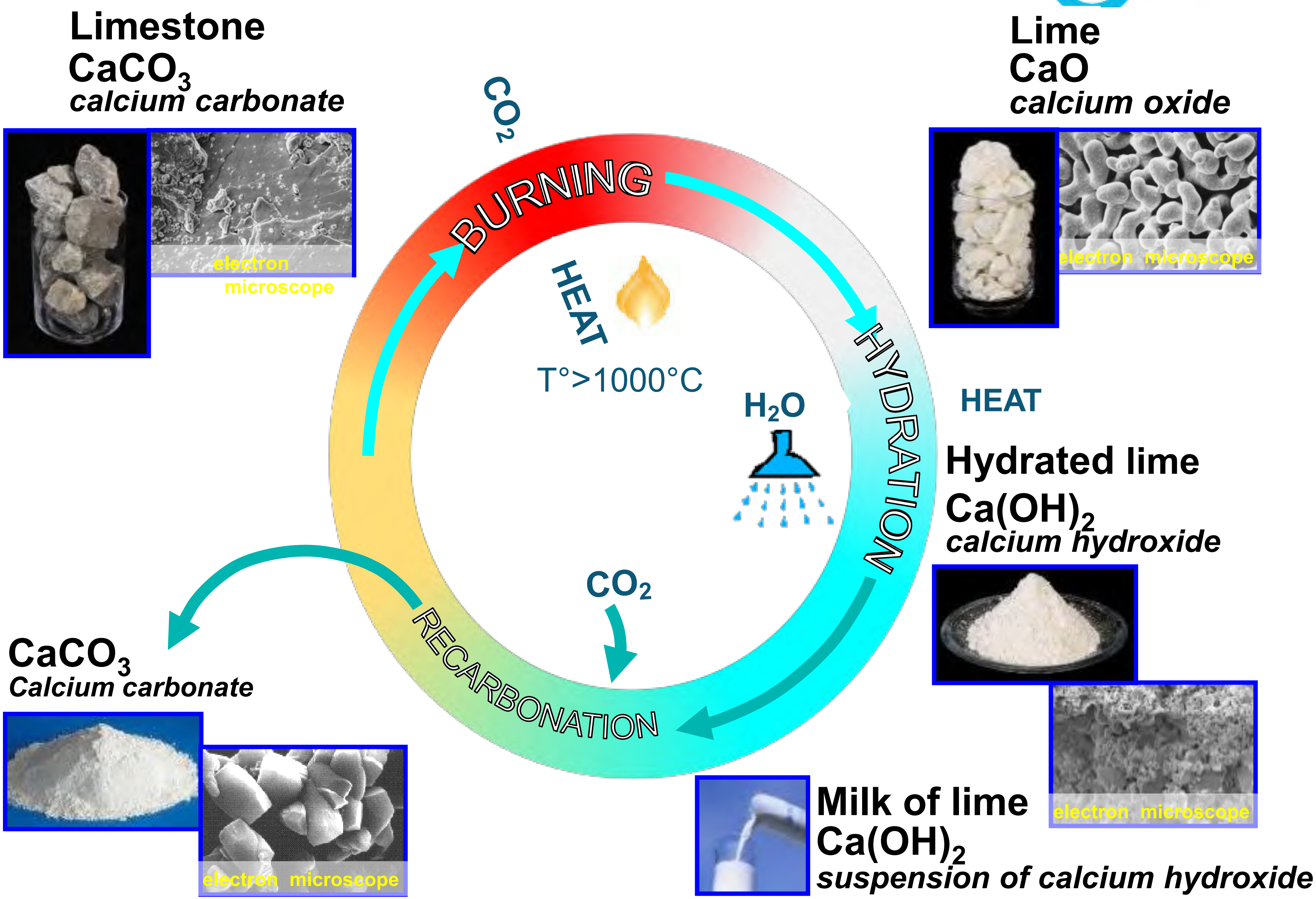
Dry Sorbent Injection System Anatomy

> **Key Components**
- Conveying air island
- Solids metering island
- Distribution – piping/splitters/lances

> **Typical DSI System Components**
- Inlet chiller
- Dehumidifier
- Motive air source
- Storage & dosing system
- Aftercooler and HX
- Piping/distribution/lances
- Process automation



Lime Reactivity Cycle



Hydrated lime is highly reactive with acids

$Ca(OH)_2$ is a base and can neutralize acids

- SO_2, SO_3/H_2SO_4, HCl, HF, SeO_2, As_2O_3, $HSeO_3$

SO_2

- $Ca(OH)_{2(s)} + SO_{2(g)} + ½\ O_{2(g)} \Leftrightarrow CaSO_{4(s)}$

HCl

- $Ca(OH)_{2(s)} + 2\ HCl_{(g)} \Leftrightarrow CaCl_{2(s)}$

SO_3/H_2SO_4

- $Ca(OH)_{2(s)} + SO_{3(g)} \Leftrightarrow CaSO_{4(s)}$
- $Ca(OH)_{2(s)} + H_2SO_{4(g,l,aq)} \Leftrightarrow CaSO_{4(s)} + 2\ H_2O_{(g)}$

SeO_2

- $Ca(OH)_{2(s)} + SeO_{2(g)} \Leftrightarrow CaSeO_{3(s)}$

As_2O_3/As_2O_5

- $6\ Ca(OH)_2 + As_4O_{10(g)} \Leftrightarrow 2\ Ca_3(AsO_4)_{2(s)} + 6\ H_2O_{(g)}$

Piping Challenges &

Design Considerations

When it goes wrong…

DSI is a chemical process

> Scaling and pipe occlusion

$$\mathrm{Ca(OH)_2 + CO2} \xrightarrow[\text{heat}]{\text{moisture}} \mathrm{CaCO3 + H2O}$$

- Carbonate formation initiates at liquid-solid interfaces
- Nucleation begins
- Soft scale formation
- Hard scale formation

Conveying Velocity

- Conveying velocity is a critical (*momentum = m·v*)
  - Too high = impingement and sticking/nucleation
  - Too low = soft plugs → scaling
- Implications for conveying velocity
  - Gas density is dependent on pressure and temperature
  - ***Gas velocity increases and decreases along the system with incremental dP in the system***
  - Gas volume is dependent on gas temperature…PV=nRT…V α T

Soft plugs may be more likely in cold weather due to volumetric changes and the effects on transport velocities

Pneumatic Conveying of Hydrated Lime

Challenges

> Velocity related impacts

> Temperature/moisture related Impacts

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Piping

- Materials
  - Carbon steel
  - Rubber hoses
  - Carbon steel with rubber hose elbows
- Elbow bend radius
  - 8x-12x pipe diameter
  - *e.g.* 4” piping → 32”-48” bend radius
- Minimize elbows
- Vertical or horizontal runs only
  - NO angled runs

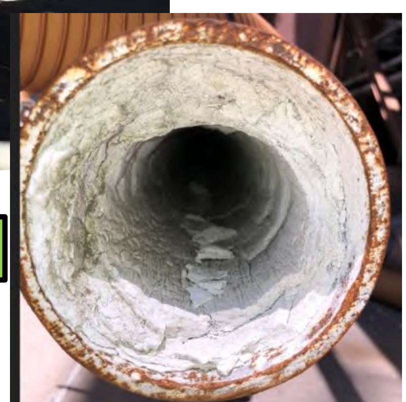
C. Donner. Reinhold Conference. 2018

Elbows / Scaling

One of the most common issues

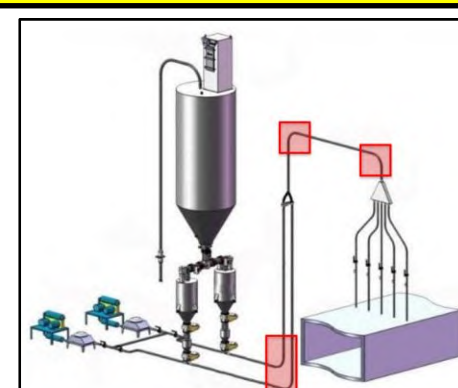
- Elbow bend radius, materials of construction, connection type all may impact scaling

Common DSI configuration → elbow scaling/plugging every 6-8 weeks



“This is how we’ve always done it”

Hose elbows in operation > 2 years without a single downtime due to scaling/plugging



Elbows

C. Donner. Reinhold Conference. 2018

Good idea: replace hard elbows with hose

Good idea: pre-cut spares with cam locks

4”- 2” Piping – Maintain Velocities!

- Velocity target – 3,300 actual feet/min ± 10%
- Must preserve velocity through entire route

$A_{cross\text{-}sec} = \pi r^2 = 12.57\ in^2 = 0.087\ ft^2$

$Q = 287\ ft^3/min$

$v_{per\ line} = 3{,}299\ ft^3/min$

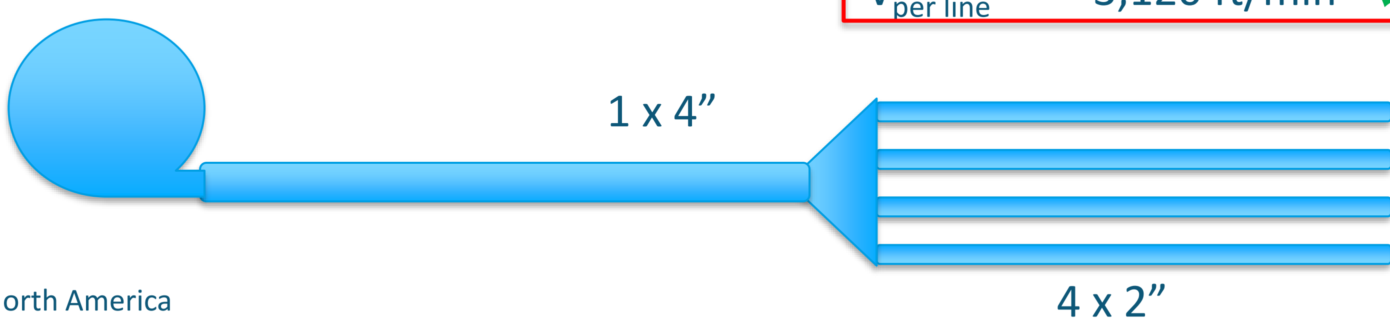
$A_{cross\text{-}sec} = \pi r^2 = 3.14\ in^2 = 0.023\ ft^2$

$Q_{total} = 287\ ft^3/min$

$V_{total} = 12{,}478\ ft/min$

Lines = 4

$V_{per\ line} = 3{,}120\ ft/min$ ✓

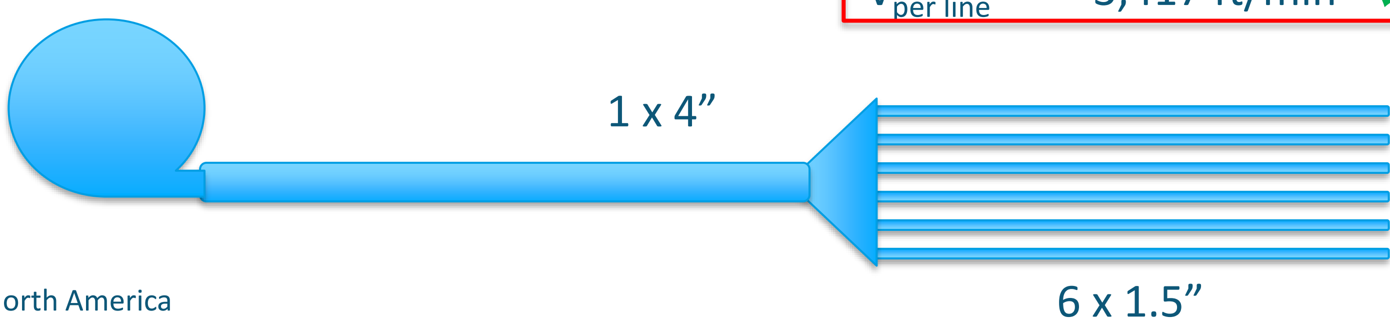


4”- 1.5” Piping – Maintain Velocities!

- Velocity target – 3,300 actual feet/min ± 10%
- Must preserve velocity through entire route

$A_{cross\text{-}sec}$	$= \pi r^2 = 12.57\ in^2 = 0.087\ ft^2$
Q	$= 287\ ft^3/min$
$v_{per\ line}$	$= 3{,}299\ ft^3/min$

$A_{cross\text{-}sec}$	$= \pi r^2 = 3.14\ in^2 = 0.014\ ft^2$
Q_{total}	$= 287\ ft^3/min$
V_{total}	$= 20{,}500\ ft/min$
Lines	= 6
$V_{per\ line}$	$= 3{,}417\ ft/min$ ✓



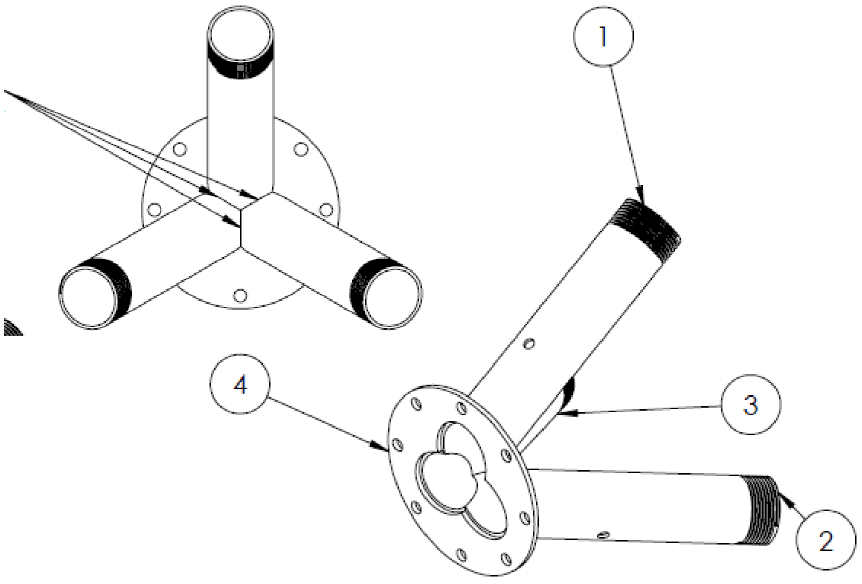
Splitters

> Should be isotropic – *the same in all directions*

<u>Poor Design</u>

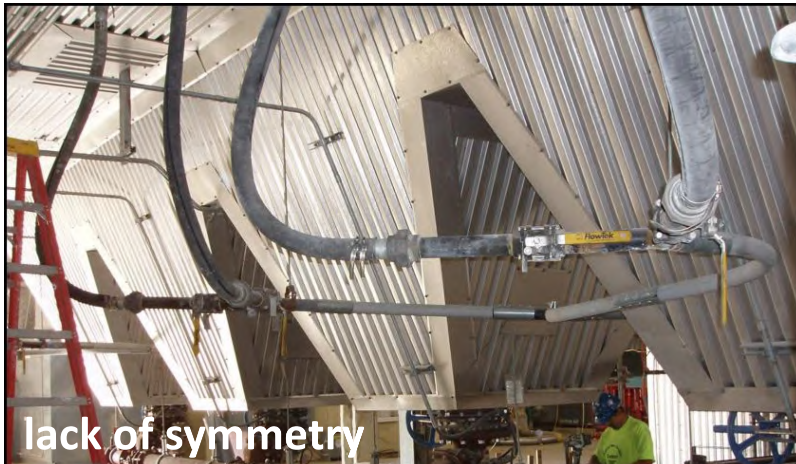
- build up in corners
- anisotropic
- no cleanouts

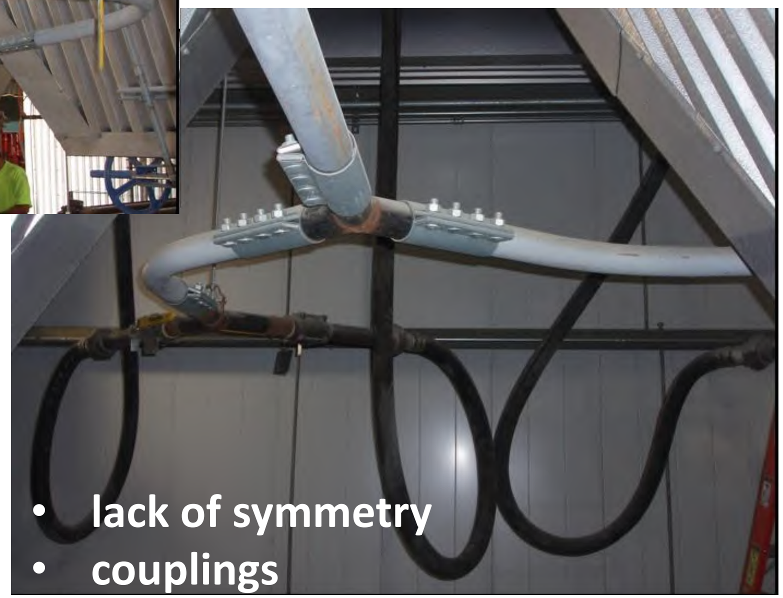
<u>Better Design</u>



- no buildup spots
- isotropic

Splitters – Bad Splits





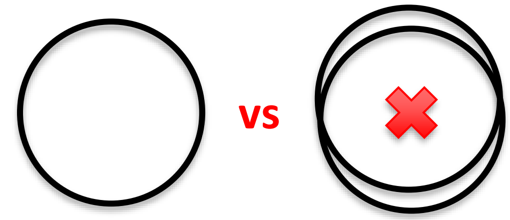
> Sorbent will flow towards path of least resistance
> Symmetry is critical
> Maintain cross section area (beware of couplings/fittings)

Poor Fittings Choices

- lack of symmetry
- Internal diameter changes
- Directional changes

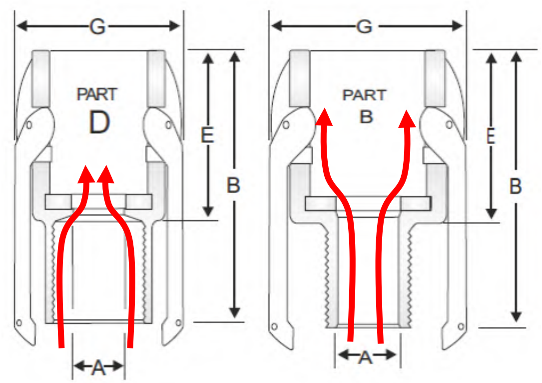
Morris Couplings

Morris Couplings – not ideal



Looking down the line

Traditional Camlocks

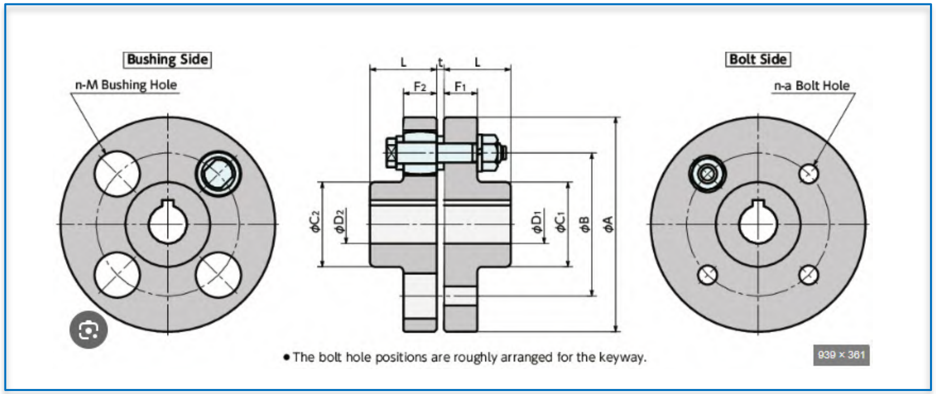


> Reduction in cross-section area = BAD!

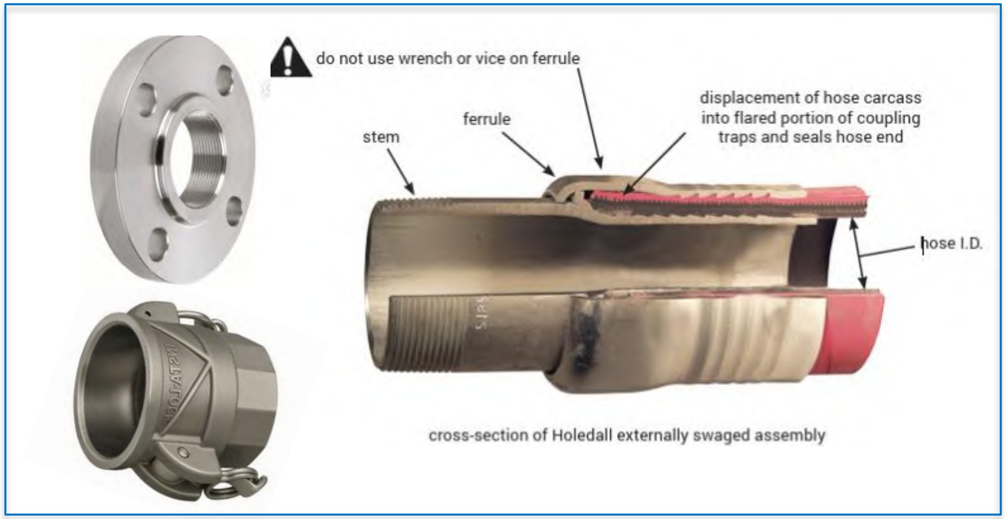
> Steps or rough internal surfaces = BAD!

Better Fittings Choices

Flanged Couplings



Holedell External Swage + FNPT coupling



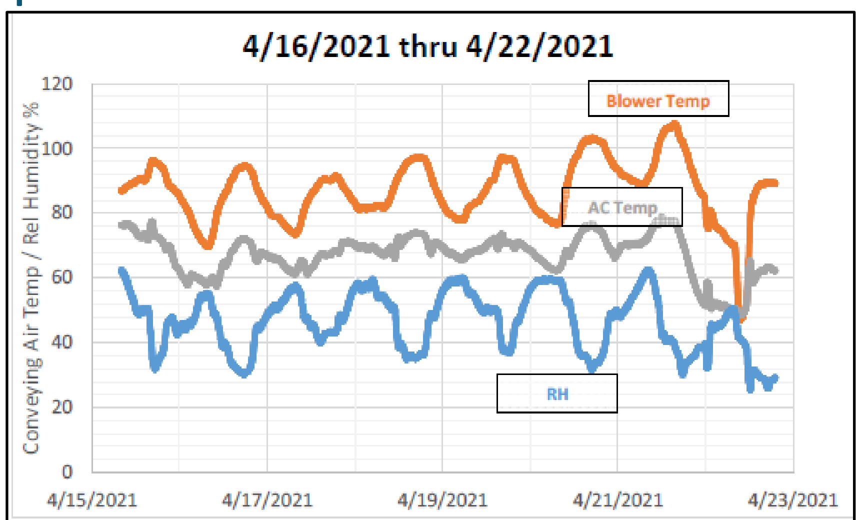
- Preserve internal diameter throughout
- Smooth surfaces

Conveying Air Systems

Conveying Air - Blowers

- Target velocity : 3,300 ft/min ± 10%
- PD blowers are the standard
  - Fans are inexpensive but designed for minimal backpressure
- Measure ACFM not SCFM
  - Flow/velocity will change with temperature
  - *Adequate* – spot measurements with Testo 405i
  - *Better* – logging gauges or readouts
  - *Best* – flow measurement tied to PLC and blower VFD
- VFD on blowers provide flow control

Testo 405i



Conveying Air – Moisture & Temperature

> Moisture
  - RH > 8% = increased carbonation rate

> Temperature
  - T_{air} > 158 °F = increased carbonate rate

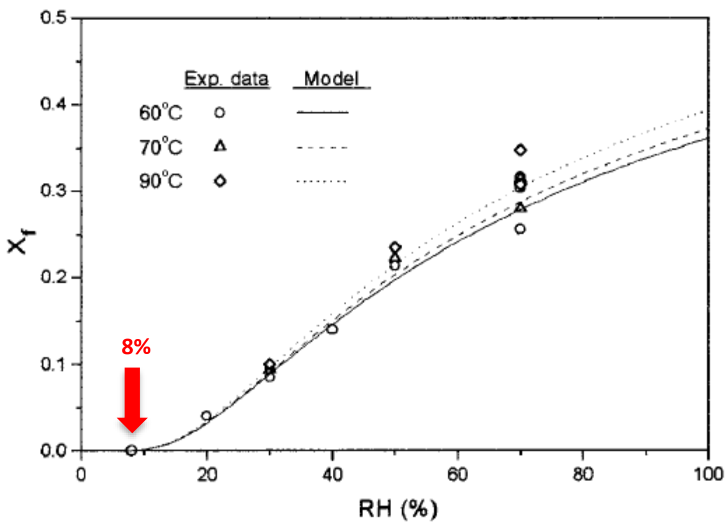


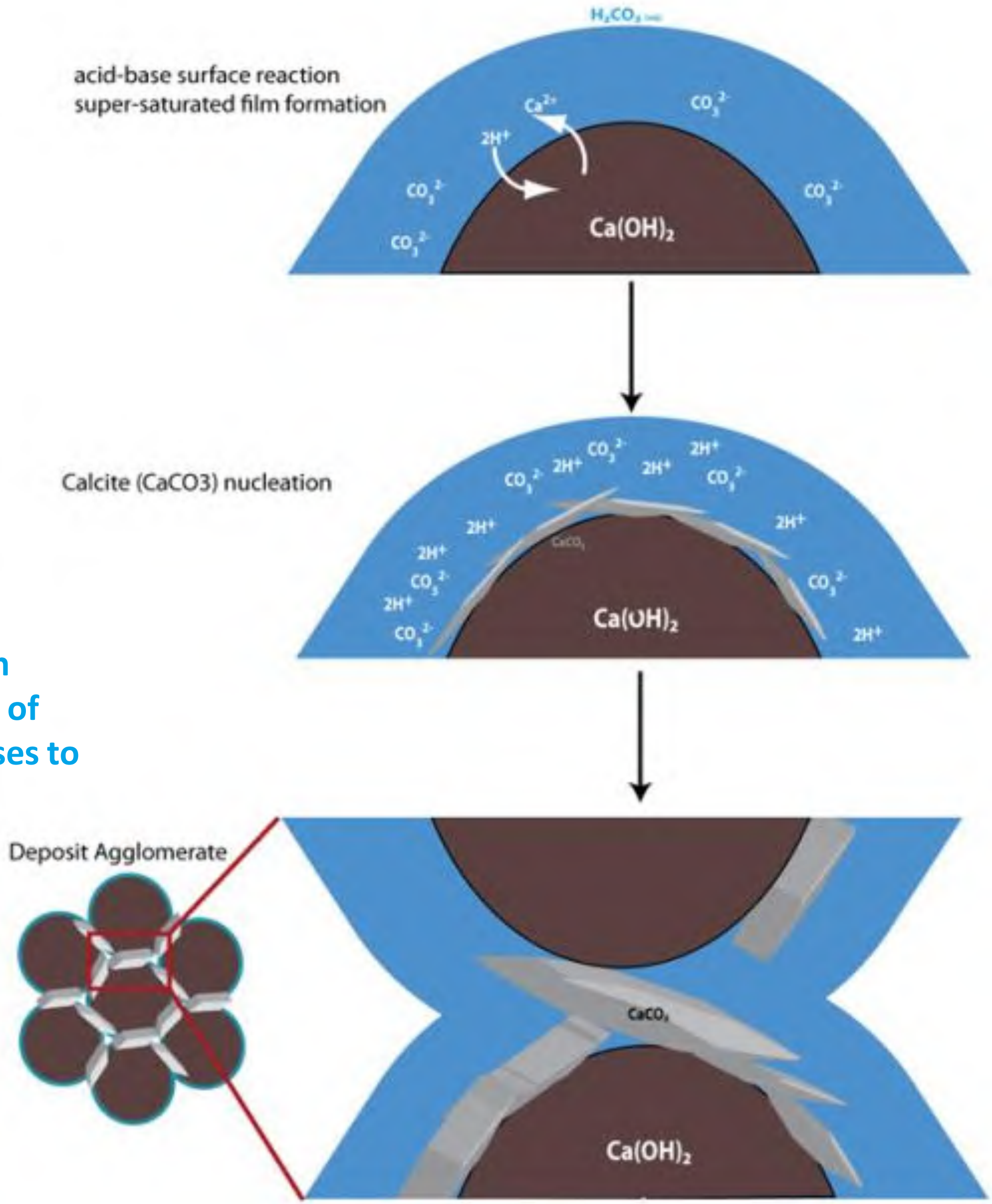
Figure 5. Final conversion for the carbonation of $Ca(OH)_2$. The curves represent the results calculated by using eqs 8a and 16.

Conclusion

The kinetics of the reaction of $Ca(OH)_2$ with CO_2 in humid N_2 has been studied at 60 to 90 °C by using a differential packed-bed reactor.

The carbonation rate diminishes rapidly before 1 h, and the conversion of $Ca(OH)_2$ is incomplete. The relative humidity is a deterministic factor affecting the reaction of $Ca(OH)_2$ with CO_2. The reaction occurs only when the relative humidity is higher than a critical value of 8%, and the reaction rate and final conversion of $Ca(OH)_2$ increase with increasing relative humidity. The reaction is slightly dependent on the reaction temperature and is zeroth order with respect to gas phase CO_2 concentration.

Carbon dioxide migrates through a boundary layer of moisture on the hydrate



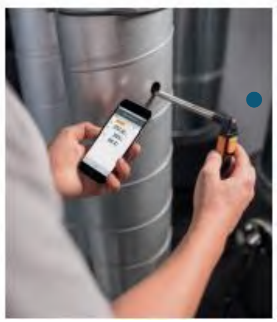
Ion diffusion in solution initiates the nucleation of carbonate and progresses to scale formation.

Carbonate formation initiates at the liquid-solid interfaces on the hydrate particle and ultimately the modified particles collect as hard deposited agglomerates on the pipe walls .

Saratovsky, I.; **Analysis of Pipe Scale and Recommendations to Delay and Prevent $Ca(OH)_2$ Deposition on Transfer Pipes, Private Paper, 2009**

DSI System Diagnostic Tools

> Sample port upstream of sorbent pick-up point useful for diagnostic instruments



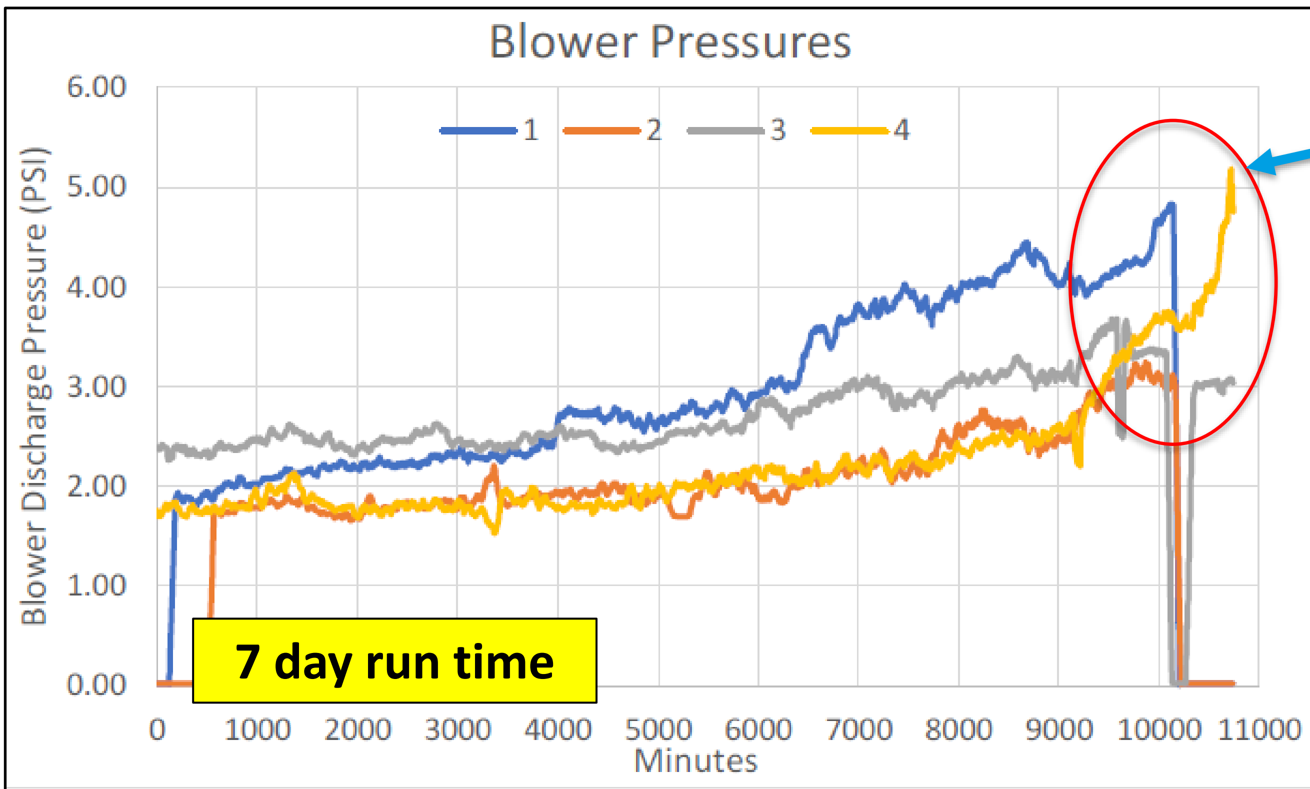
- Testo 405i for conveying velocity (<$150 on Amazon)

- Testo 605i for conveying air relative humidity (~$150 on Amazon)

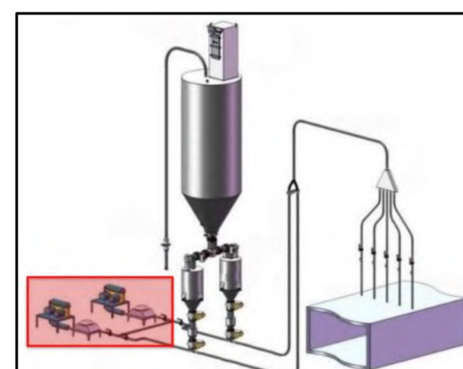
Pressure Gauges vs. Transmitters

Data for proactive maintenance, not reactive

- Pressure trends provide valuable data for maintenance
- Blower discharge pressure indicates when scaling is occurring



Within 1 day scaling issues worsened to point that required maintenance activity



Storage and Feed Systems

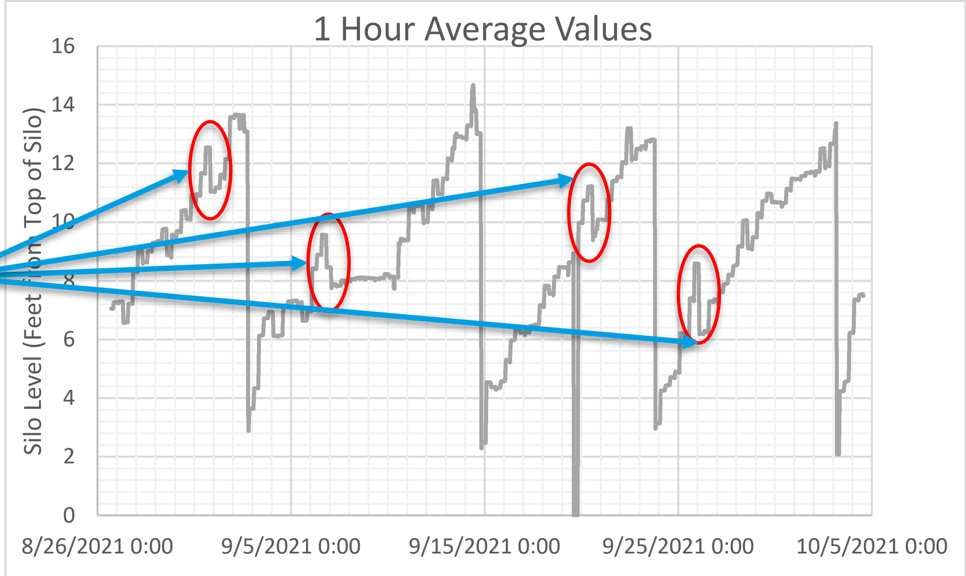
Storage Silo

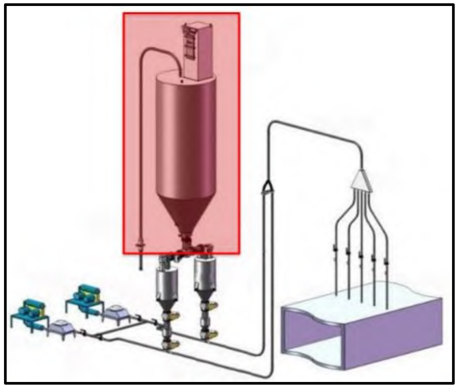
Level measurement & tramp material

- <u>Silo Fill Line</u>: Screener box = low cost insurance policy

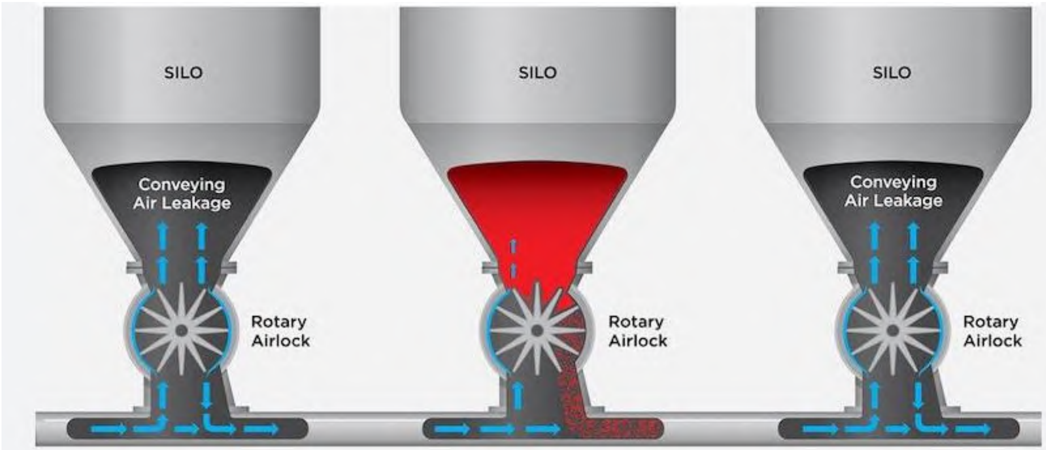
- <u>Silo Level Measurement</u>: Transmitter data is *not always accurate* due to ratholes, LIW data can be used for inventory calculator

Combine LIW data with silo levels for complete picture?

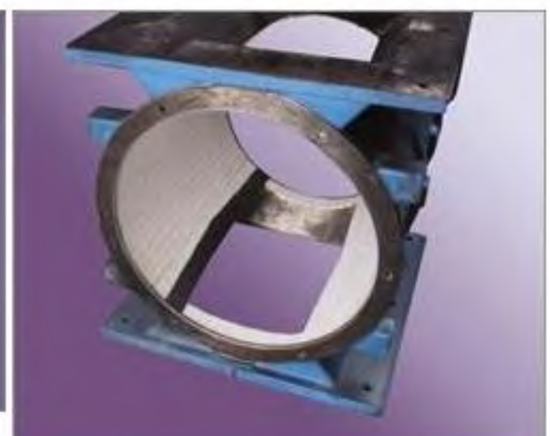




Airlock Leakage



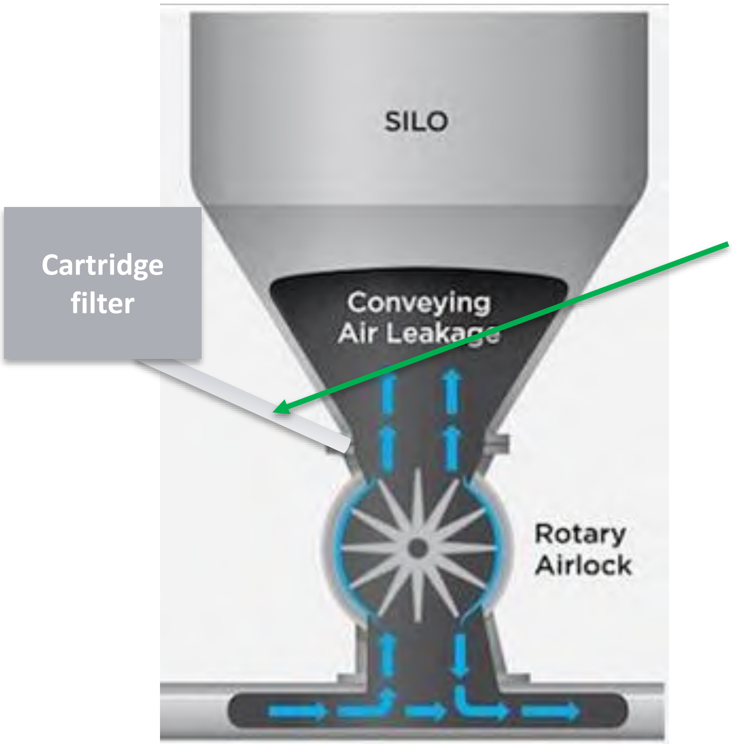
- Rotary vanes are a wear part
- Wear causes air leakage

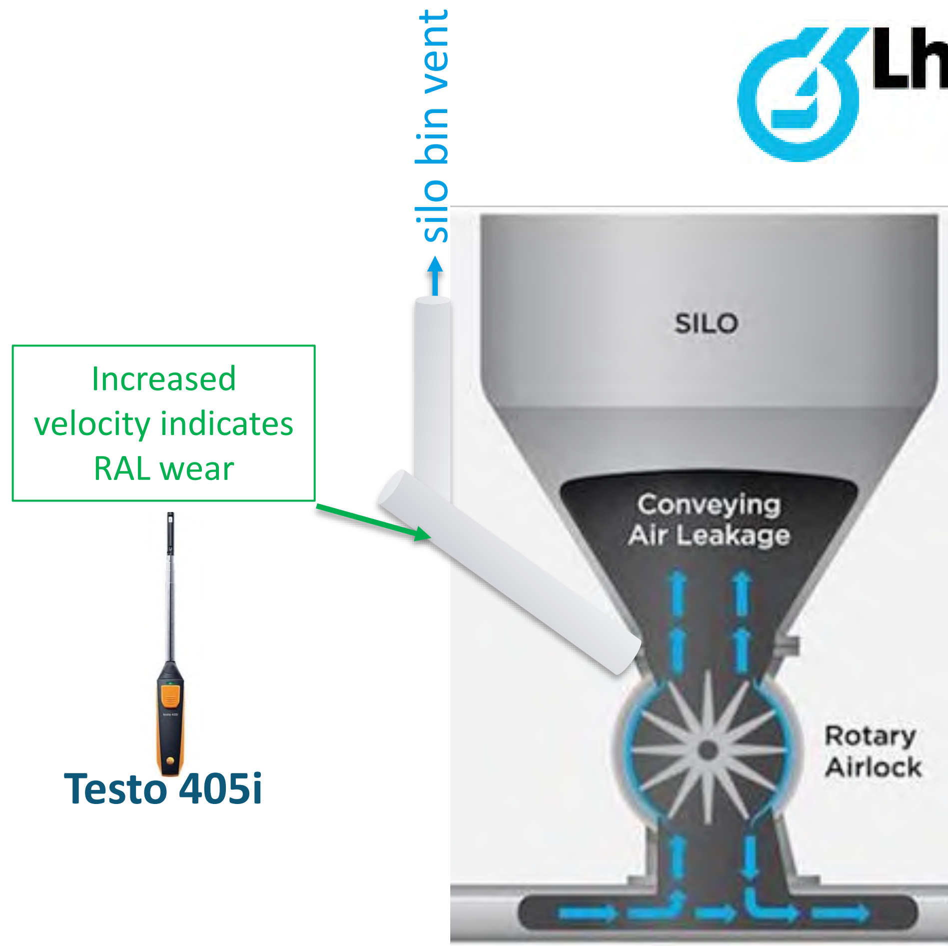


Ceramic coated tips and barrel

Barrel grooves can form

Venting



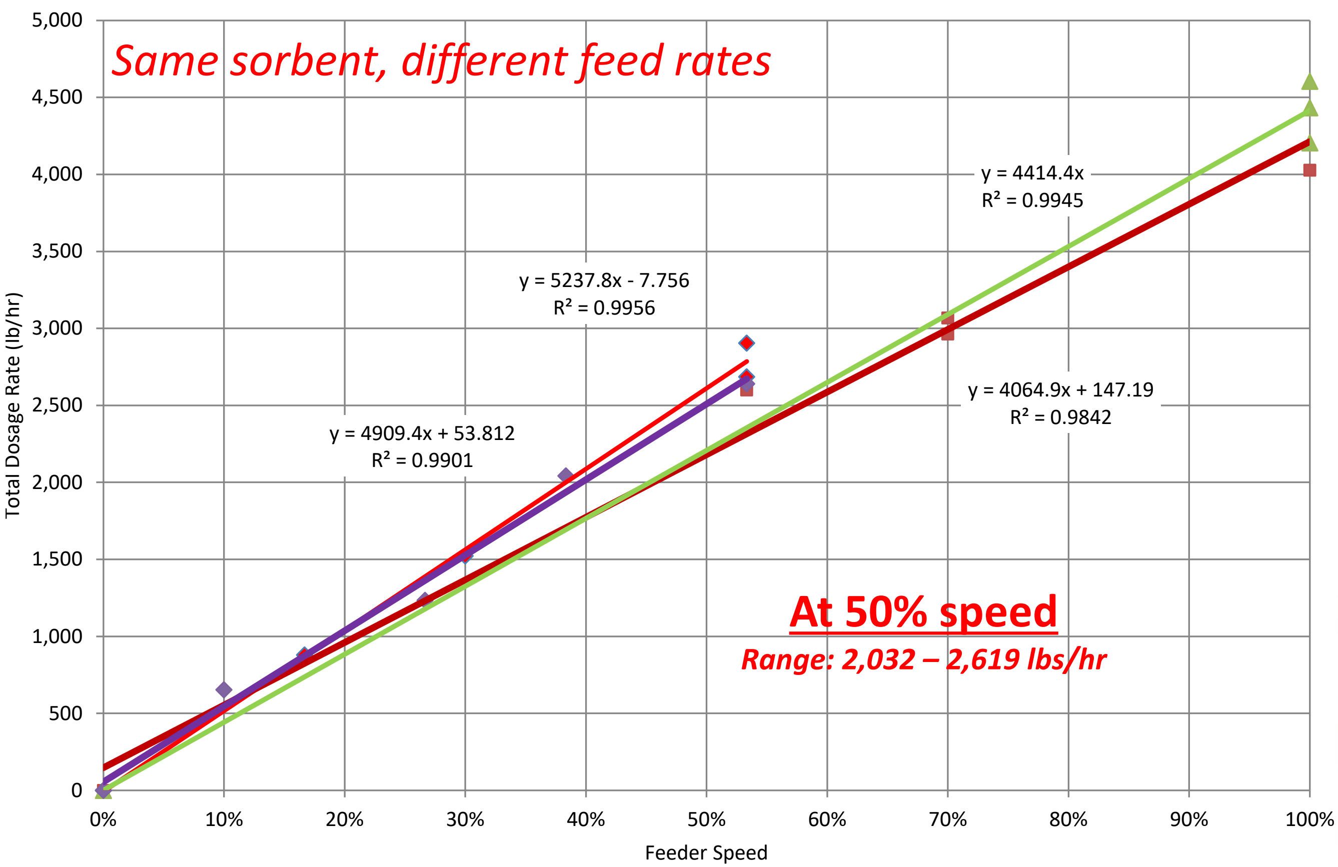


- Many design options
  - Venting is often poorly designed and can cause system-wide issues
- Clean outs are helpful
- Vent size and geometry should be designed to minimize powder carryover
  - Design for worst case, not new system
- Measure airflow velocities on brand new valve and frequently after
  - Can establish point at which airlock needs to be replaced

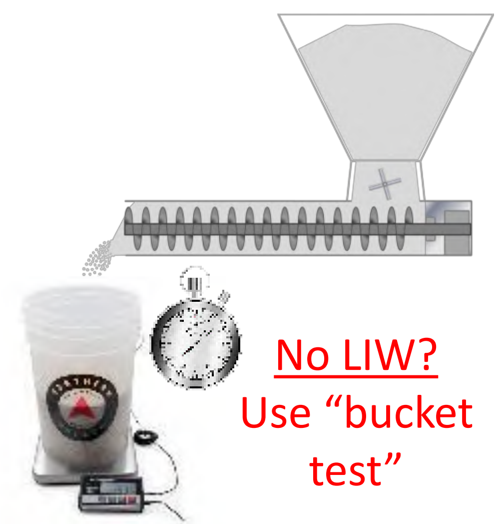
Gravimetric vs. Volumetric Feeding

How Long Can You Trust a Calibration Curve?

- Sorbent flowability can change over time
- Calibrate volumetric feeders periodically



Optimal: LIW capability with logic to control to feed rate set point



No LIW?
Use "bucket test"

Expansion Joints

Safety risks

> System Design / Best Practices

Safety

Operating Issues & Best Practices

> System Design / Best Practices

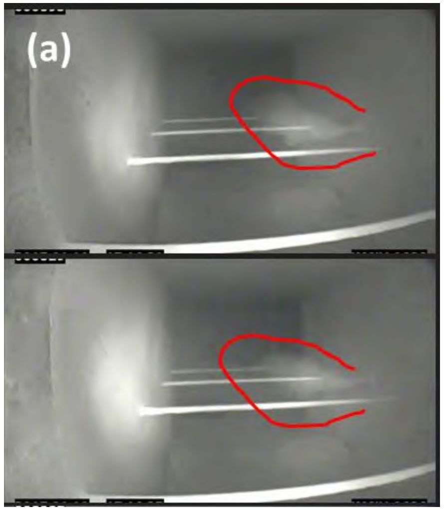
- Silo Skirt / Unloading Station & Duct

Dispersion & Lance Design

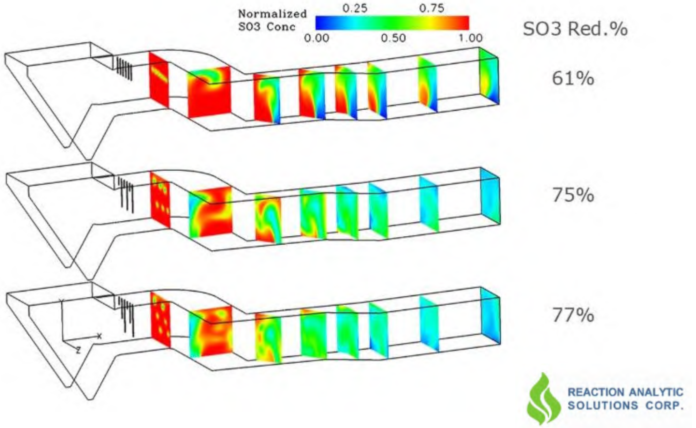
Sorbent Dispersion – Standard Lances

- > Standard pipe lances
  - Straight pipe lances are often sufficient
  - Bent lances are poor design choice
- > Lance configuration
  - Small ducts – work to cover entire gas flow
  - Large ducts – May numerous long and short lances
- > Adequate
  - Multiple lances
  - Observe with duct camera
- > Better
  - CFD dispersion model
  - Validate with duct camera
- > Best
  - CFD modeling with chemistry
  - FTIR measurement with varied lance positions

Duct Camera

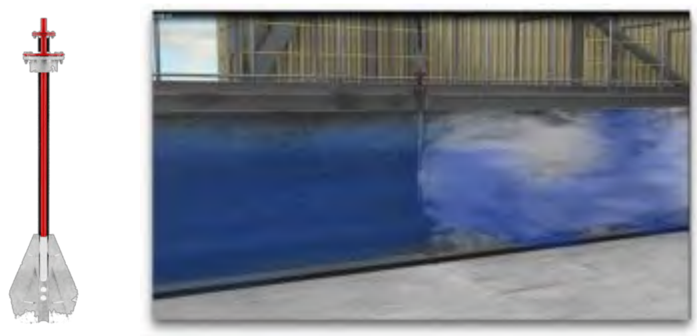


CFD Modeling



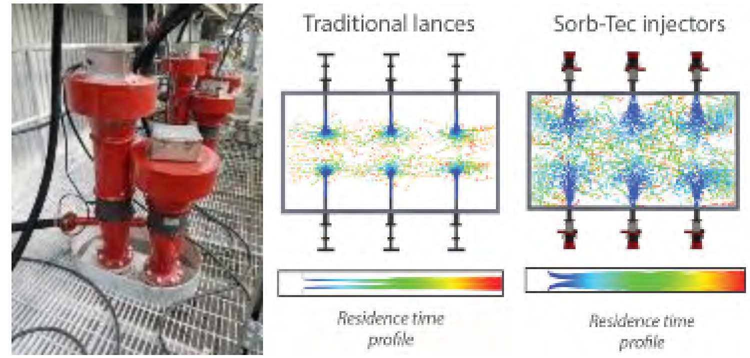
Sorbent Dispersion – Mixing Devices

Cobra Lances

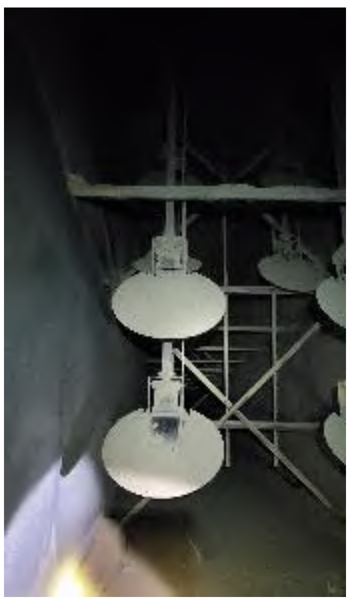


Courtesy of UCC © 2017 United Conveyor Corporation - UCC

Boosted Air, Lance-less Injector



Courtesy of Nol-Tec Systems ©2017 Nol-Tec



Thomas Lances

In-Duct Static Mixer Technology

Courtesy of BPI © 2017 Blender Products, Inc.

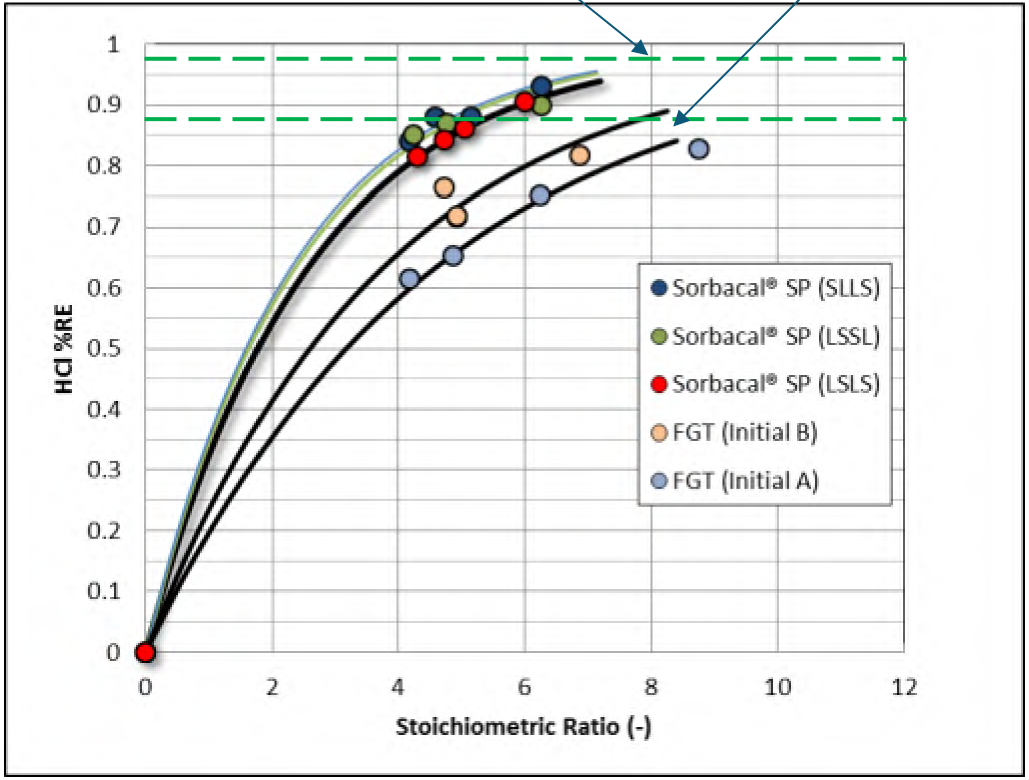
Injection Grid / Sorbent Dispersion

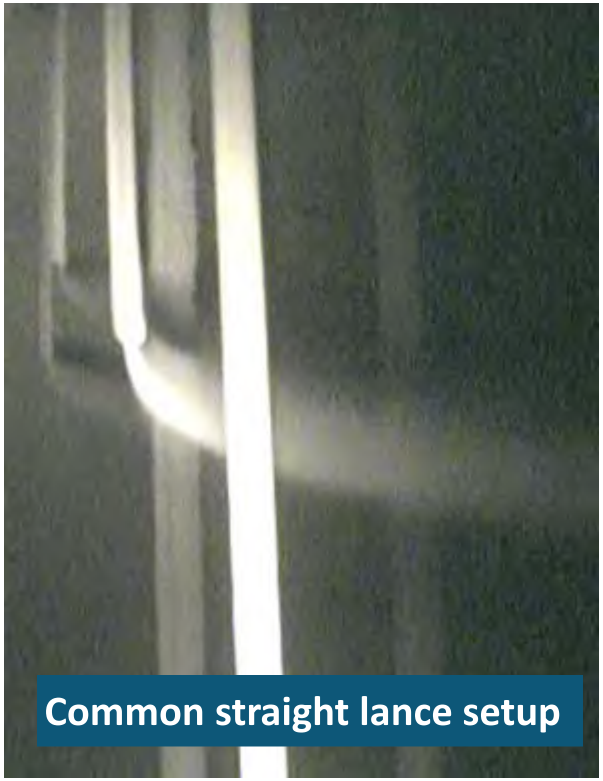
Sorbent Can't React with Gas it Does Not Contact

Lance placement and configuration affects distribution and system performance

Theoretical maximum sorbent performance asymptote

Distribution-driven sorbent performance asymptote





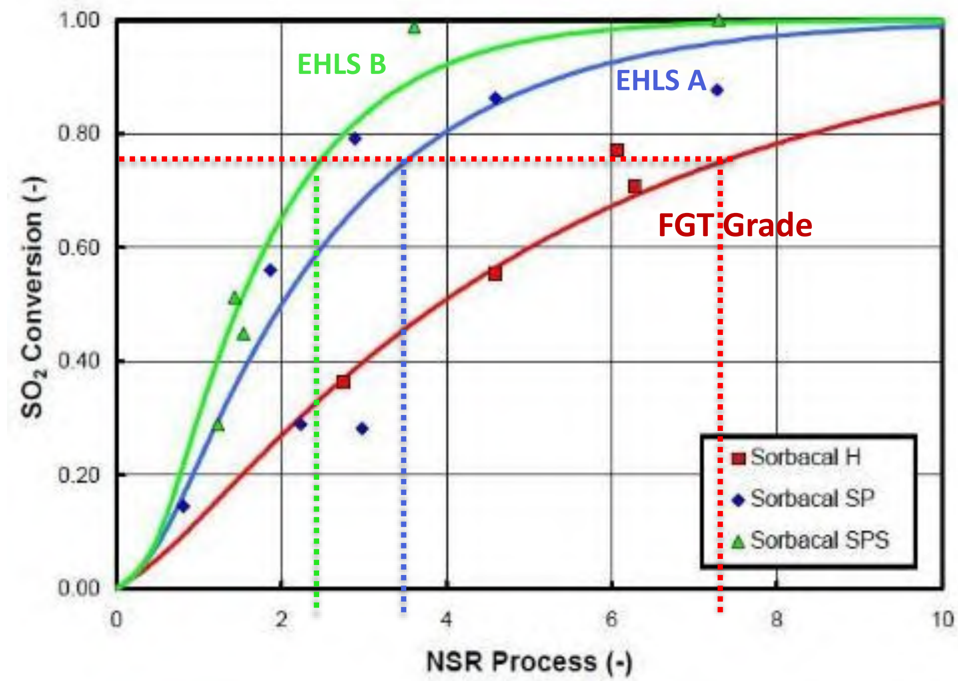
Common straight lance setup

Sorbent Selection & Performance

Not All Hydrates Are Equal

> Increasing porosity = increasing efficiency

	Standard Grades		Engineered	
Sorbent	Standard Hydrated Limes	FGT Grade	EHLS A	EHLS B
Figure				ACTIVATION 
Typical Available $Ca(OH)_2$ - [%]	92 – 95	93	93	93
Typical Surface Area - [m^2/g]	14 – 18	20	40	40
Typical Pore Volume - [cm^3/g]	~0.07	0.08	0.20	0.20
Typical D_{50} - [microns]	5 – 7	5 – 7	8 – 12	8 – 12



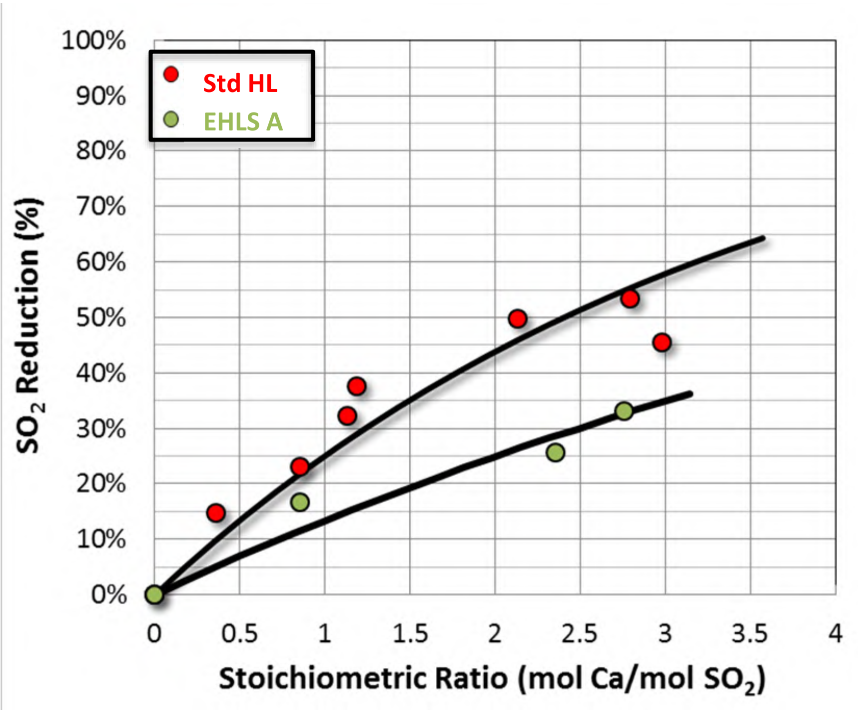
NSR = normalized stoichiometric ratio = moles Ca/moles SO_2

- > Choose wisely
  - ○ Buy on total cost of ownership NOT on delivered price
- > Testing can/should drive decisions
- > Write broad specifications to provide options
  - ○ Careful not to get into a sole source supply situation!

Testing Alternatives

> Don't be afraid to test sorbents
  - Ask your friendly sorbent supplier to assist

> Lowest delivered cost ≠ lowest total cost



Total Cost of Ownership (TCO) Sample Calculation			
Type: *Product:*		Std HL	EHLS A
Delivered sorbent price ($/ton)[1]	$/ton	$300	$550
Sorbent usage (tons/yr)	tons	1,000	500
Sorbent expenditure ($/yr)	$	$300,000	$275,000
Residue generated (tons/yr)[2]	tons	1,840	920
Residue disposal cost ($/ton)[3]	$/ton	$30	$30
Residue disposal expenditure ($/yr)	$/yr	$55,200	$27,600
Total cost of ownership ($/yr)	**$/yr**	**$355,200**	**$302,600**
$ savings			*$52,600*
% savings			*15%*

Test/Trial Injection Systems

> Bulk Trailer Injection System
  - 26 ton capacity
  - Feed range: 200 to 16,000 lbs/hr

> Super Sack Injection System
  - 2 ton capacity
  - Feed range: 25 to 1,500 lbs/hr

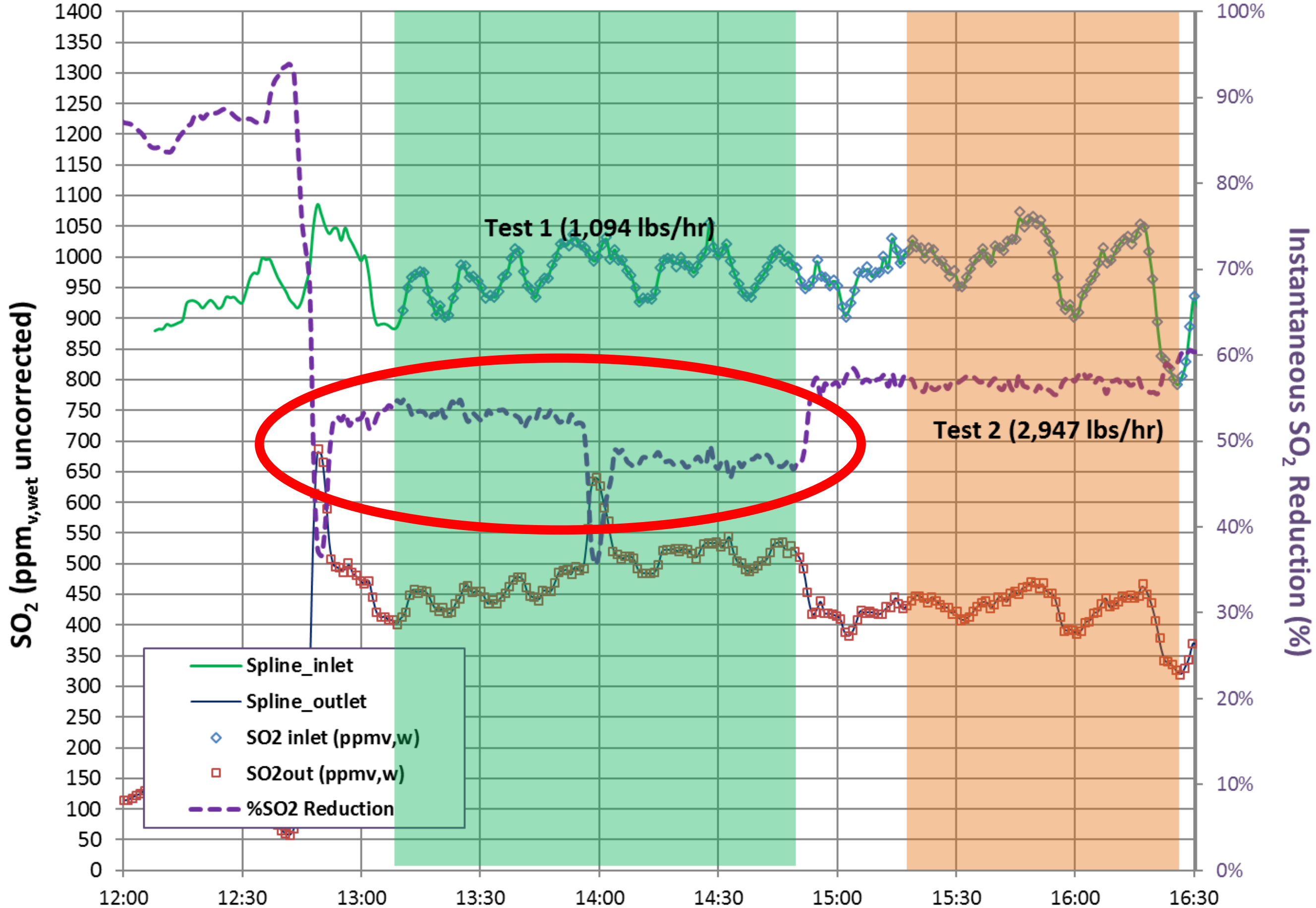
Measurements During Testing

- Dual FTIR spectrometers
  - Real time Measurement
    - > SO_2, HCl, HF, CO_2, H_2O, NO_x, NH_3
  - Simultaneous measurements at two locations

- Sorbent Traps
    - > Hg sorbent traps
    - > SO_3 traps
    - > Arsenic and selenium traps
- In-duct Camera
  - Observe sorbent dispersion, pluggage, etc.

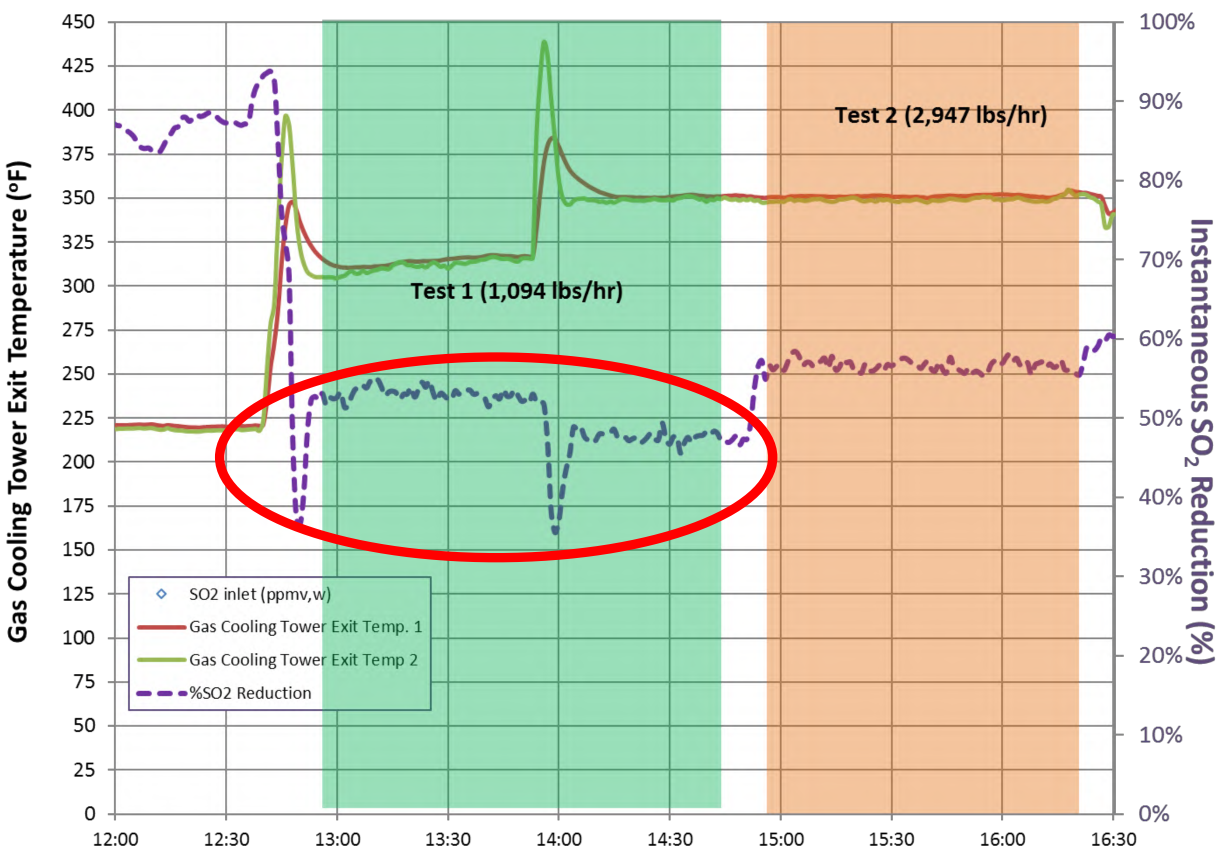
- Gas flow and temperature measurements

Measurements During Testing



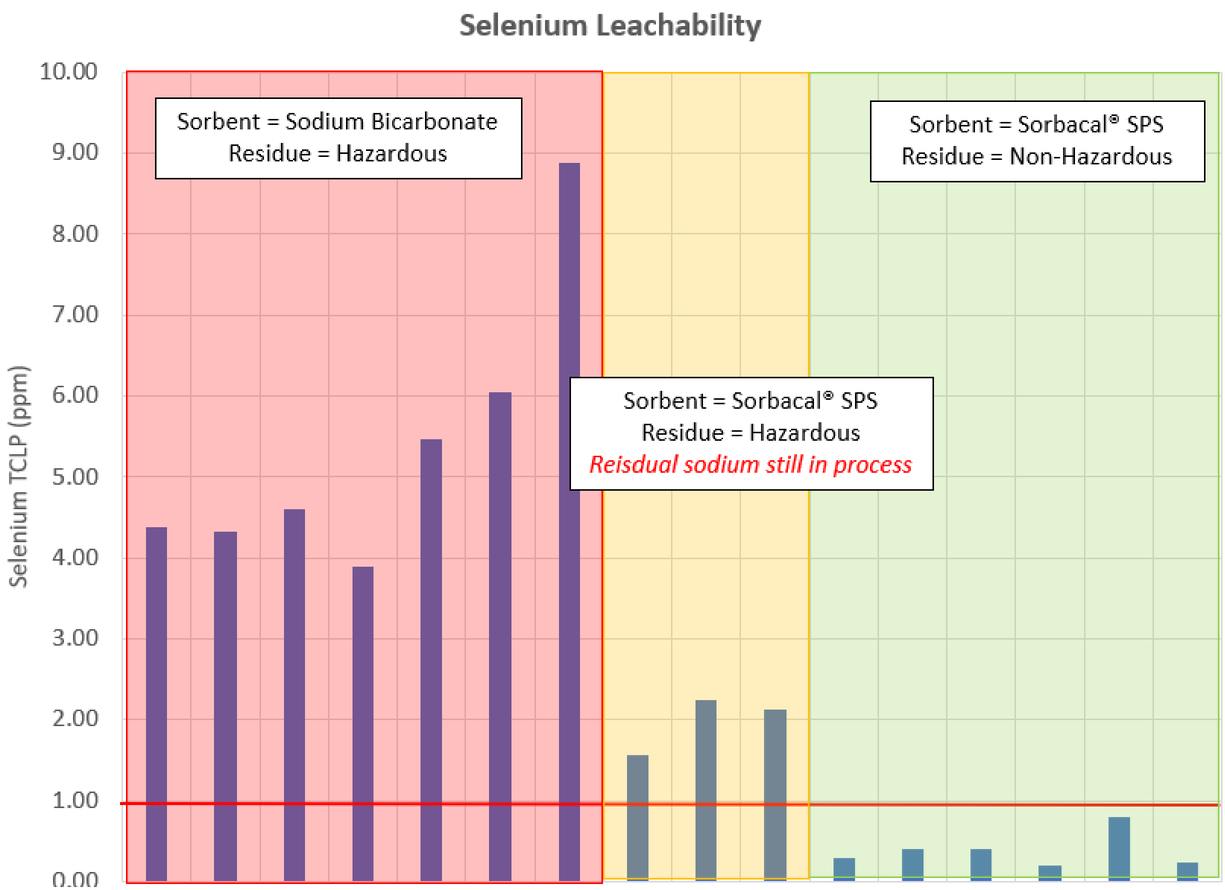
> Simulatenous FTIR measurements ahead of a stack test can be highly instructive

Measurements During Testing



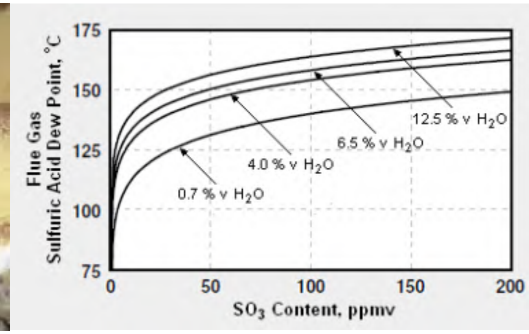
Residue Chemistry

> Understanding residue chemistry is important!
  - Efficiency/performance
  - Hazardous/non-hazardous = disposal costs



Why is SO_3 a Problem?

> Corrosion – high acid dewpoint



> Visible plume (usually > 3-5 ppm_v)

> In CO_2 capture with amines, forms $(NH_4)_2SO_4$

- Thermally stable and consumes expensive amines

Desired product → $(NH_4)_2CO_3$

Compound	Decomp. Temperature (°C)
$(NH_4)_2CO_3$	~ 58 °C
$(NH_4)_2NO_3$	~170 °C (explodes >230 °C)
$(NH_4)_2SO_4$	~250 °C

History of Treating $SO_{3(g)}$

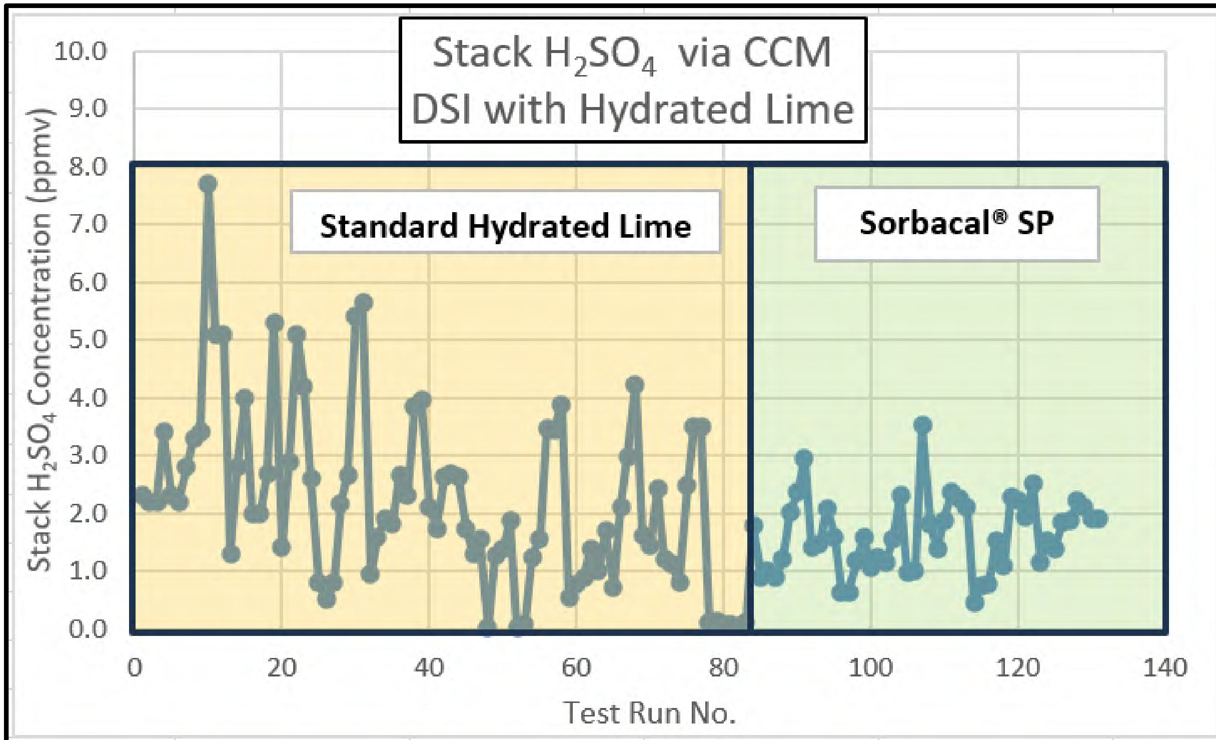
- Coal-fired power plants in USA since ~2003
  - Plants installed SCR for NOx control
  - Catalyst drives NO reduction, but also $SO_2 \rightarrow SO_3$
  - Wet scrubbers didn't catch $SO_{3(g)}$
- Acid rained down on towns surrounding coal plants with SCR
  - American Electric Power purchased the town of Chesire, Ohio
- Hydrated lime and trona injection testing began
  - Consistent injection via DSI since ~2003-2004

Cheshire was once a bustling small town, but now the majority of its residents have gone (Credit: Harmon Leon)

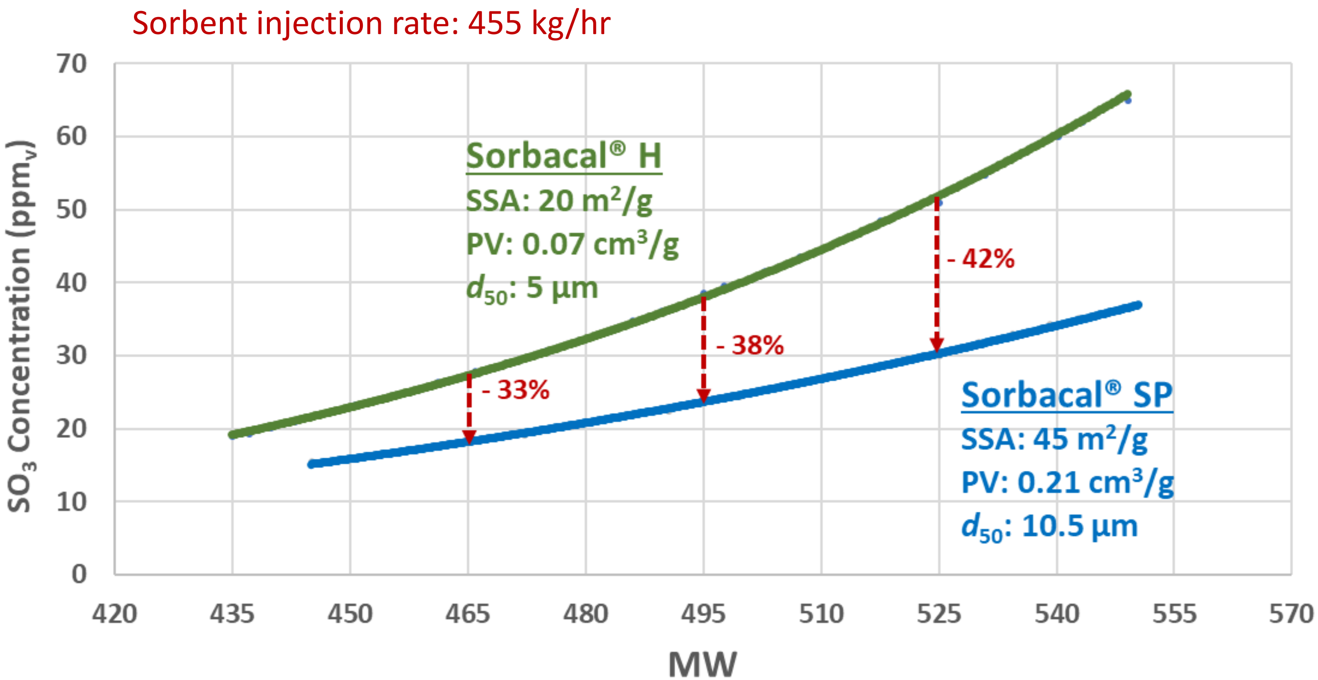
SO_3 Reduction Capabilities

DSI Case Study – SO_3 / H_2SO_4

- 750 MW power plant
  - ✓ ESPs for particulate, WFGD for SO_2, DSI for SO_3/H_2SO_4
  - ✓ Goal: eliminate corrosion and blue plume
- > 130 test runs from 3+ year period
- Once on Sorbacal® SP stack SO_3/H_2SO_4 averaged ~1.5 ppm_v
- Goal: < 3 ppm_v SO_3



SO_3: Breen Sorbacal H vs. SP Study

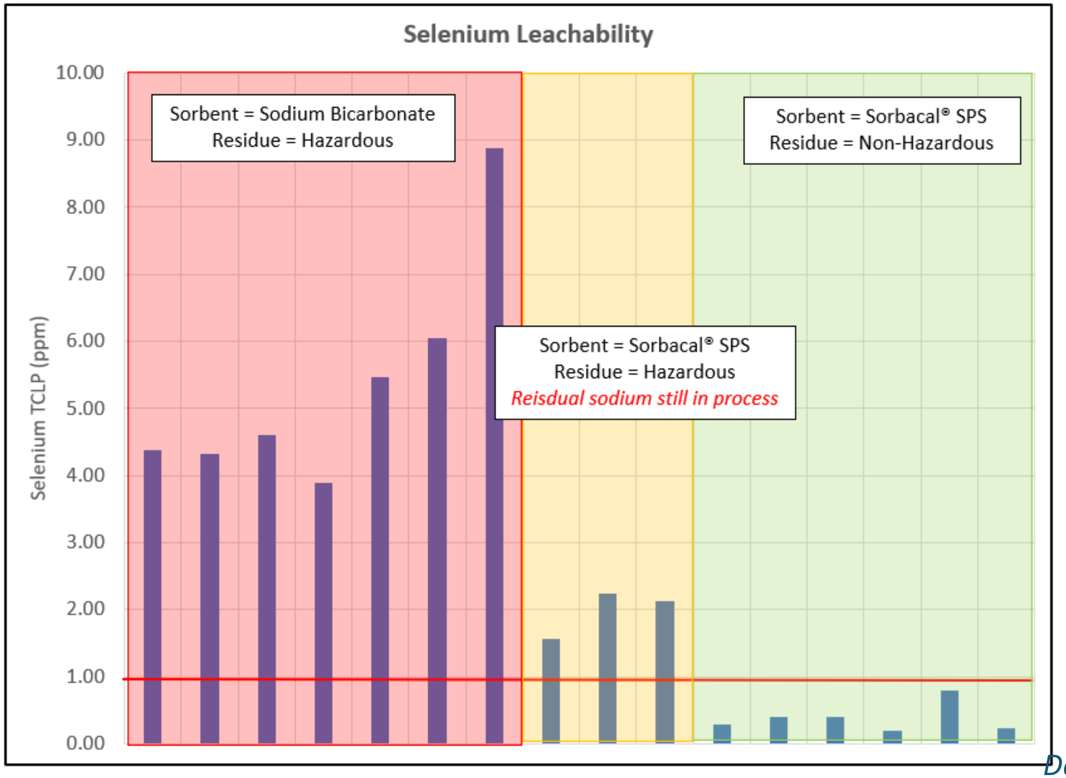


- **Performance improvement of ~30%-50%**
  - Typical of all acid gases

Calcium vs. Sodium

Impacts on Selenium

- LNA customer was leaching selenium with sodium bicarbonate injection
  - ✓ Trial with Sorbacal® SPS demonstrated reduced selenium leaching
- Additional lab results provided supporting evidence to extend testing
  - ✓ Use of Sorbacal® SPS reduced selenium leachability below RCRA limit
  - ✓ Residue re-classified as non-hazardous with Sorbacal® SPS



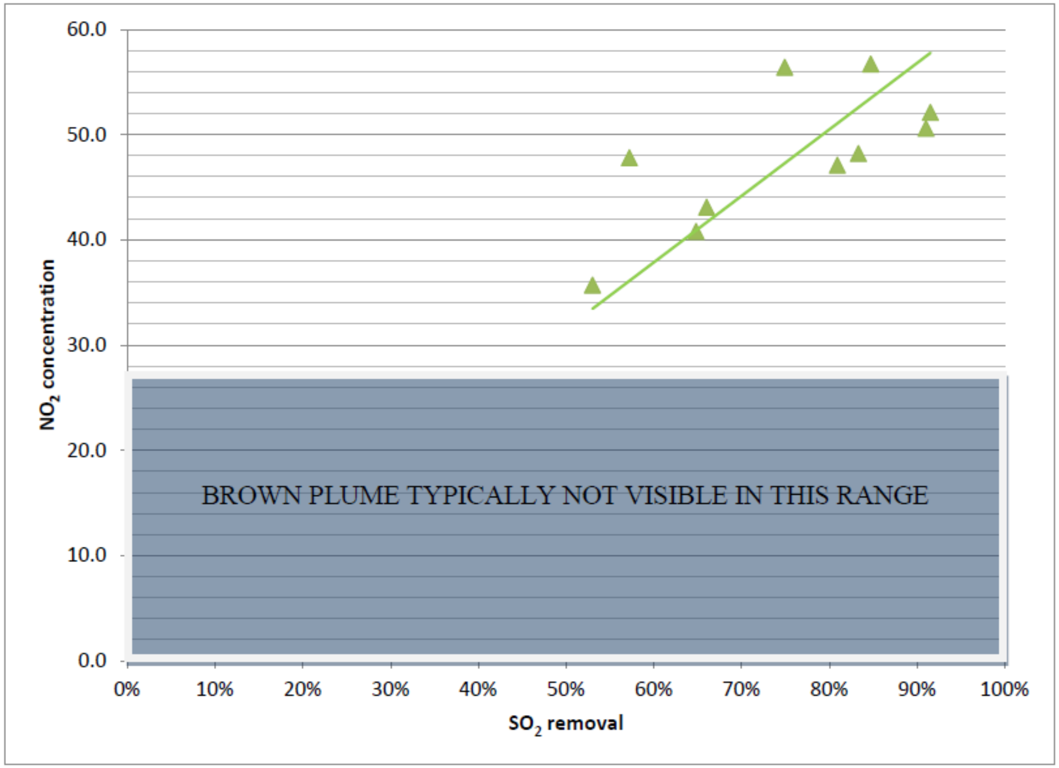
Data generated from Lhoist Irving, TX laboratory

Calcium vs. Sodium Sorbents

NO_2 Formation with Sodium Sorbents

- Work conducted by Babcock & Wilcox to demonstrate impact sodium sorbent has on NO_2 formation
- In some cases, visible brown plume
- Calcium based sorbents do not generate NO_2 as a side reaction with implementation of DSI

Figure 6 – Plot of NO_2 concentration vs. SO_2 removal with trona injection on a PJFF system.

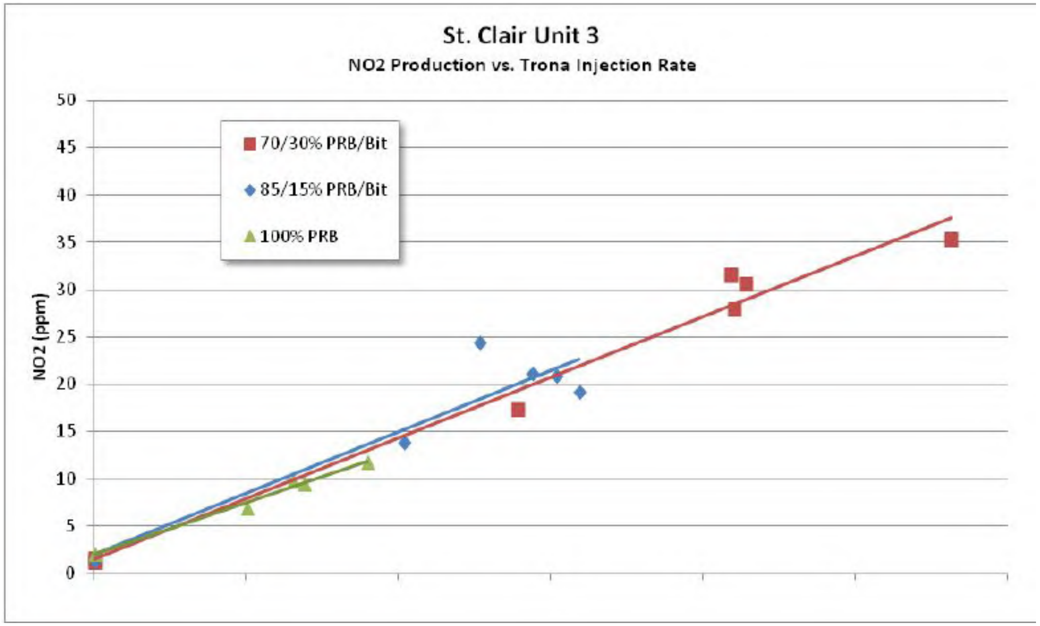


Reference: Silva, A., Snyder, R. (2014). DSI Impacts on Visual Opacity. *MEGA Symposium*.

Calcium vs. Sodium Sorbents

NO_2 Formation with Sodium Sorbents

- Work conducted by Babcock & Wilcox to demonstrate impact sodium sorbent has on NO_2 formation
- In some cases generation of NO_2 has resulted in visible brown plume
- Calcium based sorbents do not generate NO_2 as a side reaction with implementation of DSI



Trona injection rate →

Reference: Senior, C. Air Pollution Control Conference, St. Louis, MO, 2013

Calcium vs. Sodium Sorbents

NO_2 Formation Mechanism with Sodium Sorbents

Step Number	Description of the reaction step.
1	A sulfation step where sodium sulfite is produced by the reaction of sodium bicarbonate or sodium carbonate with SO_2. $2NaHCO_3 + SO_2 \rightarrow Na_2SO_3 + 2CO_2 + H_2O$ $Na_2CO_3 + SO_2 \rightarrow Na_2SO_3 + CO_2$
2	A nitration step where sodium nitrate is produced by reaction of the sodium sulfite from step 1 with NO $Na_2SO_3 + 2NO + 2O_2 \rightarrow 2NaNO_3 + SO_3$
3	An NO_2 release reaction step where NO_2 is released from the collected sodium nitrate by reaction with SO_2 in the flue gas. $2NaNO_3 + SO_2 \rightarrow Na_2SO_4 + 2NO_2$

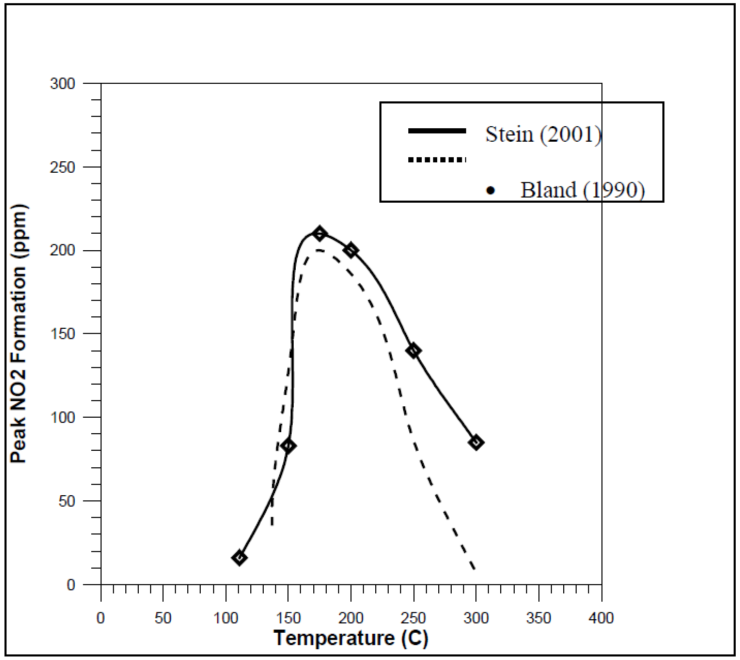


Figure 5-1 Validation test results of peak NO_2 formation versus temperature.
The data obtained in this study are shown with the solid line. The data obtained by Bland (1990) are dashed.

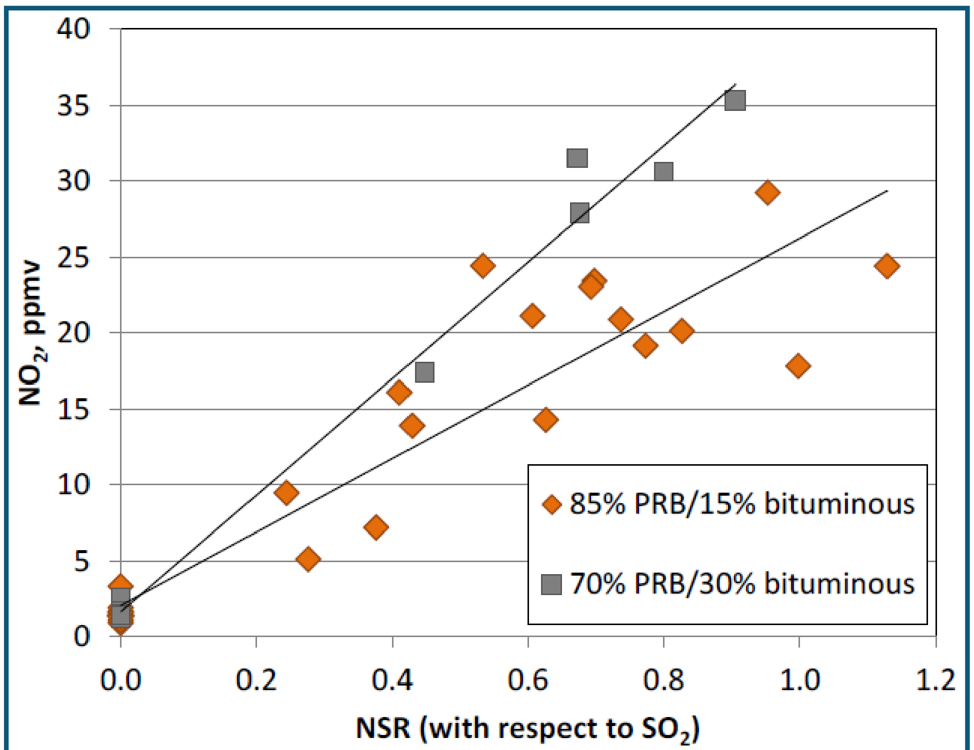
References:

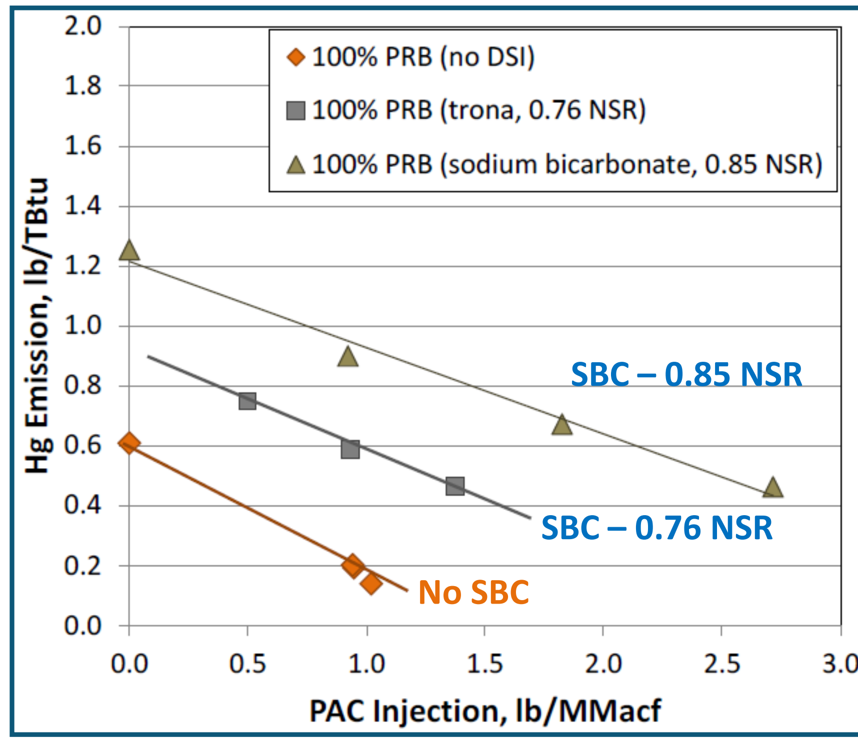
1. Bland, V. V. and Martin, C. E., Full-Scale demonstration of Additives for NO_2 Reduction With Dry Sodium Desulfurization, EPRI GS-6285, Electric Power Research, Institute, Palo Alto, California, June 1990.
2. Stein, A. W., Investigation of Gaseous NO2 Formation during FGD with Dry Sodium Bicarbonate Injection, Ph.D. dissertation, University of Cincinnati, 2001.

Calcium vs. Sodium Sorbents

Impact on Hg Emissions

- Alkaline sorbents can impact Hg emissions by removal of halogens that oxidize elemental Hg
- Sodium sorbents detrimental to Hg emissions due to formation of NO_2 byproduct





Reference: Dry Sorbent Injection for Acid Gas Control: Process Chemistry, Waste Disposal and Plant Operational Impacts. *Institute of Clean Air Companies White Paper (2016).*

Calcium vs. Sodium Sorbents

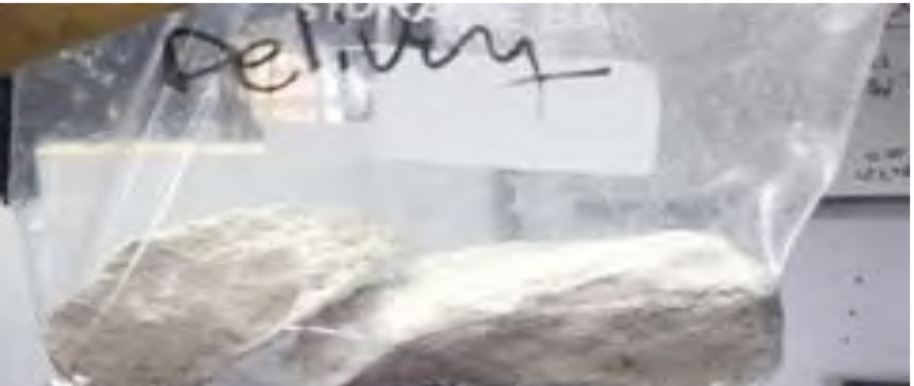
Impacts of Milling Equipment

- SBC requires milling equipment
- Milling systems require additional capital and O&M expense
- Pre-milled SBC = higher sorbent cost and lead time

Calcium vs. Sodium Sorbents

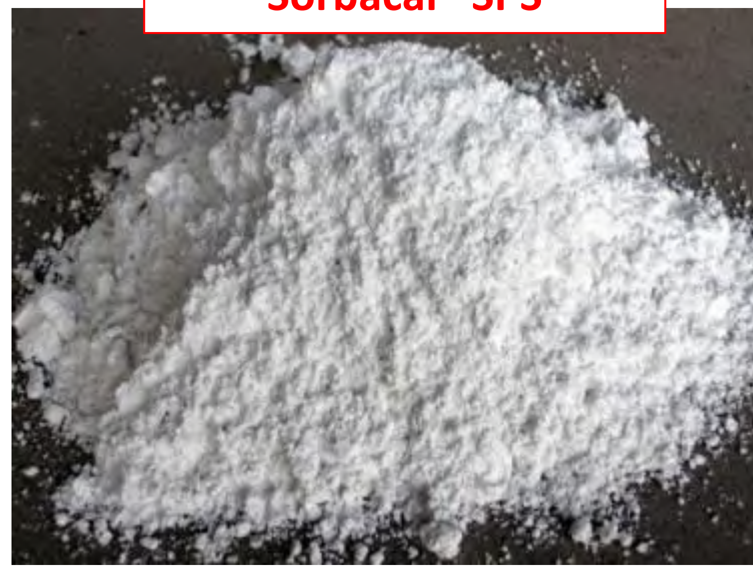
Product Quality

Lhoist



Sodium sorbents pulled from truck

Sorbacal® SPS



Quality is essential for premium products from production to delivery

SO_3 Measurements

SO_3 Sorbent Traps

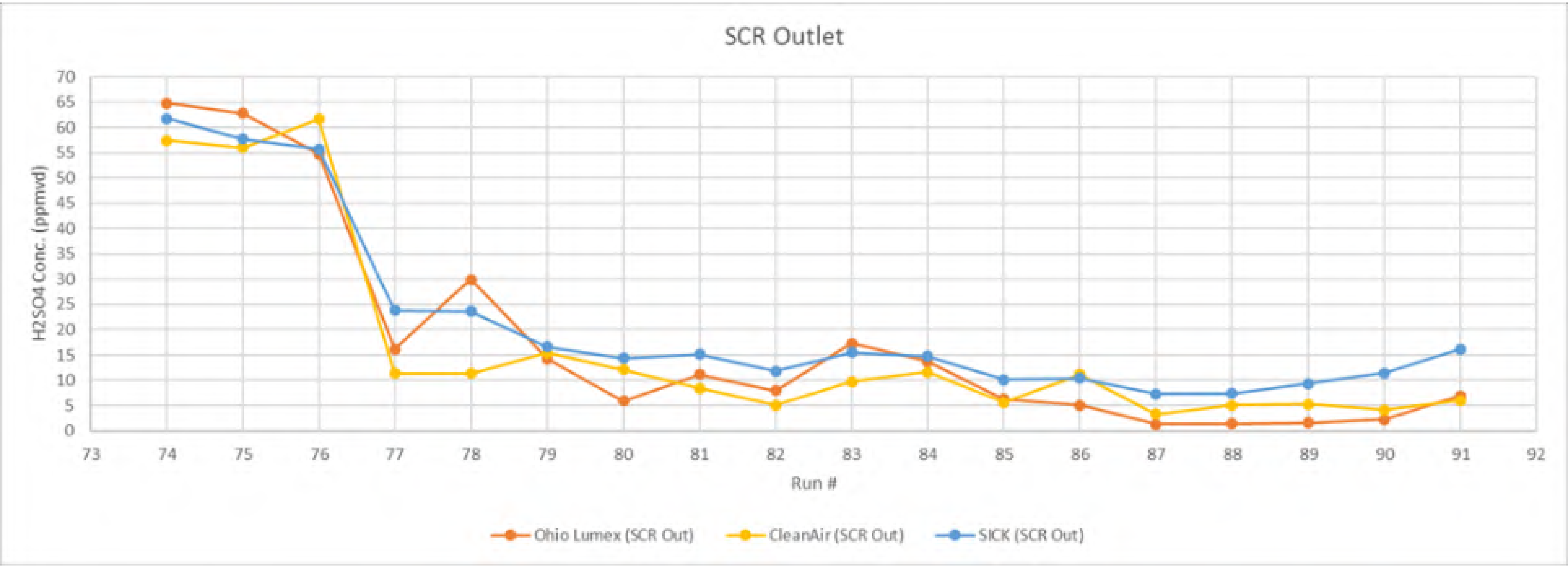
- Single in-situ measurement to measure H_2SO_4 and SO_3 (dry)
- Sampling locations from SCR to stack
- Side by side testing at utilities vs. EPA Method 8A (next slide)

- Sampling equipment similar to EPA Method 30B system
- Probe must be cooled if sample gas is > 170°C
- High particulate environments, filter tips should be attached to traps

SO_3 Measurements

SO_3 Sorbent Traps

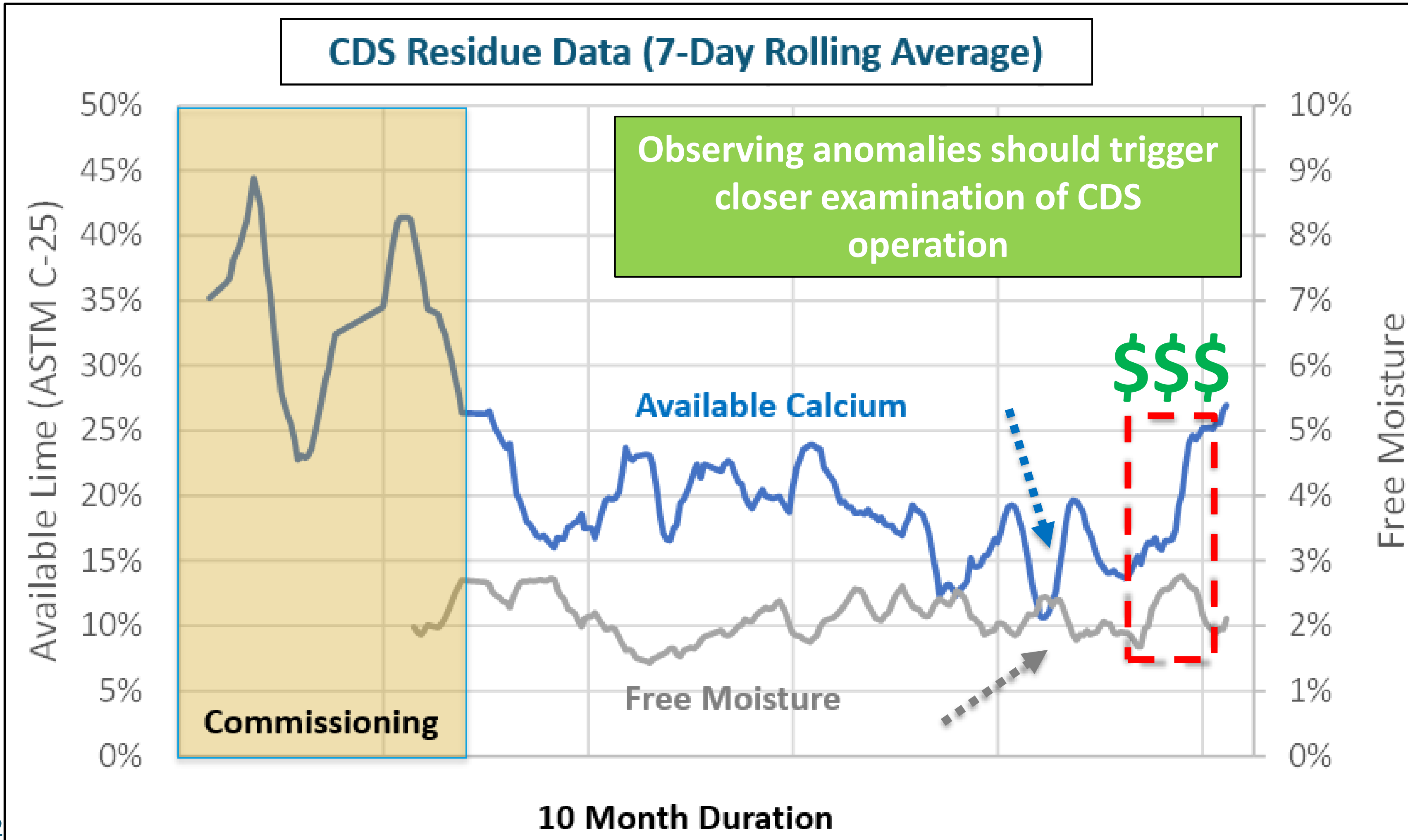
- Responsive to variable operating conditions
- Close agreement with EPA Method 8A with similar sampling method
- Relatively simple method
- Inexpensive and easy to use



Residue for Performance Optimization

Observations from On-Going Analysis

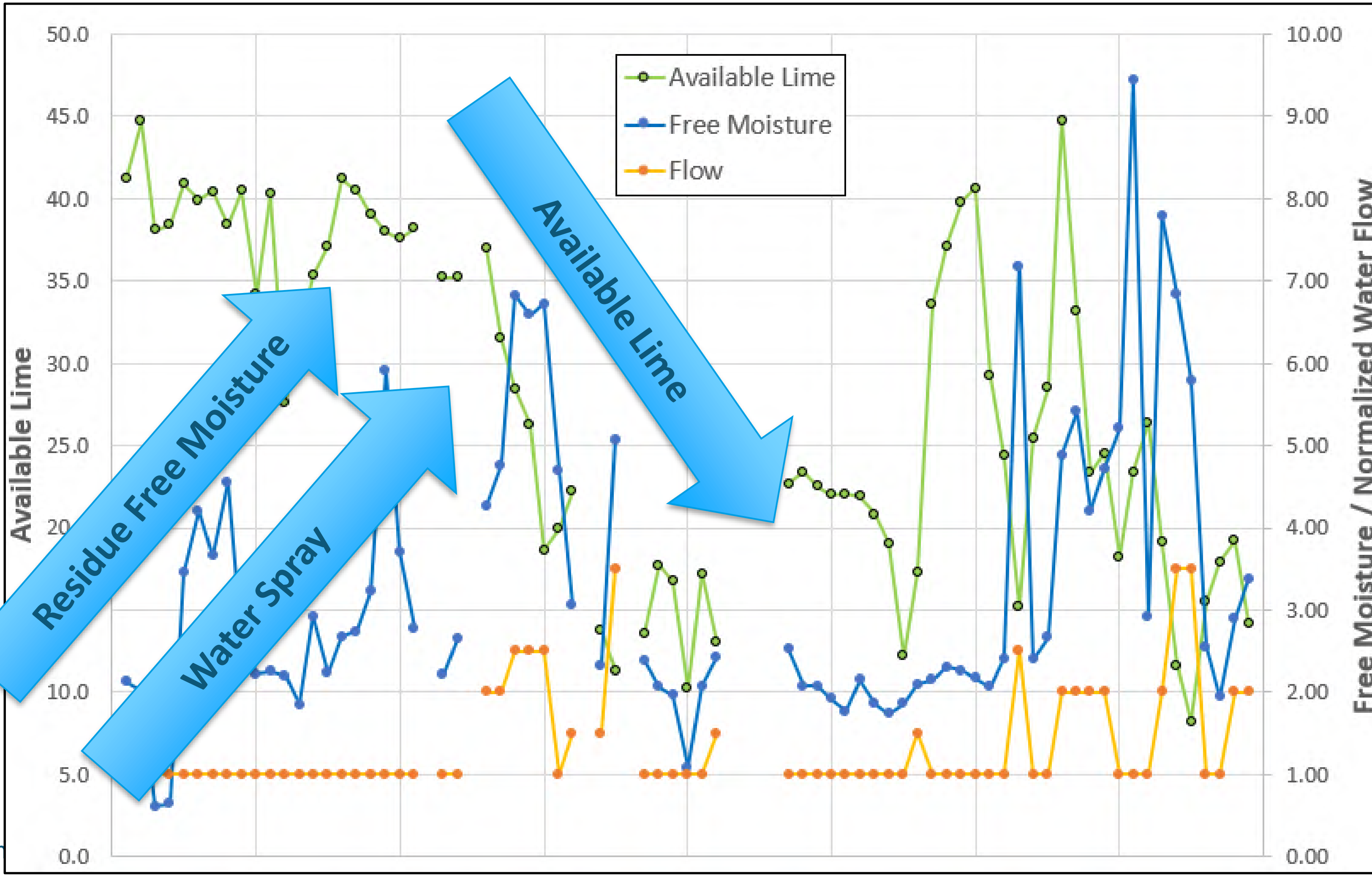
- Daily data and rolling average for CDS provides further insight by minimizing 'noise'



Residue for Performance Optimization

Assessing Impact of Moisture

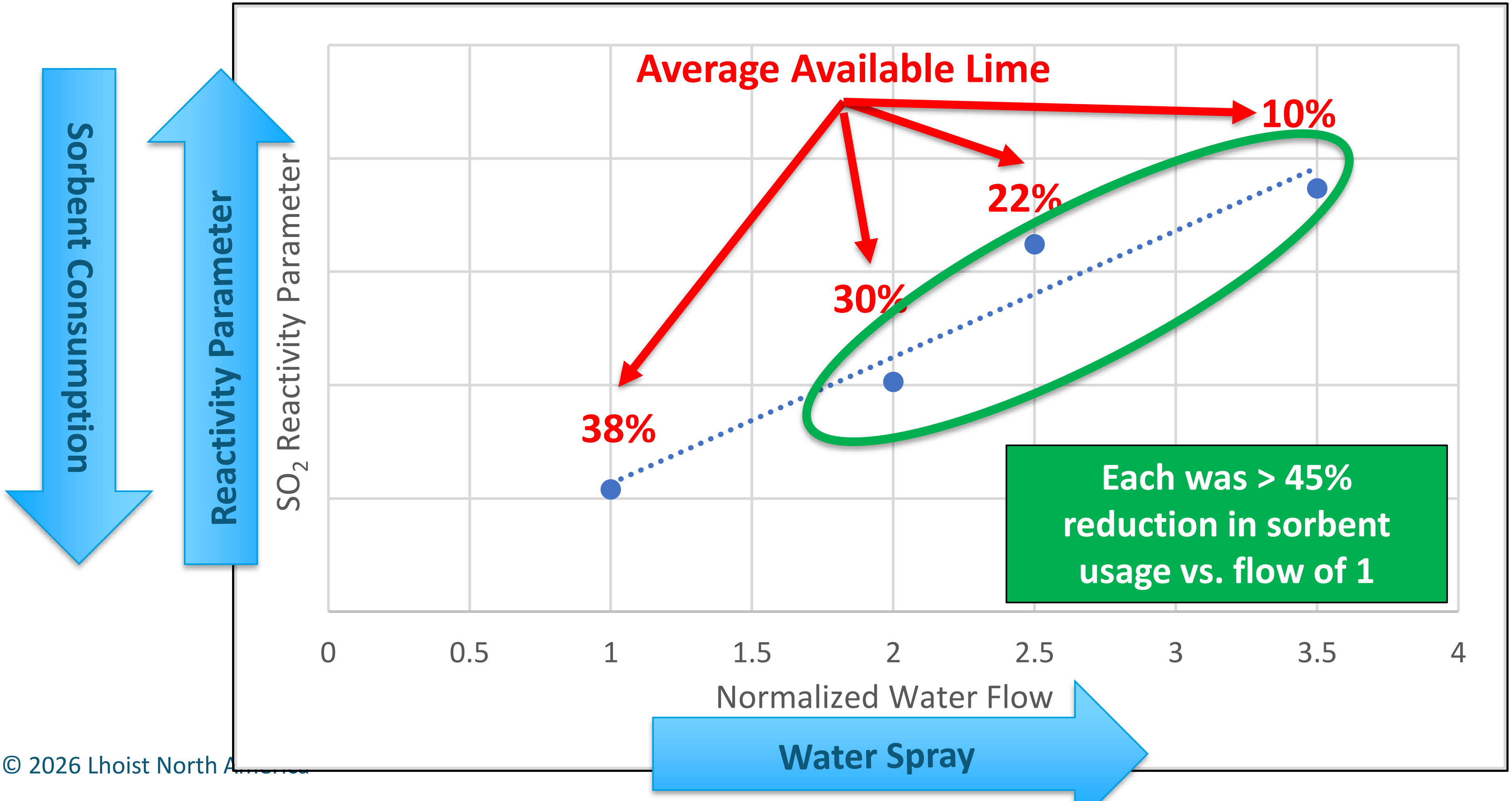
- Multi-month optimization work with CDS user to assess performance impacts optimizing water spray



CDS Case Study #2

Observations from Objective Data

- Emission data was analyzed to model water spray impact on efficiency and compared to residue chemistry



Key Take Aways

Keep it slow!

- Conveying velocities of 3,300 ft/min (55 ft/sec) +/- 10% minimizes soft scaling

Keep it cool!

- Conveying temperatures < 158 ^{o}F reduce recarbonation rate

Keep it dry!

- Dehumidification (RH < 8%) prevents recarbonation

Materials of Construction

- Mild steel rotary air locks WILL LIKELY FAIL within ~ 1 year or less
- Have a spare! Or, get new airlocks ceramic coated (> 5 years observed)

Vent properly

- Size venting not for new (no leakage) scenario, but for worst case scenario

Maintain velocity throughout - pipe properly, use hoses at elbows or on entire system

Sorbent dispersion/distribution is a key performance driver

Closing Thoughts

> **Velocity**
- Too fast and the system may choke
- Too slow and the material will settle out
- Consider pipe geometry

> **Temperature**
- Over 160 ^oF = carbonate scale formation
- Nominally, 85 ^oF is preferred

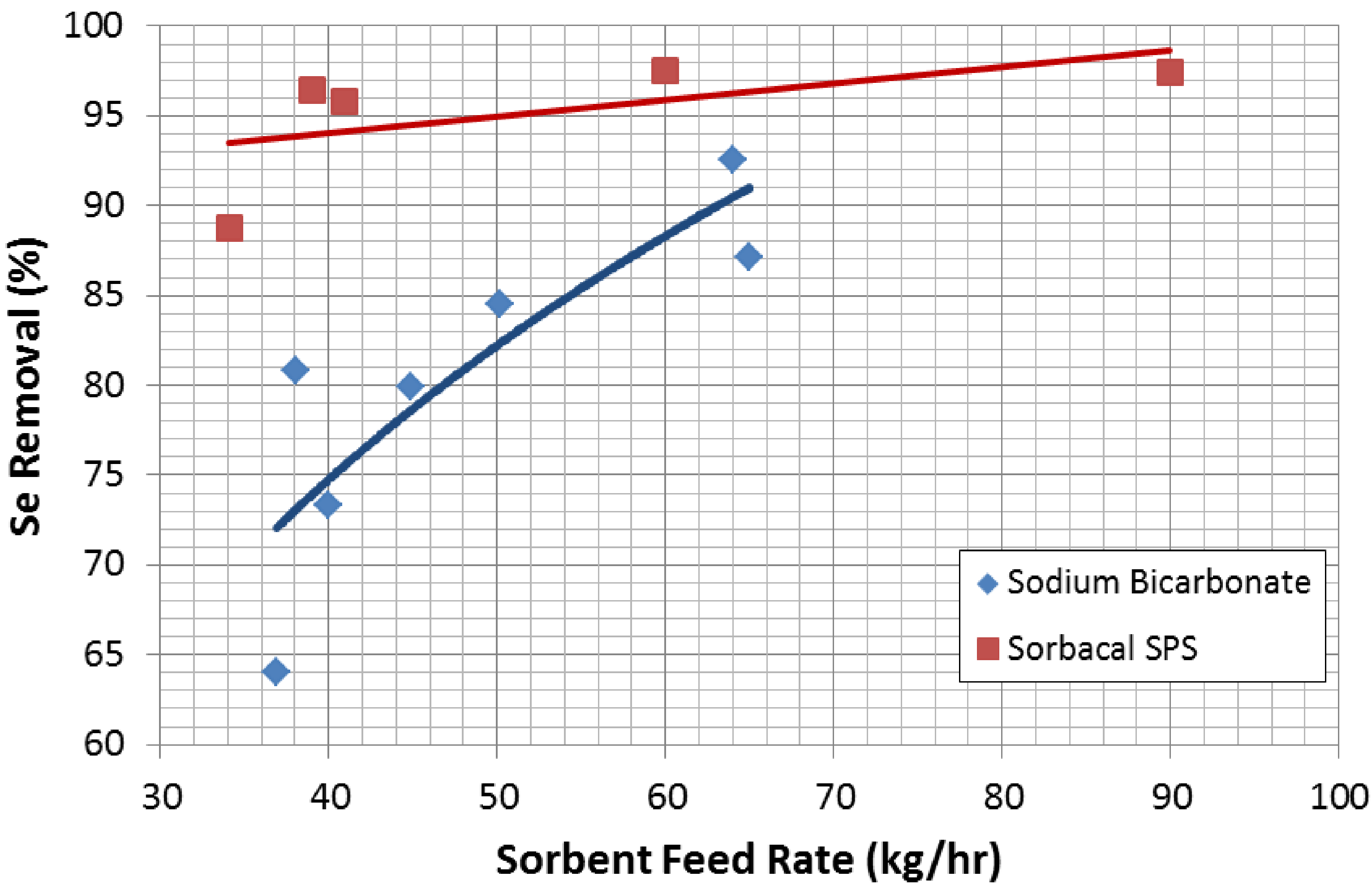
> **Moisture**
- Low moisture is key to minimizing carbonate formation
- % RH greater than 0.5% to reduce potential static
- % RH less than 8% to inhibit carbonization

> **Watch your data to control the system**

Thank you!

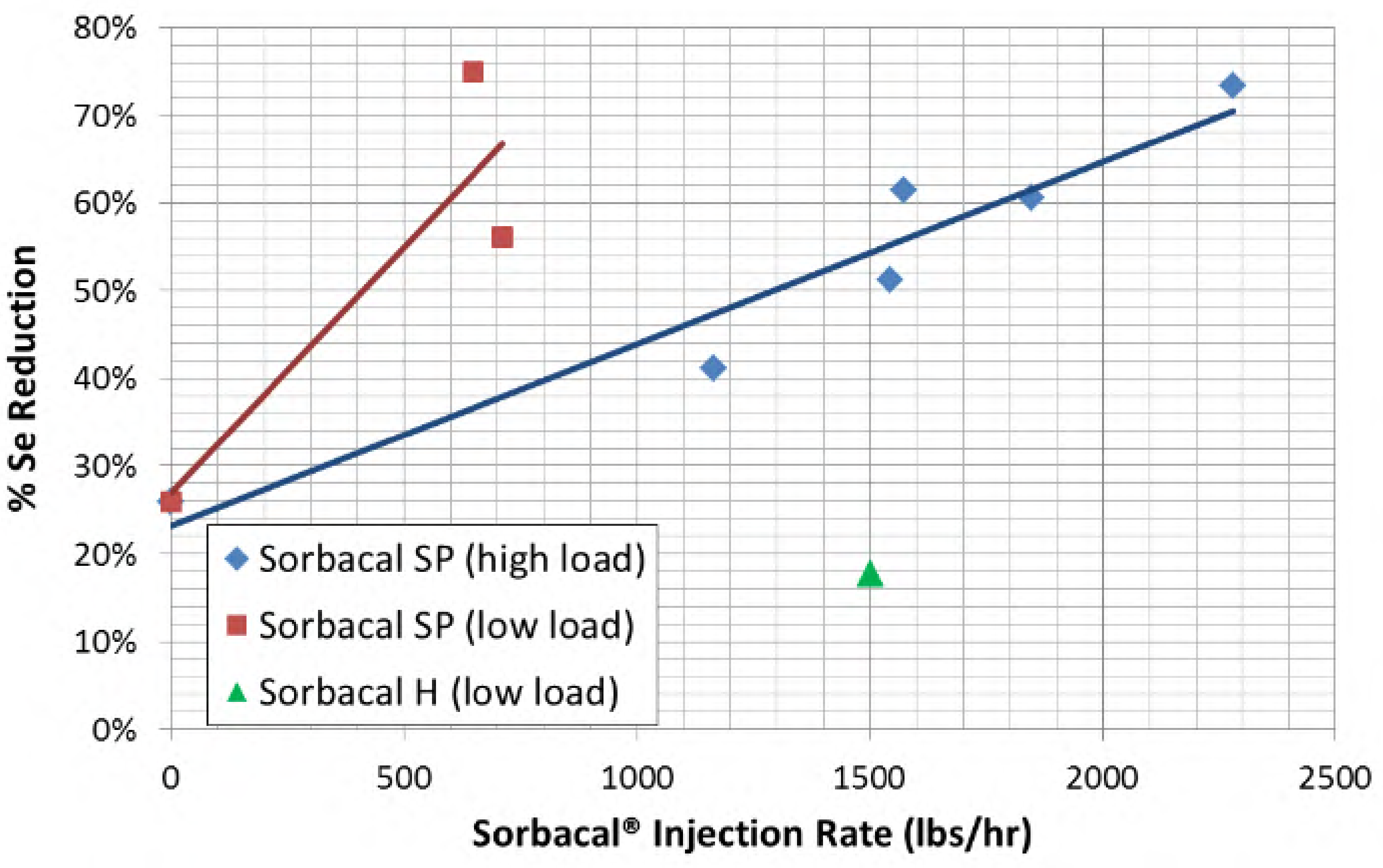
New Advancements in Sorbent Technology

Se Reduction – Glass Plant



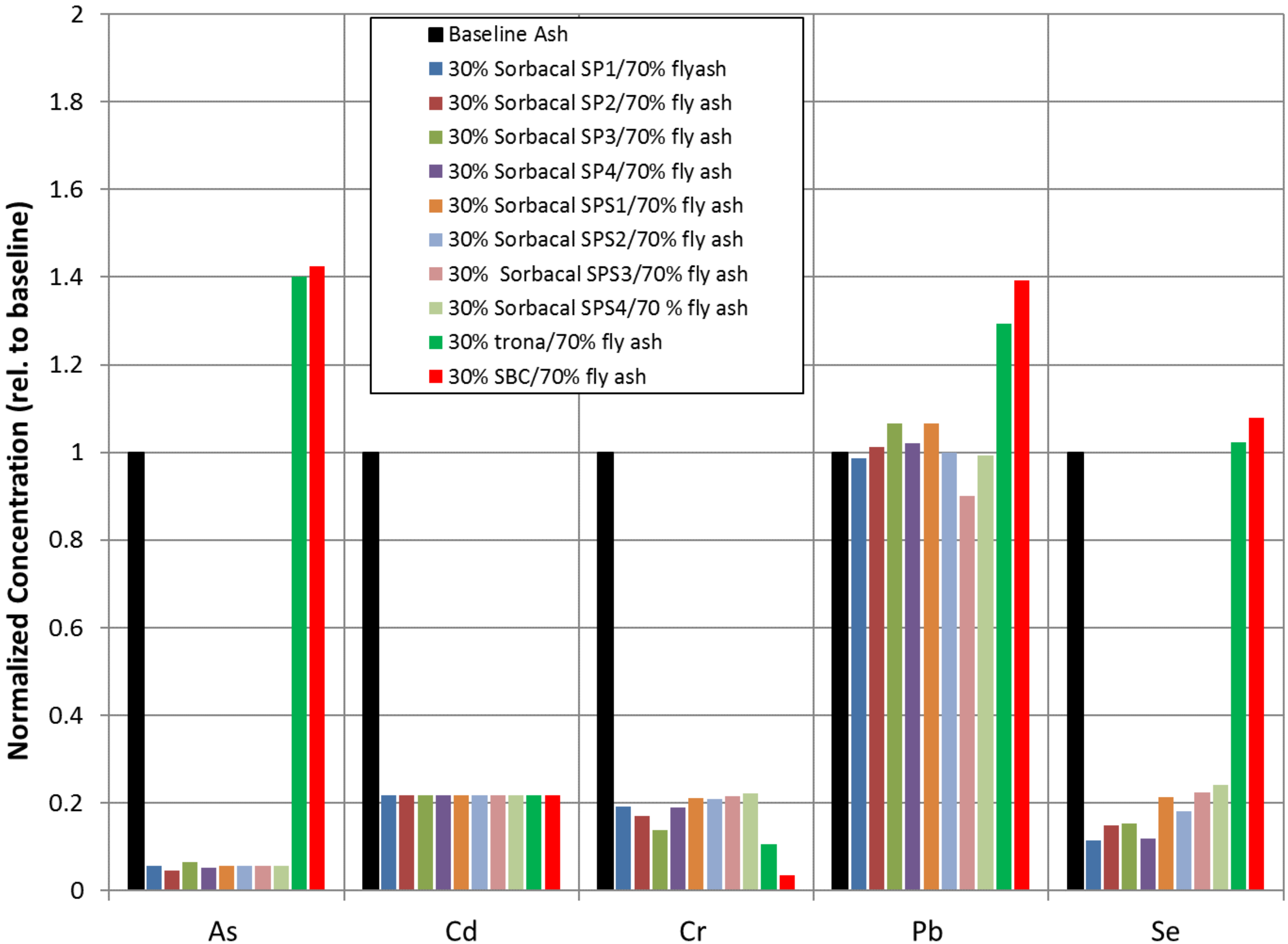
- Feeding Sorbacal® SPS continuously since 2008
- Primarily driven by Se, HF, and SO_2 capture

Se Reduction - Utility Unit (2017)



- Se capture more efficient at lower loads
- Enhanced sorbents more efficient than standard hydrated lime
  - Surface area and pore volume drive performance

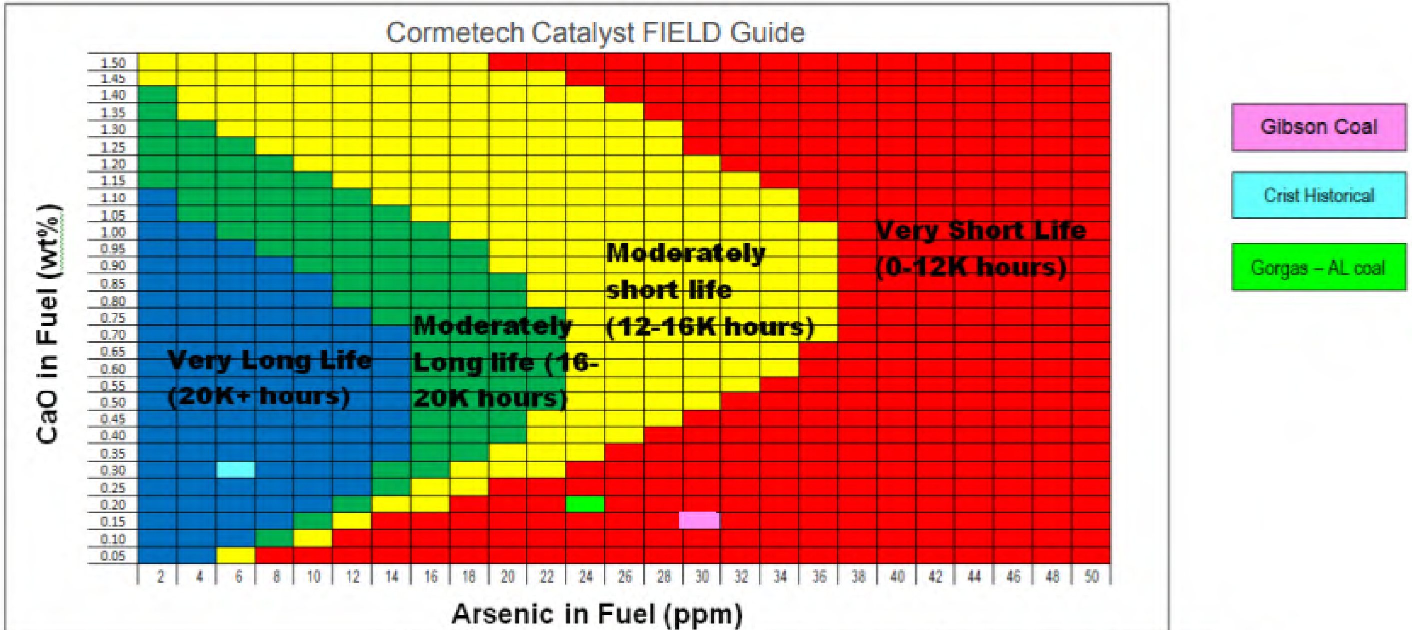
Reduced Impact on Leaching



- Sorbacal® SP and SPS injection reduce leaching of RCRA metals in bituminous fly ash

Impact of Arsenic on SCR Catalyst Life

- Observation: Ca in ash can extend catalyst life

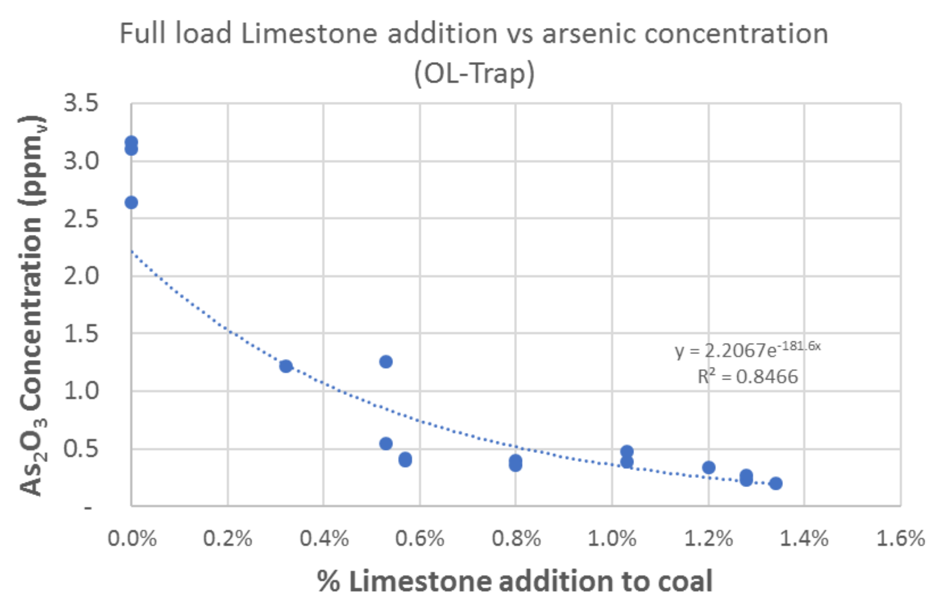


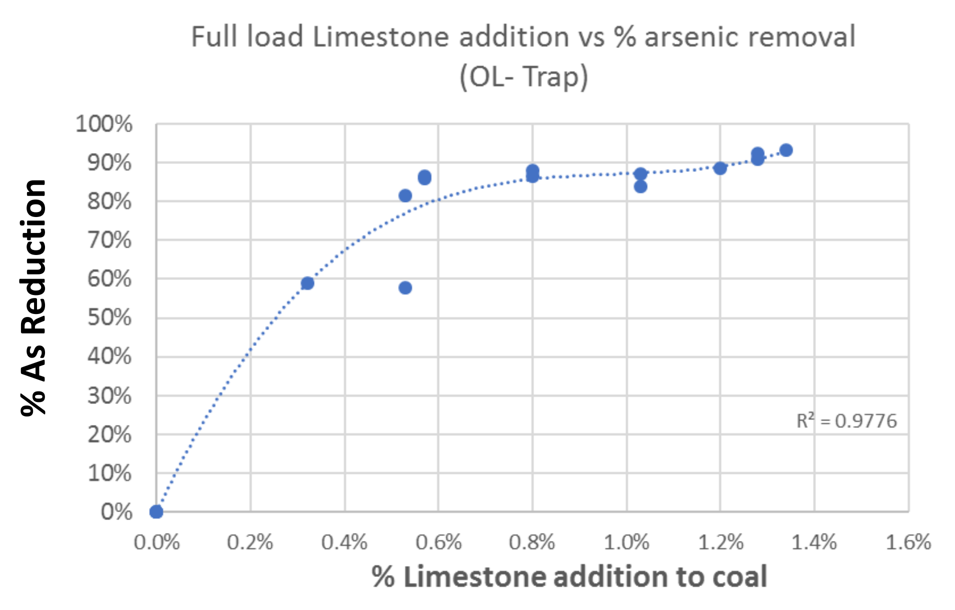
Fuel	Gibson Coal	Crist Historical	Gorgas (AL coal)
CaO in Ash (%, dry)	1.66%	3.13%	1.78%
Ash% (dry)	8.01%	9.79%	12.46%
Cao in Fuel (%,dry)	0.13%	0.31%	0.22%
As in fuel (ppmw, dry)	29.69	4.53	23.97
CaO/As Ratio (x 10^5)	4.5	67.6	9.3
Deactivation rate @ 16k hrs.	0.35	0.65	0.485

(1) Bookout, J. Mitigating Arsenic Poisoning of SCR Catalyst from Burning Gibson IB Coal. 2018 NO_x-Combustion Round Table, St. Louis MO. Workshop 08

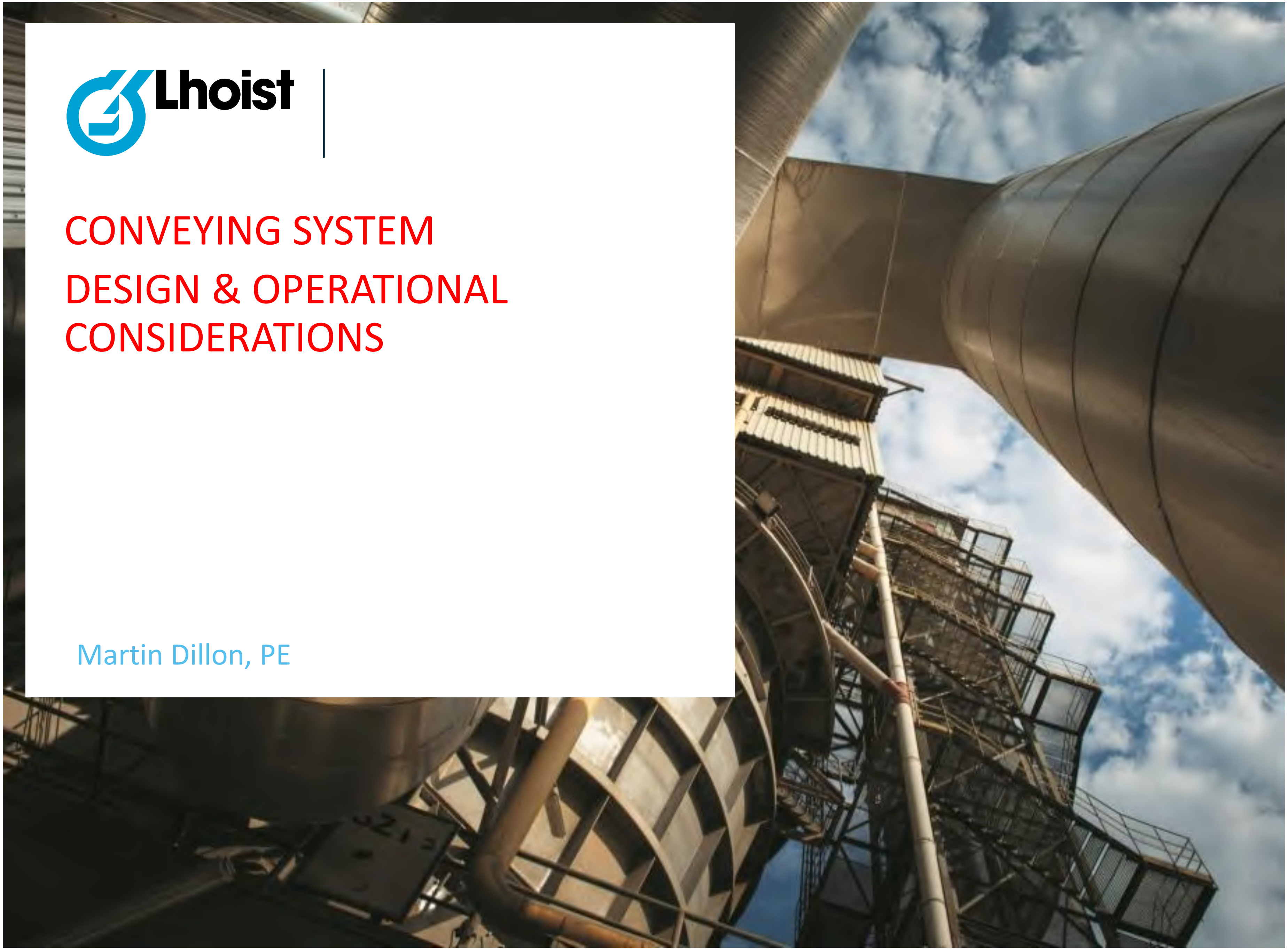
Managing Catalyst Poisoning

- Calcium compounds can mitigate impacts of As and P poisoning
  - $3CaO_{(s)} + As_2O_{3(g)} + O_{2(g)} \Leftrightarrow Ca_3(AsO_4)_{2(s)}$
  - $3CaO_{(s)} + As_2O_{5(g)} \Leftrightarrow Ca_3(AsO_4)_{2(s)} + O_{2(g)}$
  - $3CaO_{(s)} + P_2O_{3(g)} + O_{2(g)} \Leftrightarrow Ca_3(PO_4)_{2(s)}$
  - $3CaO_{(s)} + P_2O_{5(g)} \Leftrightarrow Ca_3(PO_4)_{2(s)} + O_{2(g)}$





(1) Bookout, J. Mitigating Arsenic Poisoning of SCR Catalyst from Burning Gibson IB Coal. 2018 NO_x-Combustion Round Table, St. Louis MO. Workshop 08



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CONVEYING SYSTEM

DESIGN & OPERATIONAL CONSIDERATIONS

Martin Dillon, PE

Impact of Particle Size on ESP Performance

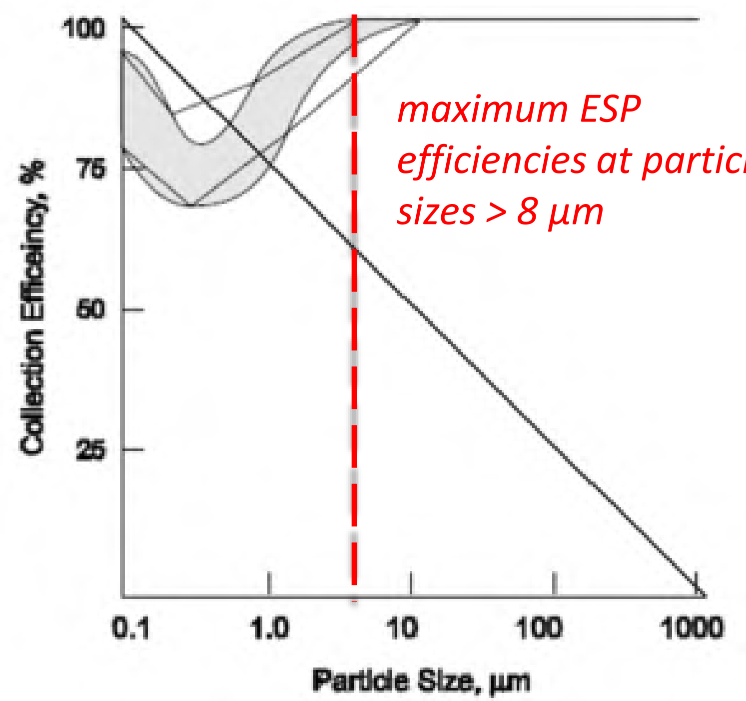
Deutsch- Anderson Equation:

$$\eta = 1 - e^{-w(A/Q)} \qquad w = \frac{d_p E_0 E_p}{4\pi\mu}$$

η = collection efficiency
w = migration velocity (ft/sec)
A = effective collection area (ft^2)
Q = Gas flow rate (ft^3/sec)

d_p = particle diameter (µm)
E_0 = field strength (V/ft)
E_p = collection field strength (V/ft)
µ = gas viscosity (cp)

Effect of particle size on ESP collection efficiency



Richards, J. R. Control of Particulate Matter Emissions Student Manual Control of Particulate Matter Emissions Student Manual. *APTI Course 413, Third Ed.* **2000**, 1–358

ESP Performance Parameters:

- Particle size distribution
  - Ask for D_{10}, D_{50}, *and* D_{90}
- Mass loading
- Resistivity

Hydrated Lime Specification – *What Matters?*

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Lhoist North America
Lhoist Group

Lhoist North America of Missouri, Inc.
20947 White Sands Road, Ste. Genevieve, MO, USA 63670
Phone #: (573)-883-8514

Site:	Document Type (PSP):
LNA Ste. Genevieve, MO	**Product Specification (Plant)**
Document No.:	Revision Date/Time:
US40 - 5020 - PSP	**6/25/2018 12:00:00 PM**

Subject: **US40 - 5020 - SORBACAL® SP BAG**

Hard copies of this document are not controlled unless authorized.

1.0 SPECIFICATIONS

CHARACTERISTIC	SPECIFICATION	LIMIT	REFERENCE
Available Ca(OH)2 (%)	92.0	Min	ASTM C25
Free Moisture - 25-150 C (%)	1.4	Max	Moisture Balance
Median Particle Size (µm)	5.0 - 18.0	Range	Particle Size Analyzer (Laser)
7-Point BET Specific Surface Area (m2/g)	40.0	Min	BET Instrument
Pore Volume 17-1000 Å (cm3/g)	0.20	Min	BET Instrument

2.0 SIZING - For more information, please contact your Lhoist North America (LNA) Sales Representative.

3.0 CERTIFICATE OF ANALYSIS/CONFORMITY - Available upon request and/or provided with the shipment.

4.0 IDENTIFICATION - Bulk and semi-bulk bagged product will be identified with the product code and date on the shipping documents.

5.0 STORAGE - This material should be stored in an enclosed environment away from elevated levels of moisture and/or humidity.

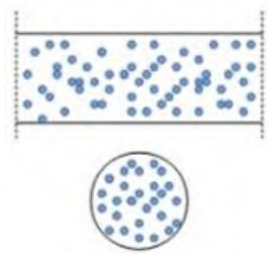
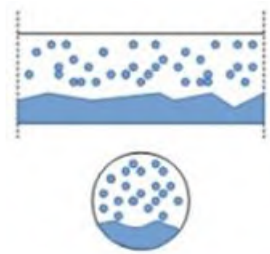
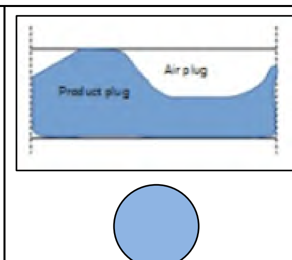
- Keep specification sufficiently general to avoid sole sourcing
  - *Available $Ca(OH)_2$ is not as critical* as particle size, surface area, and pore volume

Topics

- Review basic pneumatic conveying concepts
- Conditioned air characteristics/composition considerations in conveying hydrate
  - Velocity
  - Temperature
  - Moisture
- The significance of the right geometry
- Mass flow implications
- Discussion & Questions

Pneumatic Conveying

- Vacuum systems (*think…similar to ID fan*)
- Pressure systems (*think…similar to FD fan*)
  - Dilute phase
  - Dense phase

Flow Regime	Conveying Velocity	Pipe Aspect	Comments
Dilute Phase	>3000 fpm		* Conveyed particles in suspension * No material deposition
Dense Phase - Saltation	1500 fpm to 3000 fpm		*Material deposition and pickup continuously in flux *Material concentration asymmetric throughout the system *Velocity gradients appear in the system
Dense Phase - Discontinuous	< 1500 fpm		* Material deposition and full-section plugs appear * Increasing pressure

Conveying Air Temperature

> Pneumatic conveying of hydrated lime is a chemical process

- Hydrated lime reacts with carbon dioxide (CO_2) to form calcium carbonate ($CaCO_3$) and water

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$$

- T < 85°F - **adsorbed** water necessary for carbonation of hydrated lime (*)

- T > 158 °F carbonation is inevitable

Keep it cool!

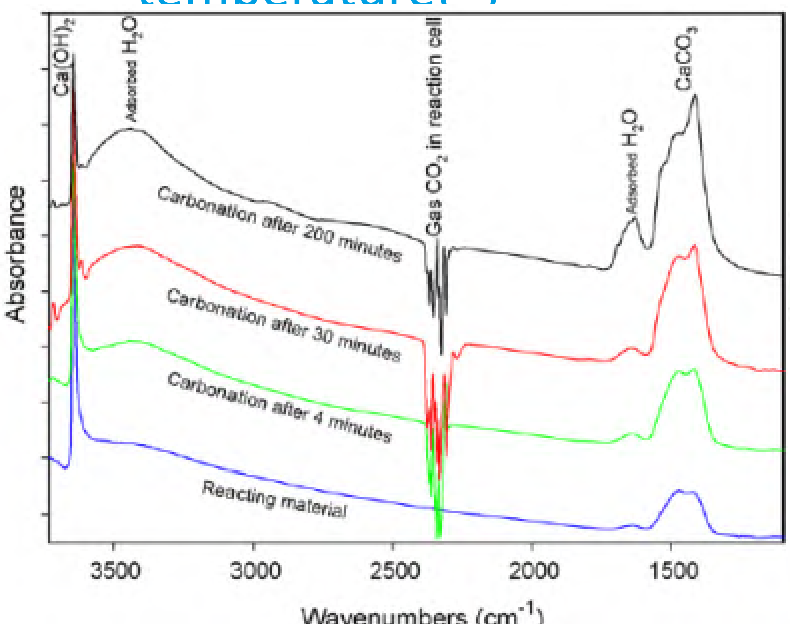
(*) Source: Montes-Hernandez, G.; Pommerol, A.; Renard, F.; Beck, P.; Quirico, E.; Brissaud, O. In Situ Kinetic Measurements of Gas–solid Carbonation of Ca(OH)2 by Using an Infrared Microscope Coupled to a Reaction Cell. Chem. Eng. J. 2010, 161 (1-2), 250–256
(**) Source: Wenlong Wang,* Mingqiang Hu, Yong Dong, and Chunyuan Ma, Study on the Effect of CO2 on the Consumption of Desulfurizing Agent Ca(OH)2 in Flue Gas Desulfurization, *Ind. Eng. Chem. Res.* 2010, *49,* 1444–1449

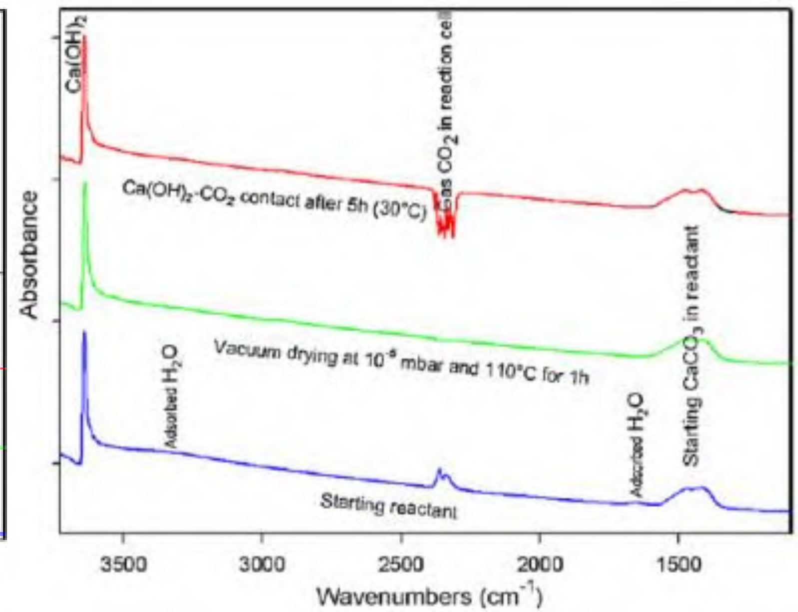
Conveying Air Temperature/Moisture

> Pneumatic conveying of hydrated lime is a chemical process

- Water plays a catalytic role in carbonation at low temperature(*)

$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$





How much H_2O is too much?

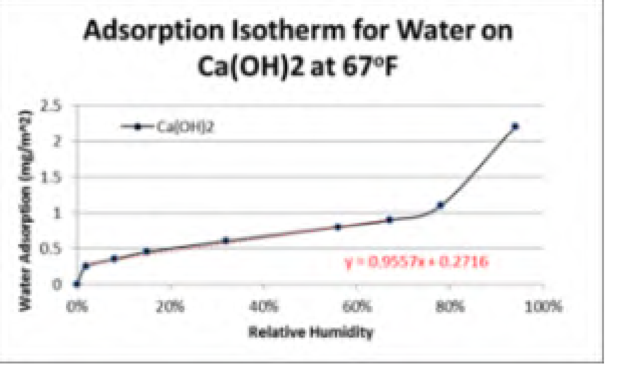
((*) Source: Montes-Hernandez, G.; Pommerol, A.; Renard, F.; Beck, P.; Quirico, E.; Brissaud, O. In Situ Kinetic Measurements of Gas–solid Carbonation of Ca(OH)2 by Using an Infrared Microscope Coupled to a Reaction Cell. Chem. Eng. J. 2010, 161 (1-2), 250–256

Conveying Air Moisture

- The carbonation of hydrated lime requires the presence of adsorbed water (*)
- The following reactions may take place at the water-adsorbed surface (*)

$$Ca(OH)_2 \longrightarrow Ca2^{+} + 2OH^{-}$$
$$CO_2 + H_2O \longrightarrow CO_2 \cdot H_2O$$
$$CO_2 \cdot H_2O + 2OH^{-} \longrightarrow CO_3^{2+} + 2H_2O$$
$$Ca^{2++} CO_3^{2} \longrightarrow CaCO_3$$

- Only a molecular layer of water is necessary for the reaction with CO_2 and the underlying hydrate(**)
  - Water adsorption as a function of %RH is a
    values between 5% and 70%
  - Increase in relative humidity catalyzes gas-



(*) Source: Shin-Min Shih,* Ch'un-Sung Ho, Yuen-Sheng Song, and Jyh-Ping Lin, Kinetics of the Reaction of Ca(OH)2 with CO2 at Low Temperature, *Ind. Eng. Chem. Res.* 1999, *38,* 1316-1322
(**) Source: Dario T. Beruto*, Rodolfo Botter, Liquid-like H2O adsorption layers to catalyze the Ca(OH)2/CO2 solid-gas reaction and to form a non-protective solid product layer at 20C, J.of the European Ceramic Society 20 (2000) 497±503

Conveying Air Moisture

Carbonation of hydrated lime is dependent on the relative humidity of the conveying air (*)

- Critical relative humidity has been determined to be at ~ 8% RH
  - \> RH < 8% RH carbonation of $Ca(OH)_2$ does not proceed
  - \> RH > 8% the carbonation increases with relative humidity and temperature
- % RH < 0.5% → triboelectric effects seem to play a part in material "clinging" to the conveying system

Conveying Air Pressure Dew Point ("TD")	Conveying Air Temperature ("T")														
(°F)	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160
-70	0.8%	0.5%	0.3%	0.2%	0.2%	0.1%	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
-60	1.5%	1.0%	0.7%	0.5%	0.3%	0.2%	0.2%	0.1%	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%
-50	2.8%	1.9%	1.2%	0.9%	0.6%	0.4%	0.3%	0.2%	0.2%	0.1%	0.1%	0.1%	0.1%	0.0%	0.0%
-40	5.1%	3.4%	2.3%	1.5%	1.1%	0.8%	0.5%	0.4%	0.3%	0.2%	0.2%	0.1%	0.1%	0.1%	0.1%
-30	9.0%	5.9%	4.0%	2.7%	1.9%	1.3%	1.0%	0.7%	0.5%	0.4%	0.3%	0.2%	0.2%	0.1%	0.1%
-20	15.3%	10.1%	6.8%	4.6%	3.2%	2.3%	1.6%	1.2%	0.9%	0.6%	0.5%	0.4%	0.3%	0.2%	0.2%
-10	25.3%	16.7%	11.2%	7.7%	5.3%	3.8%	2.7%	2.0%	1.4%	1.1%	0.8%	0.6%	0.5%	0.4%	0.3%
0	40.9%	27.0%	18.1%	12.4%	8.6%	6.1%	4.4%	3.2%	2.3%	1.7%	1.3%	1.0%	0.8%	0.6%	0.5%
10	64.7%	42.6%	28.7%	19.6%	13.6%	9.6%	6.9%	5.0%	3.7%	2.7%	2.1%	1.6%	1.2%	0.9%	0.7%
20	100.0%	66.0%	44.3%	30.3%	21.1%	14.9%	10.6%	7.7%	5.7%	4.2%	3.2%	2.4%	1.9%	1.4%	1.1%
30		100.0%	67.2%	46.0%	31.9%	22.5%	16.1%	11.7%	8.6%	6.4%	4.8%	3.7%	2.8%	2.2%	1.7%
40			100.0%	68.4%	47.5%	33.6%	24.0%	17.4%	12.8%	9.5%	7.2%	5.5%	4.2%	3.2%	2.5%
50				100.0%	69.5%	49.1%	35.1%	25.5%	18.7%	13.9%	10.5%	8.0%	6.1%	4.7%	3.7%
60					100.0%	70.6%	50.5%	36.7%	27.0%	20.1%	15.1%	11.5%	8.8%	6.8%	5.3%

(*) Source: Shin-Min Shih,* Ch'un-Sung Ho, Yuen-Sheng Song, and Jyh-Ping Lin, Kinetics of the Reaction of Ca(OH)2 with CO2 at Low Temperature, *Ind. Eng. Chem. Res.* 1999, *38,* 1316-1322
Alduchov, O. A., and R. E. Eskridge, 1996: Improved Magnus' form approximation of saturation vapor pressure. J. Appl. Meteor., 35, 601–609.
August, E. F., 1828: Ueber die Berechnung der Expansivkraft des Wasserdunstes. Ann. Phys. Chem., 13, 122–137.
Magnus, G., 1844: Versuche über die Spannkräfte des Wasserdampfs. Ann. Phys. Chem., 61, 225–247.

This is where we typically observe most systems operating

Conveying Air Moisture

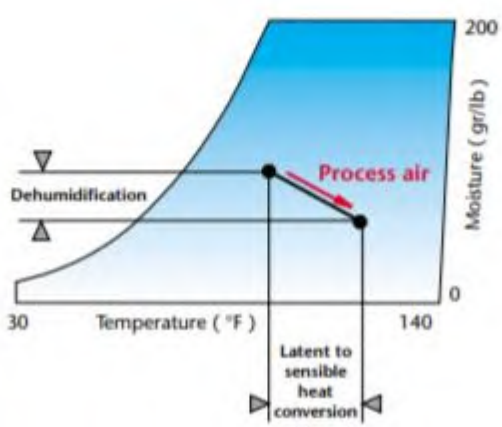
Desciccant Dehumidifiers

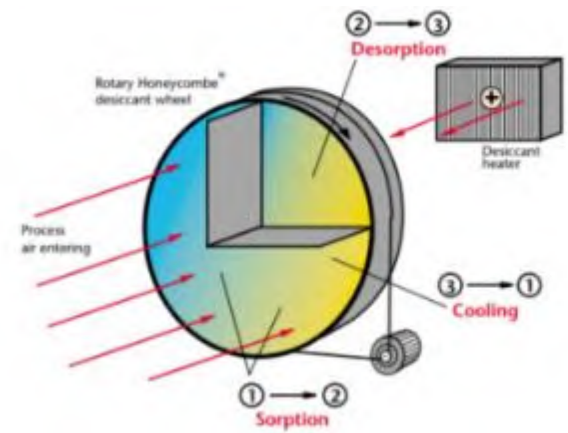
> Desiccant dehumidifiers remove moisture from the "process" inlet air and move it to the "reactivation" air

> The amount of moisture removed depends on the:
  - initial moisture in the process air,
  - temperature of the process inlet air
  - reactivation air temperature
  - process inlet air velocity

> The amount of moisture removed is variable

> Desiccant has a fixed capacity to absorb moisture; it's a function of relative humidity.



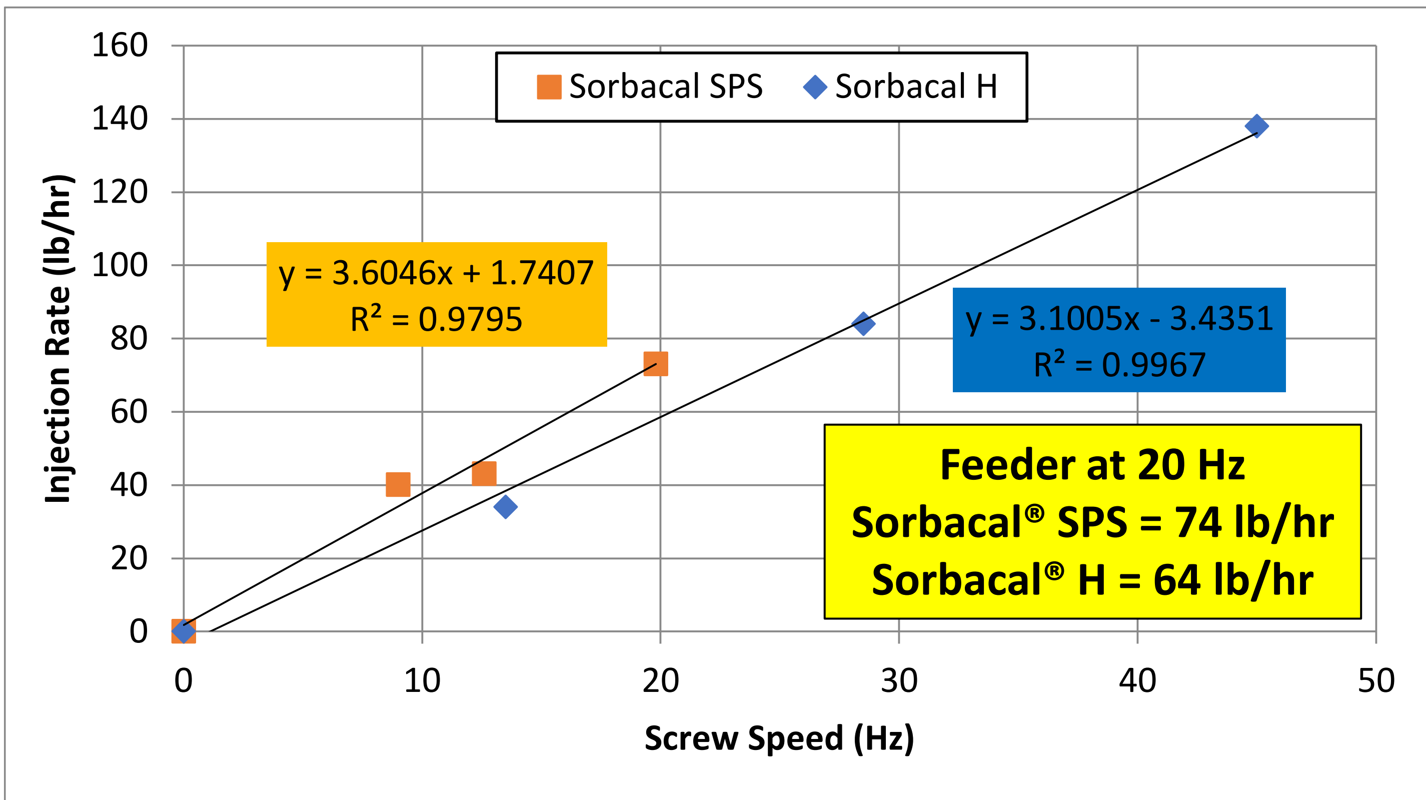


Source: The Dehumidification Handbook Second Edition ,Copyright 1989 and 2002 © Munters Corporation:

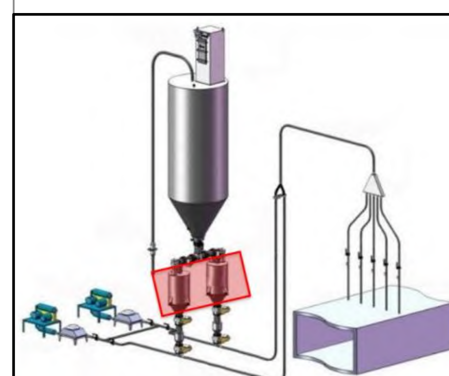
Gravimetric vs. Volumetric Feeding

How Long Can You Trust a Calibration Curve?

- Different hydrated lime products have different flow properties
- Sorbacal® SPS able to achieve same feed rate as Sorbacal® H at ~14% lower dosage rate during trial below



How would you identify sorbent flow issue <u>without</u> LIW data?



Dilute-Phase Pneumatic Conveying

> Theory and design for (pressure) dilute phase conveying
  - Mechanically simple system
  - Higher gas velocities at low pressures (nominally, 3300 fpm (±10%), 3-5 psig)

> Dilute phase conveying uses
  - High air-to-solids; low solids-to-air
    - keep the conveyed material in suspension
    - transport the required distance
    - **low choking conditions**
  - transport is continuous, not intermittent

> For dilute phase conveying
  - pick-up velocity at the beginning of the conveying
  - acceleration (velocity transitions) throughout
  - terminal velocity at the end of the conveying

Hydrated lime is a reactive chemical
Pneumatic conveying of hydrated lime a chemical process

When it goes wrong…conveying velocity

System reliability and optimizing operations

> Dry powder plugging: choked flow and saltation

$$U_{Salt} = \left[\frac{4 \times M_p \times 10^{(1440x+1.96)} \times g^{(1100x+2.5)/2} \times D^{\left(\frac{1100x+2.5}{2} - 2\right)}}{\pi \times \rho_f} \right]^{\frac{1}{(1100x+2.5)+1}}$$

- Conveying velocities sufficient to overcome saltation – consider particle slip in the adjustment
- Pipe geometry adequate to accommodate directional changes w/o choking flow
- Adequate air-to-solids ratio to maintain suspension and transport

Implementation

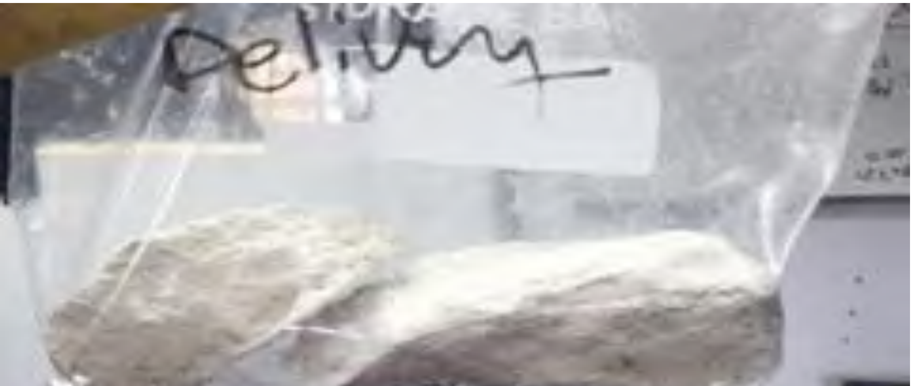
Common Issues

- Conveying Air:
  - Temperatures
    - *After cooler maintenance?*
  - Relative Humidity
    - *Desiccant dryer settings & maintenance?*
  - Velocity (too slow/ fast)
    - *Hard vs. Soft Plugs*
- Rotary Air Lock
  - Wear
    - Loss of tolerances
    - Carbonate accelerated wear
- Hopper Venting
  - Rotary Air Lock Wear
    - Commodity grade valves
  - Inadequate…
    - Air to Cloth for range of permissible range of RAL wear
    - Vent line size
  - Feed rate Control / Load cell noise

Hydrate Performance Assessment and Evaluation

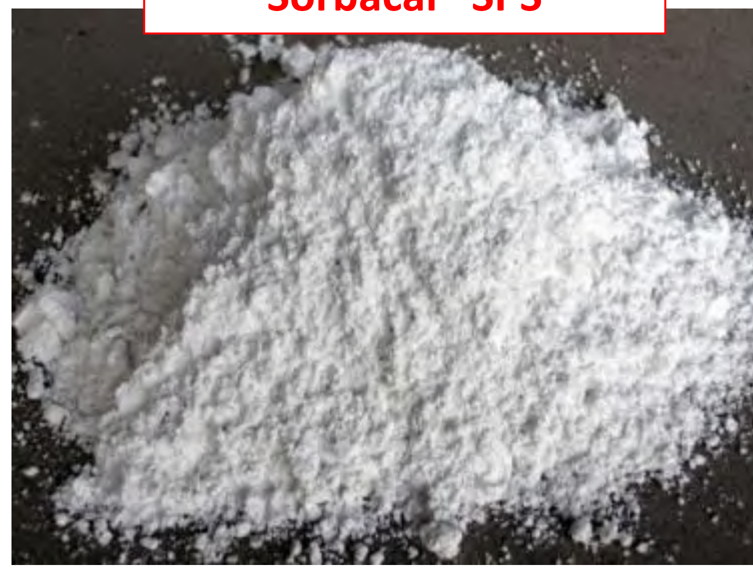
Calcium vs. Sodium Sorbents

Product Quality



Sodium sorbents pulled from truck

Sorbacal® SPS



Quality is essential for premium products from production to delivery

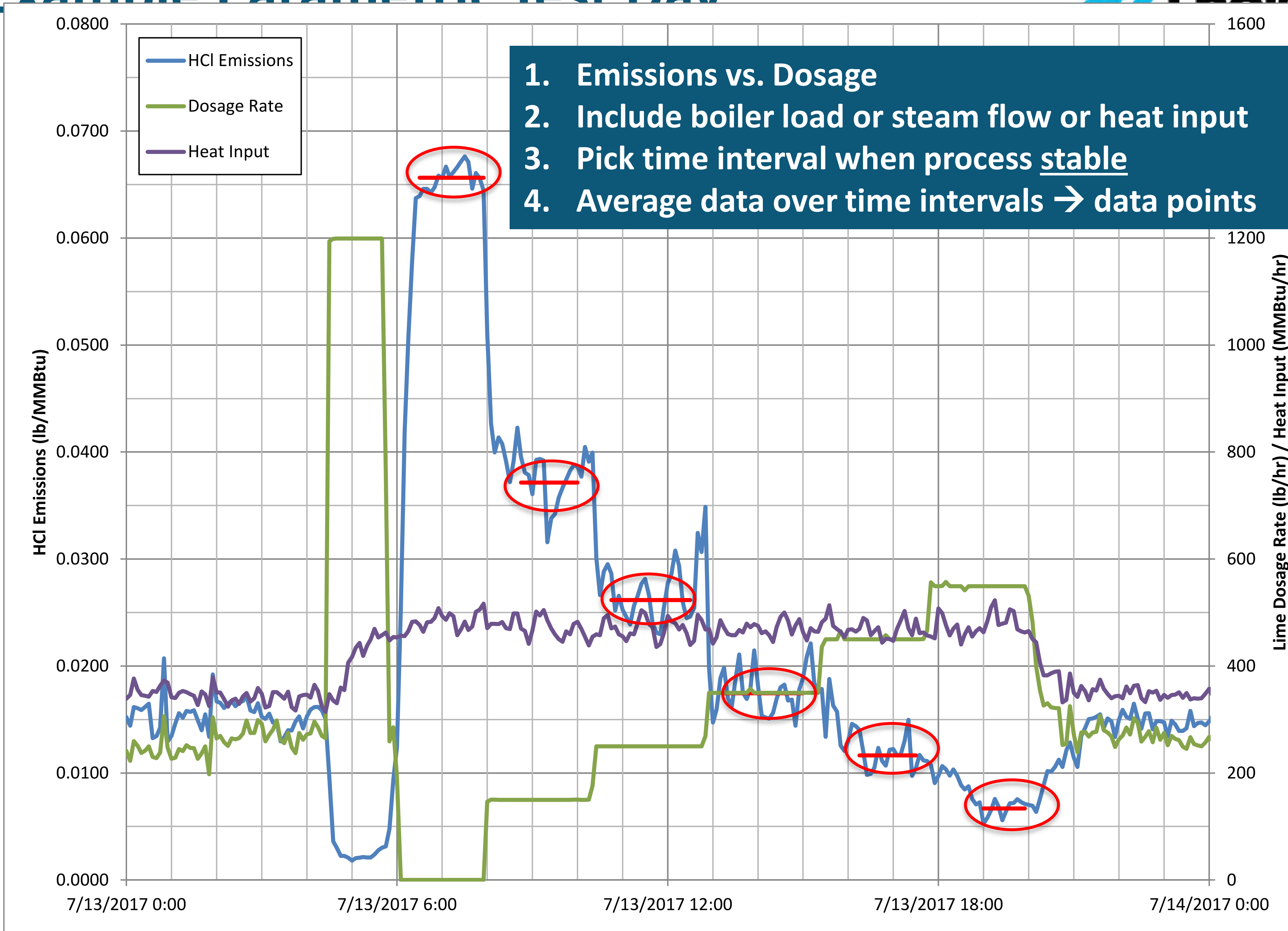
Why You Care about DSI Data Analysis?

- Increase probability of passing compliance testing
- Develop historical trends for benchmarking
- Effectively compare different sorbents
- Compare different mixing technologies
- Quantify performance delta at variable boiler loads
- Identify inefficiencies and/or potential for optimization
  - ❑ Optimize injection grid design
  - ❑ Best performing injection location
- Identify issues with data (i.e. emission measurements, readings, etc.)

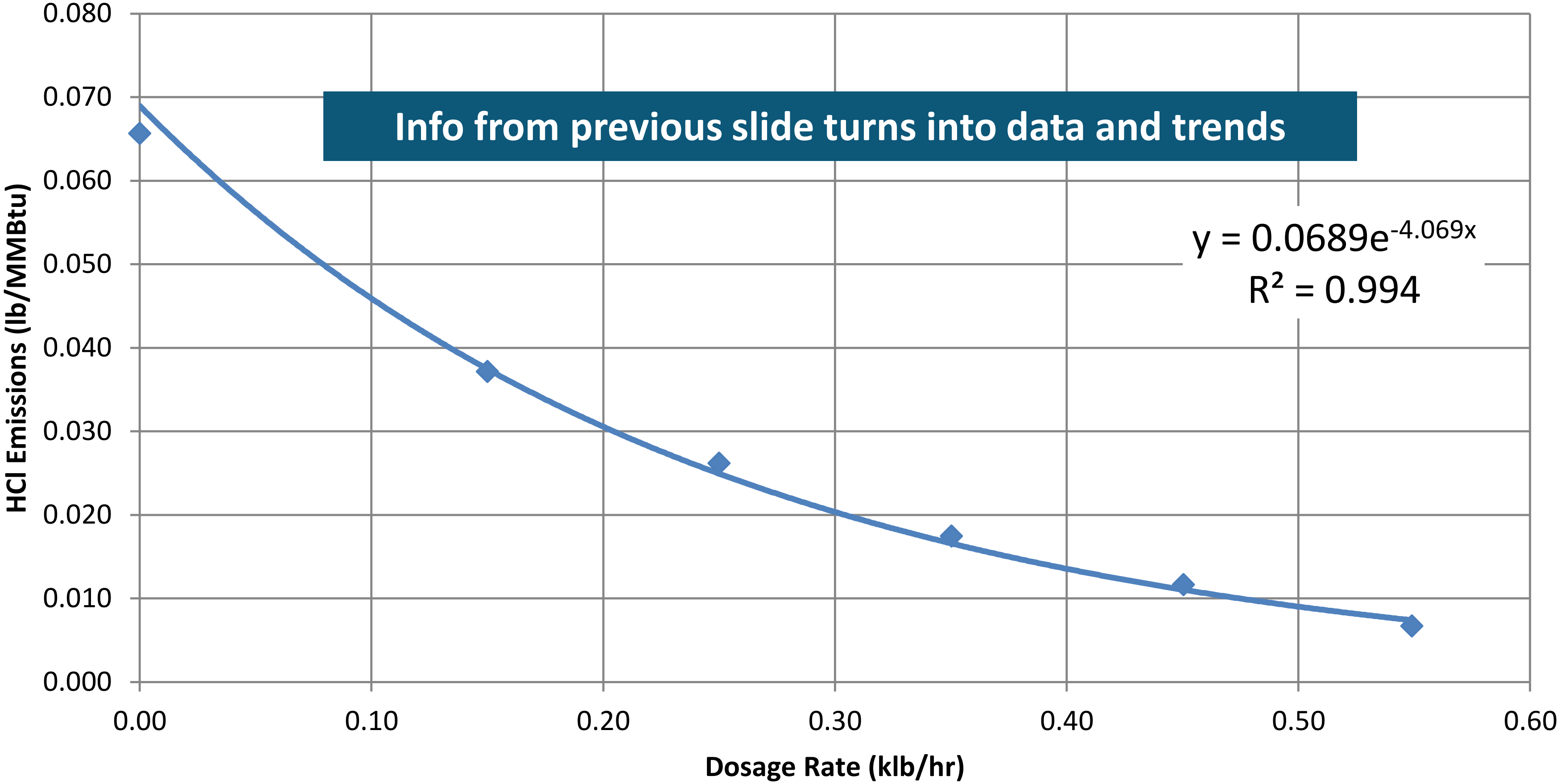
Performance Calculations

- Raw signals usually in ppm_v
  - Volumetric basis (*e.g.* ft^3 SO_2/ft^3 flue gas), must be converted to mass-basis (*e.g.* lb SO_2/lb flue gas)
  - Is the measured value wet? or dry?
    - Must be corrected to compare directly
      - All wet or all dry
  - If % reduction done on ppm_v basis, must correct to a reference O_2 value
    - Firing rates, air dilution, in-leakage
  - OR, convert to mass or mole basis and dilution is less significant
- Convert concentrations to mass-basis
  - Need to know flue gas flow rate as accurately as possible
- Convert concentrations to mole-basis
  - Direct understanding of sorbent performance
    - Poor performance (relative to other plants) can identify problems

Example Parametric Test Day

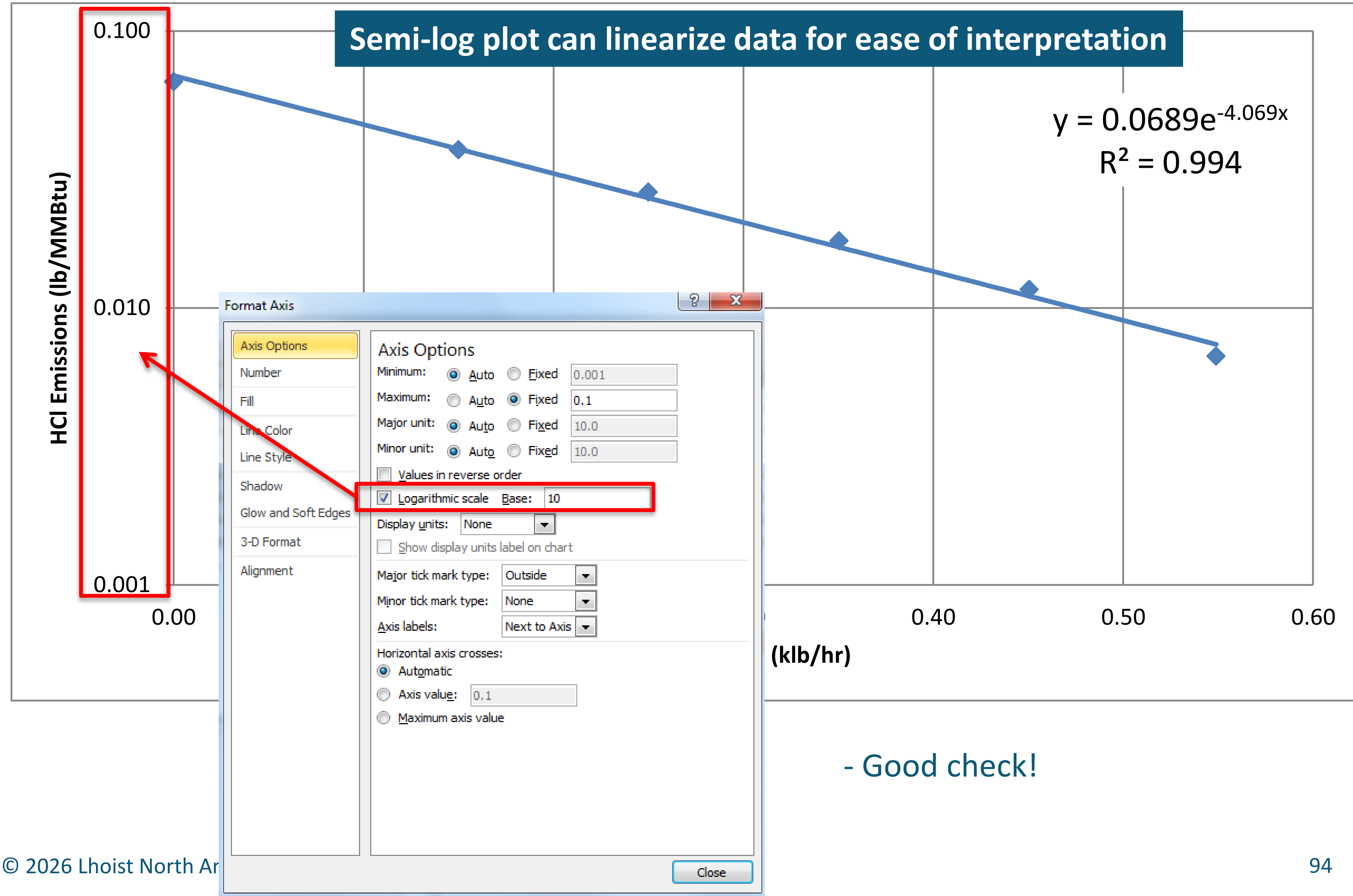


Example: Parametric Test Day



Start	Stop	HCl Emissions	Heat Input	HCl Emissions	DSI	HCl Rem	Mass Ratio	NSR	Utilization
Time	Time	lb/MMBtu	MMBtu/hr	lb/hr	lb/hr	%	lb sorbent / lb inlet HCl	Ca/2HCl	%
7/13/2017 6:30	7/13/2017 7:55	0.066	486	31.9	0	0%	0.00	0.00	-
7/13/2017 8:45	7/13/2017 10:00	0.037	471	17.5	150	43%	4.85	4.44	9.8%
7/13/2017 10:45	7/13/2017 12:30	0.026	468	12.3	250	60%	8.14	7.45	8.1%
7/13/2017 13:15	7/13/2017 15:00	0.017	470	8.2	350	73%	11.35	10.40	7.1%
7/13/2017 16:15	7/13/2017 17:30	0.012	469	5.5	450	82%	14.63	13.41	6.1%
7/13/2017 19:00	7/13/2017 19:55	0.007	485	3.2	549	90%	17.24	15.80	5.7%

Example: Parametric Test Day



- Good check!

Isolation valves

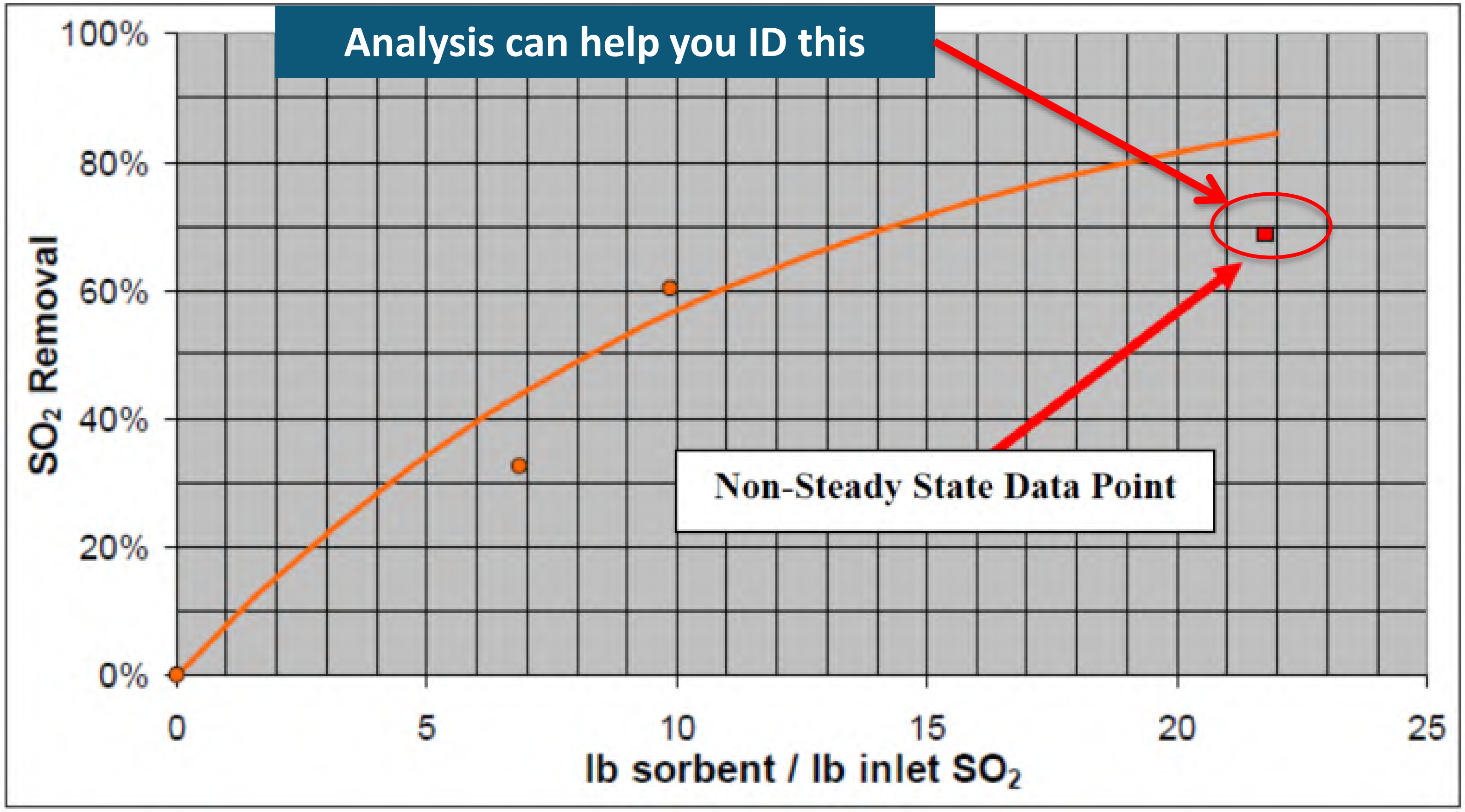
Operating Issues & Best Practices

> System Design / Best Practices

Air Cleaning Valves with integral pressure reliefs

Courtesy of Lance © 2018 Lance Valves

Benefits of DSI Data Analysis



QA/QC Check List

1. Not at steady state?
2. Issue with emission data?
3. DSI feed rate incorrect?
4. Something in the process change?

Monitoring Approaches and Technologies

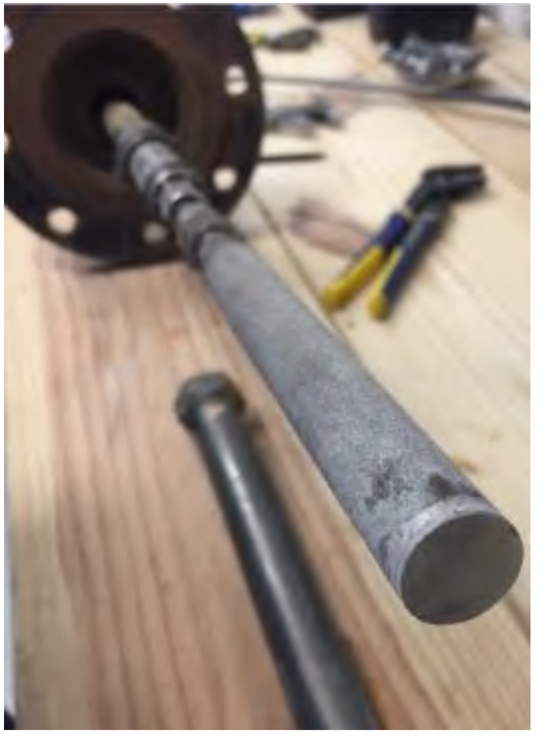
Topics

- **Analyzing Flue Gas**
  - Experiences with flue gas and analysis devices
- **Measuring SO_3/H_2SO_4**
  - Experiences with different analytical SO_3/H_2SO_4 technologies

Flue Gas Characterization

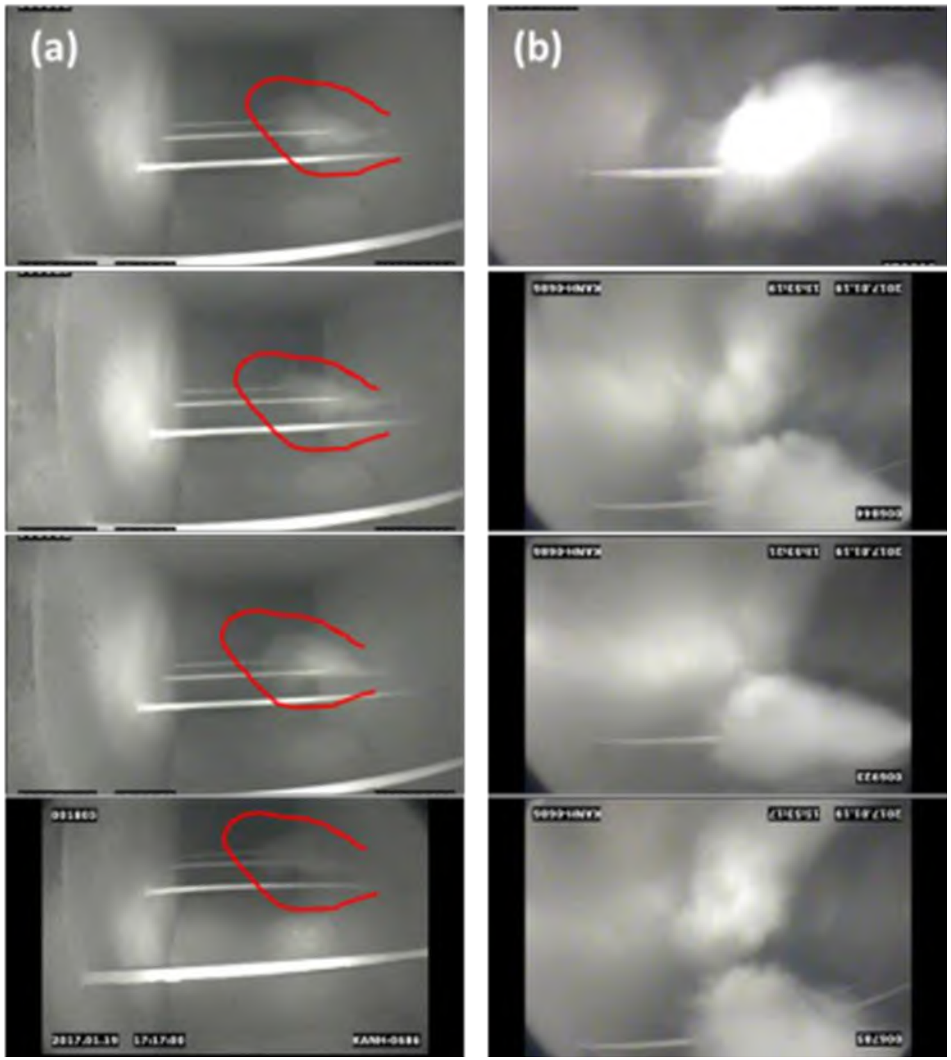
- **Advantages**
  - Pre-compliance test tuning
  - Cost optimization
    - Injection location
    - Stratification
    - Incomplete sorbent dispersion

- **Technologies**
  - FTIR
    - Filtered and inertial probes
  - TestO
  - Sorbent traps
  - Duct camera



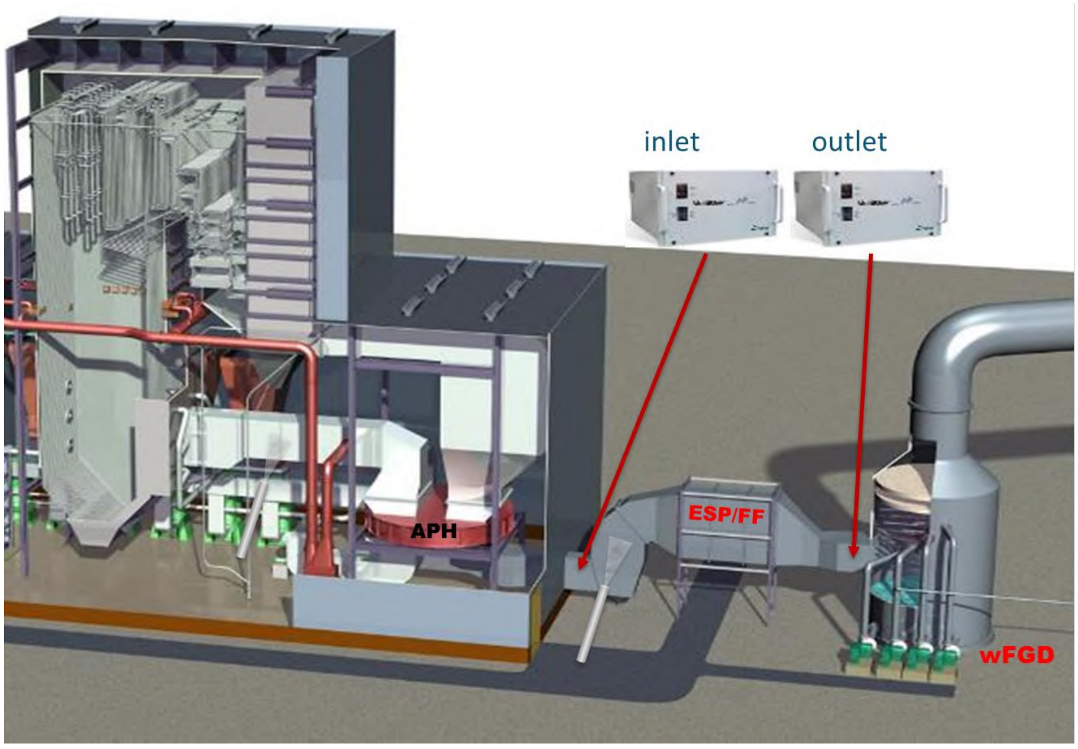
Duct Camera

Before Optimization After Optimization



FTIR (Fourier Transform Infrared Spectroscopy)

- **Continuous extractive measurement**
- **Simultaneously measures multiple gases**
  - SO_2, HCl, NO, NO_2, NH_3, CO_2, H_2O
- **Sampling locations range from SCR to stack**
  - Probe selection is critical
- **Measure in two locations**
  - Prior to injector
  - After injection



TestO

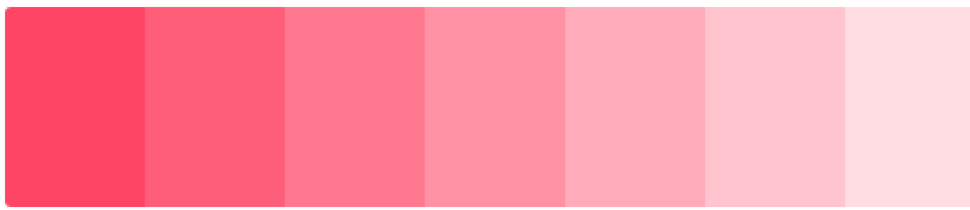
- **Continuous extractive measurement**
- **Measures multiple gases (*dry*)**
    - SO_2, NO_X, O_2, CO_2, CO
- **Sampling ranges from SCR to stack**
    - Watch out for ash buildup on probe
    - Clean periodically to prevent scrubbing

Measuring SO_3/H_2SO_4

- **Accepted Method**
  - Method 8A
- **Other Methods**
  - Ohio Lumex Traps - sorbent traps
  - Pentol - automated wet chemistry
  - Lancom 200 - dew point measurement
  - SICK – NDIR analyzer
- **With all methods, attention to sampling is critical**

Method 8A

- **Analysis via Titration**
  - Barium Perchlorate and Thorin indicator



- **Ion Chromatograph**
  - Measures ions – sulfate in this case

Ohio Lumex Sorbent Traps

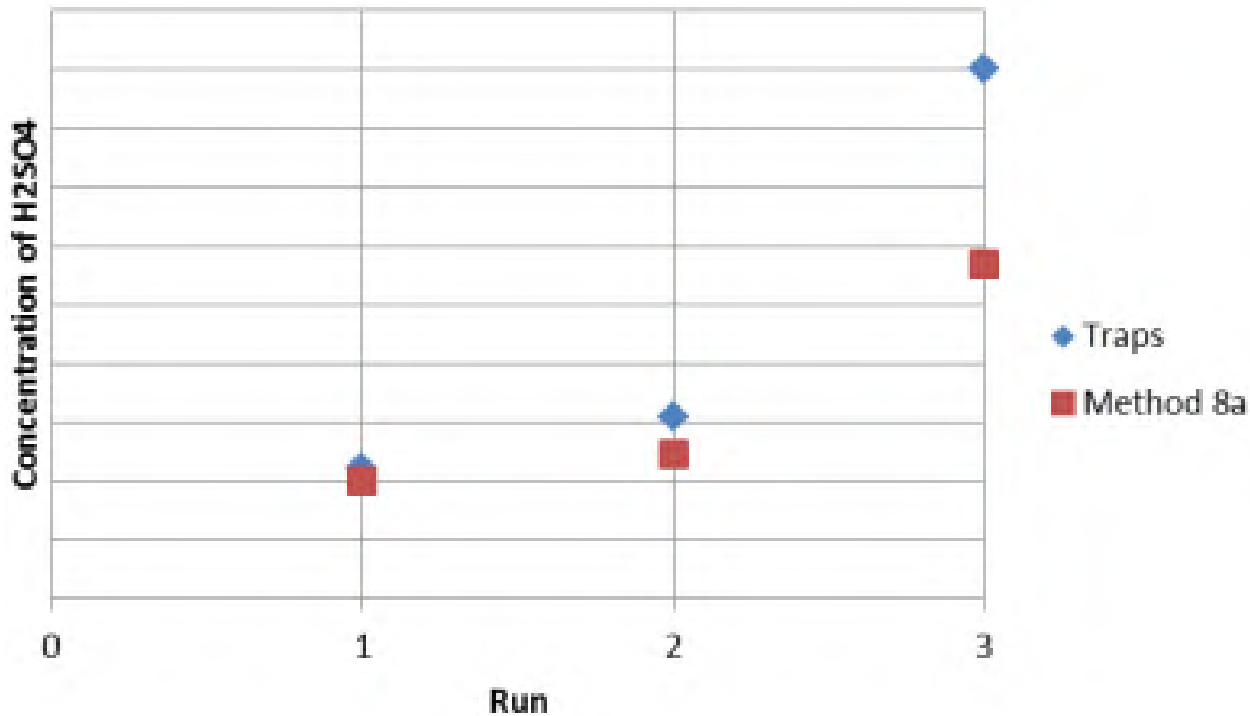
- Single In-situ measurement
- Measures H_2SO_4 and SO_3 (*dry*)
- Sampling ranges from SCR to stack
- Method validated at utility sites vs. M8A

SO_3 and Se/As Sorbent Traps: Sampling

- Sampling equipment is similar to M30B system
- Probe must be cooled if sample gas is >170°C
- In high-particulate environments, filter tips should be attached to traps.

Ohio Lumex SO_3 Traps

- **Lessons Learned**
  - Responds to load conditions
  - Close agreement with method 8A with similar sampling method
  - Inexpensive and easy to use



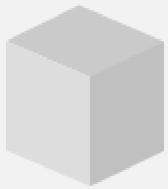
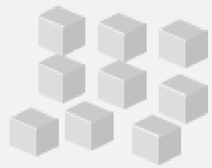
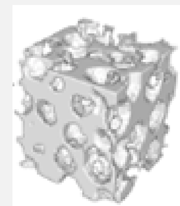
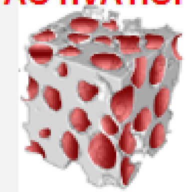
Interested in a Full Day DSI Workshop?

Useful for Operators and Engineers

Ian Saratovsky, PhD
Director, Flue Gas Treatment Solutions
Ian.saratovsky@lhoist.com
(682) 774-2037

Martin Dillon, PE
Manager, Flue Gas Treatment Applications
Martin.Dillon@lhoist.com
(303) 304-6562

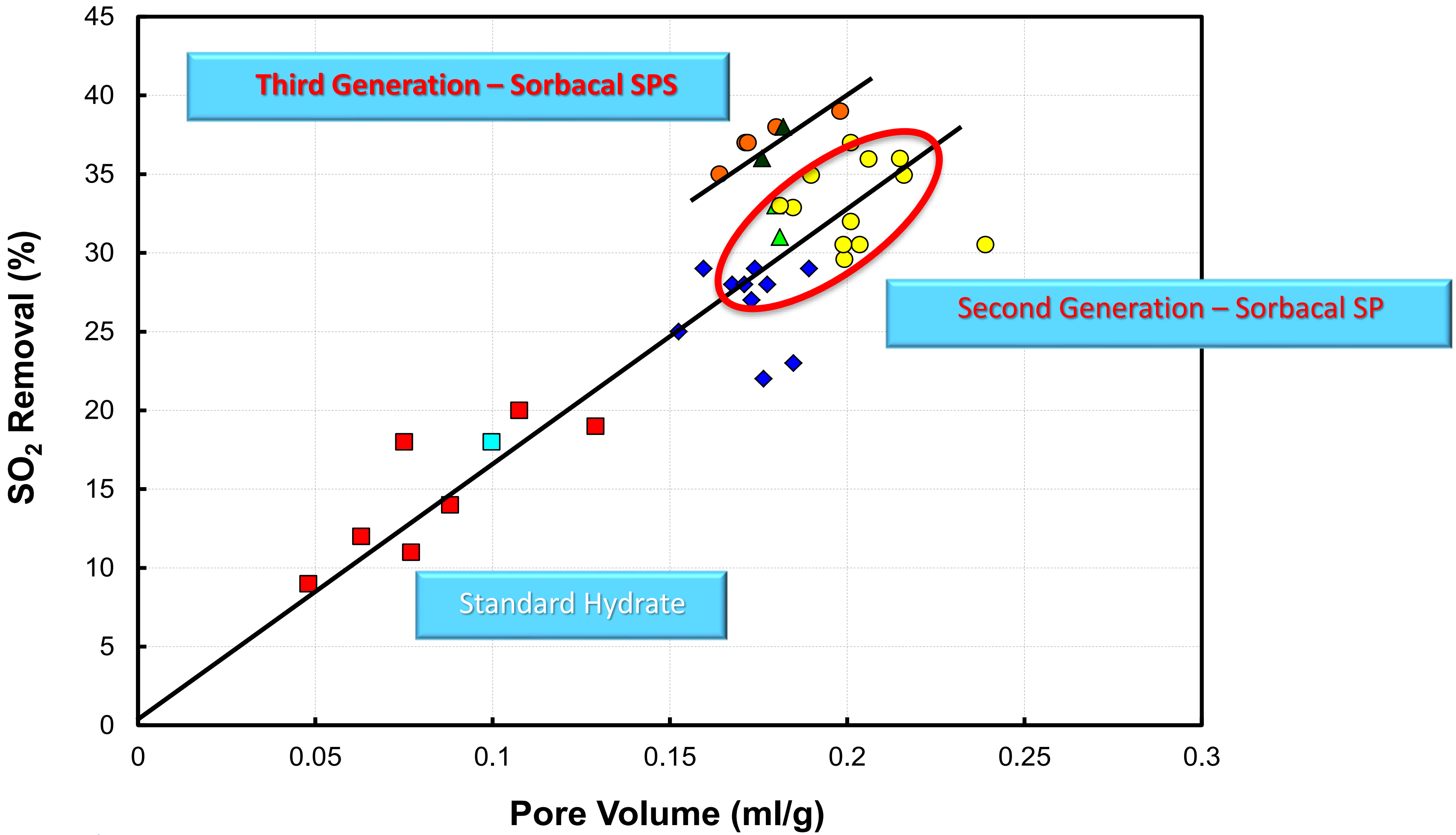
Engineering Better Sorbents

Sorbent	Standard Hydrated Limes	FGT Grade Sorbacal® H	Sorbacal® SP	Sorbacal® SPS
Figure				ACTIVATION 
Typical Available $Ca(OH)_2$ - [%]	92 – 95	93	93	93
Typical Surface Area - [m^2/g]	14 – 18	20	40	40
Typical Pore Volume - [cm^3/g]	~0.07	0.08	0.20	0.20
Typical D_{50} - [microns]	5 – 7	5 – 7	8 – 12	8 – 12

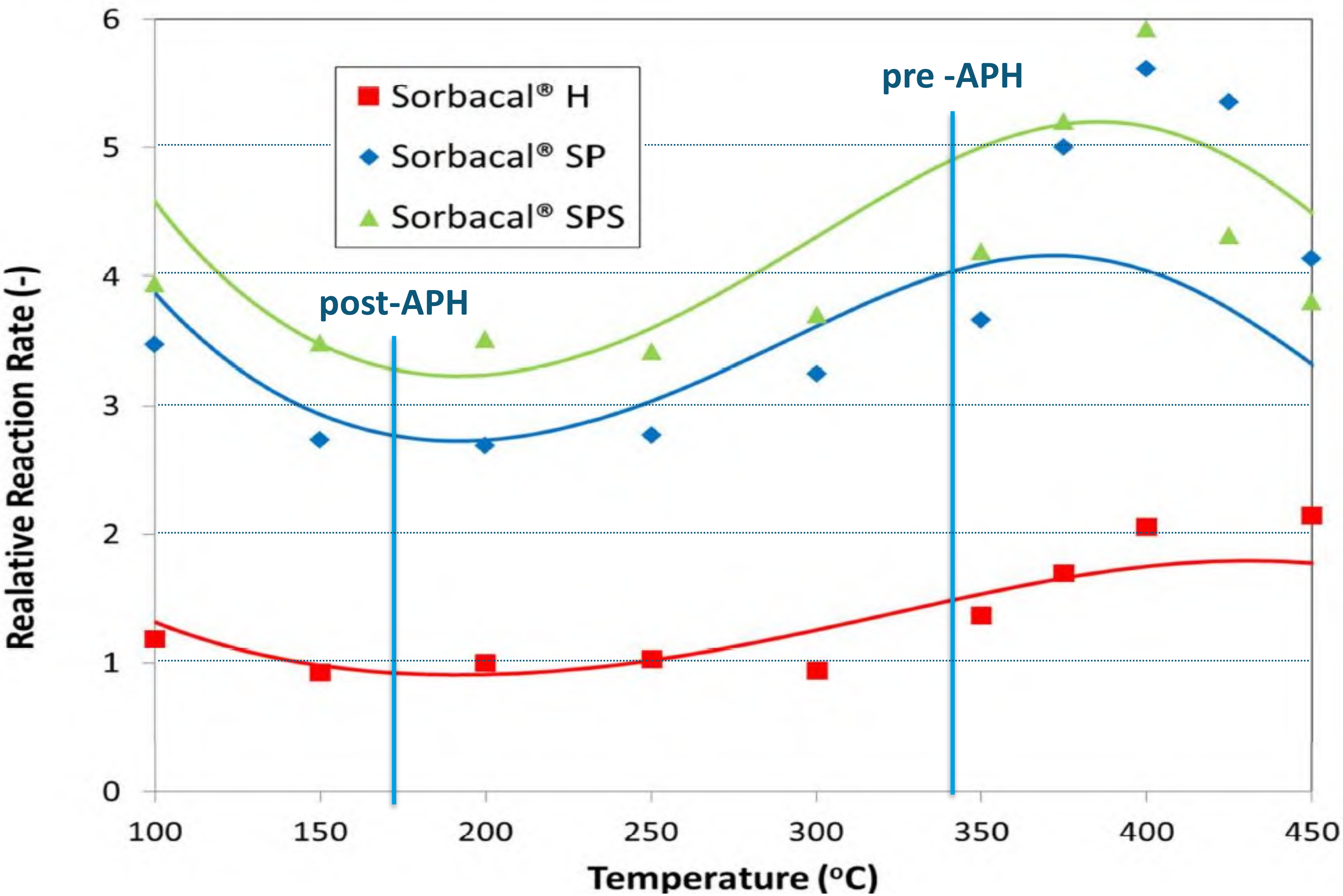
- Chemical activation of pores

Reactivity Property Relationships

- Linear relationship between reactivity and pore volume



Relative Reactivities Towards SO_2



Enhanced Hydrates: Economic Benefits

- Efficiency savings result in cost savings
- Ability to achieve greater removal rates