

WPCA/DUKE SCR Seminar

Tuesday June 7, 2005

1:30PM-2:30PM

NH₃ Injection/Gas Mixing and the Effect on Reactor Performance

Presented

by

Kevin Rogers

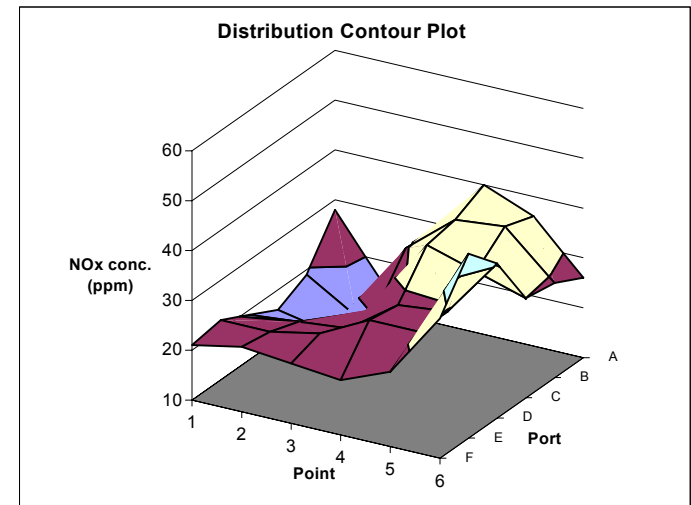
The Babcock & Wilcox Company



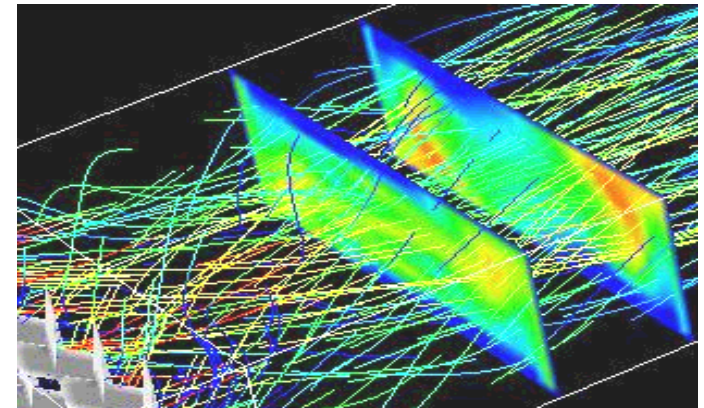
Subject Breakdown

Two General Areas of Discussion:

(1) Influence Ammonia & NOx Molar Ratio Blending has on Reactor Performance



(2) Ammonia Injection & Gas Mixing to Achieve Molar Ratio Distribution Goals



Distributions Descriptions

Distribution goals commonly stated as $X\%$ of the Data to fall within $Y\%$ of the Mean (Arithmetic Average):

- **80% of points to be within 10% of the Mean**
- **80% of points to be within 20% of the Mean**
- **85% of points to be within 15% of the Mean**
- **100% of points to be within 25% of the Mean**

Often more than one is applied to single distribution goal (i.e. – velocity or NH_3/NO_x molar ratio at a given location)

System blending and reactor performance can be more easily correlated when the distributions are adequately defined by a single parameter.



Coefficient of Variance Provides a Single Description of the Degree of Maldistribution

Coefficient of Variance (COV, Cv, CV):

- Standard deviation as a percentage of the arithmetic average
- Often called 'the % RMS'
- The Root-Mean-Square of the Deviations (σ), expressed as a percentage of the mean (\bar{x})

$$Cv = \frac{\sigma}{\bar{x}} 100 \%$$

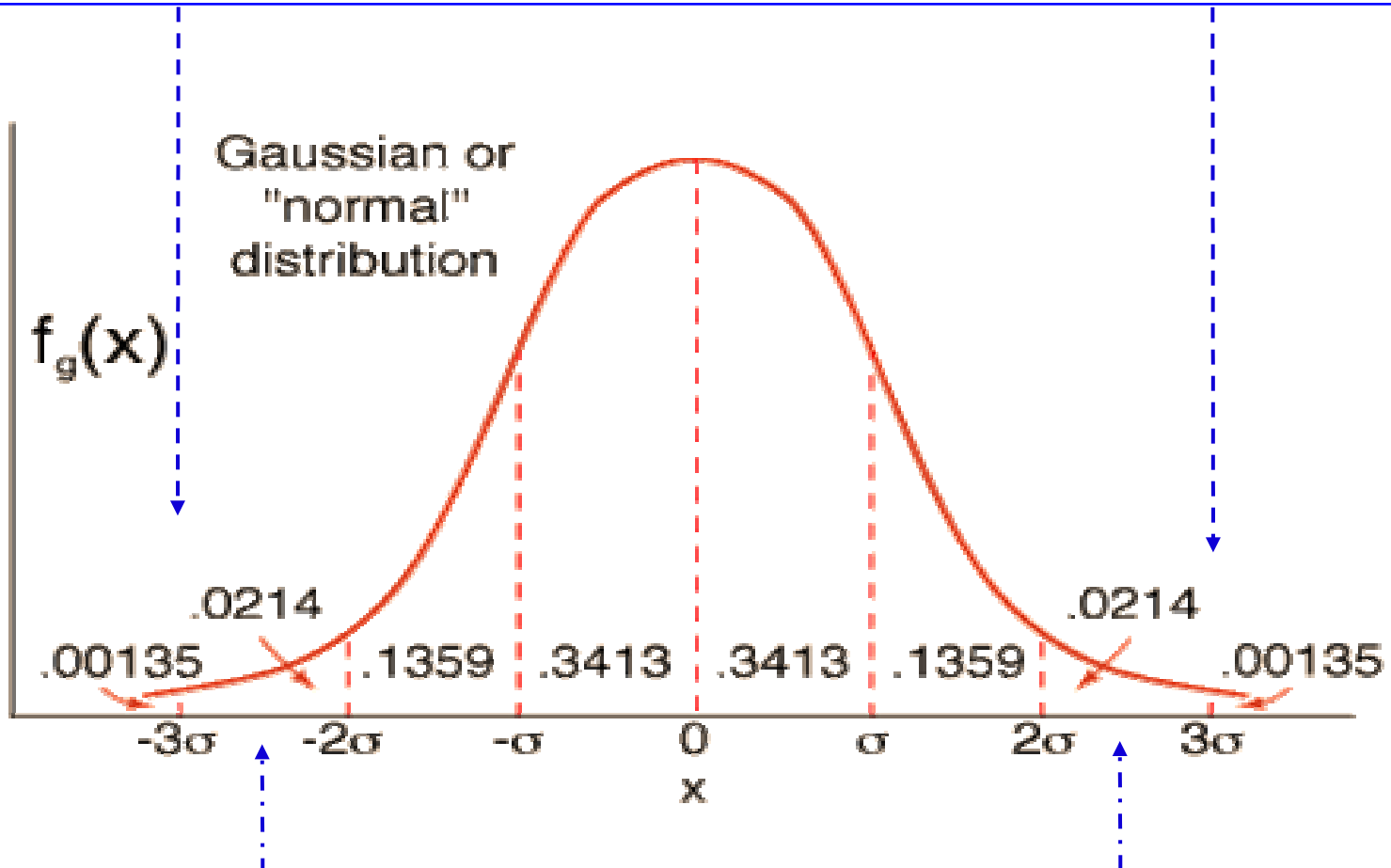
$$\sigma = \sqrt{\frac{1}{(n-1)} \sum_{i=1}^n (x_i - \bar{x})^2}$$

$$\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i$$



Normal Distribution Relationship

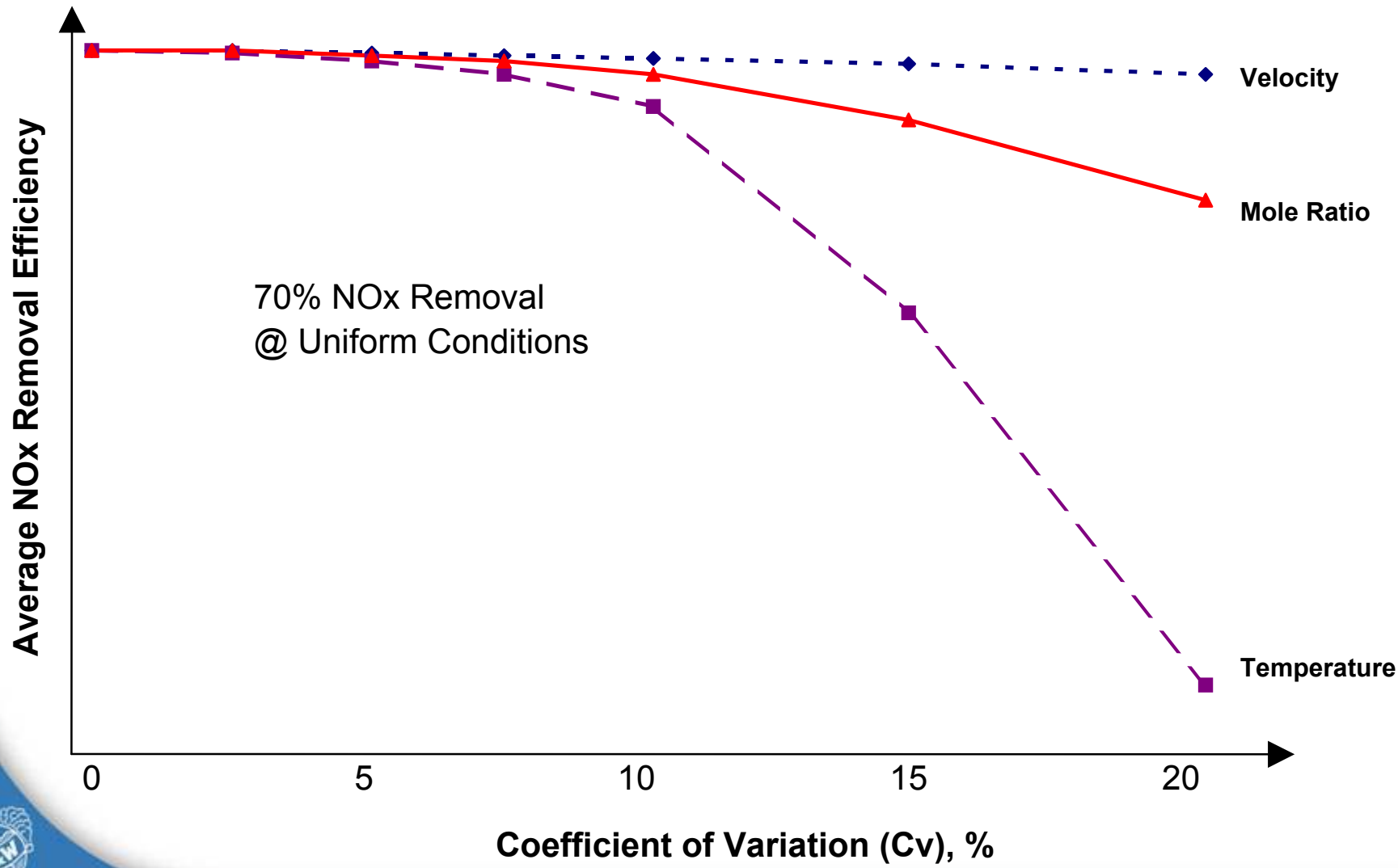
Need to measure many points to capture $\pm 3\sigma$



50 pt or less profiles often have Maximums and Minimums below 3σ



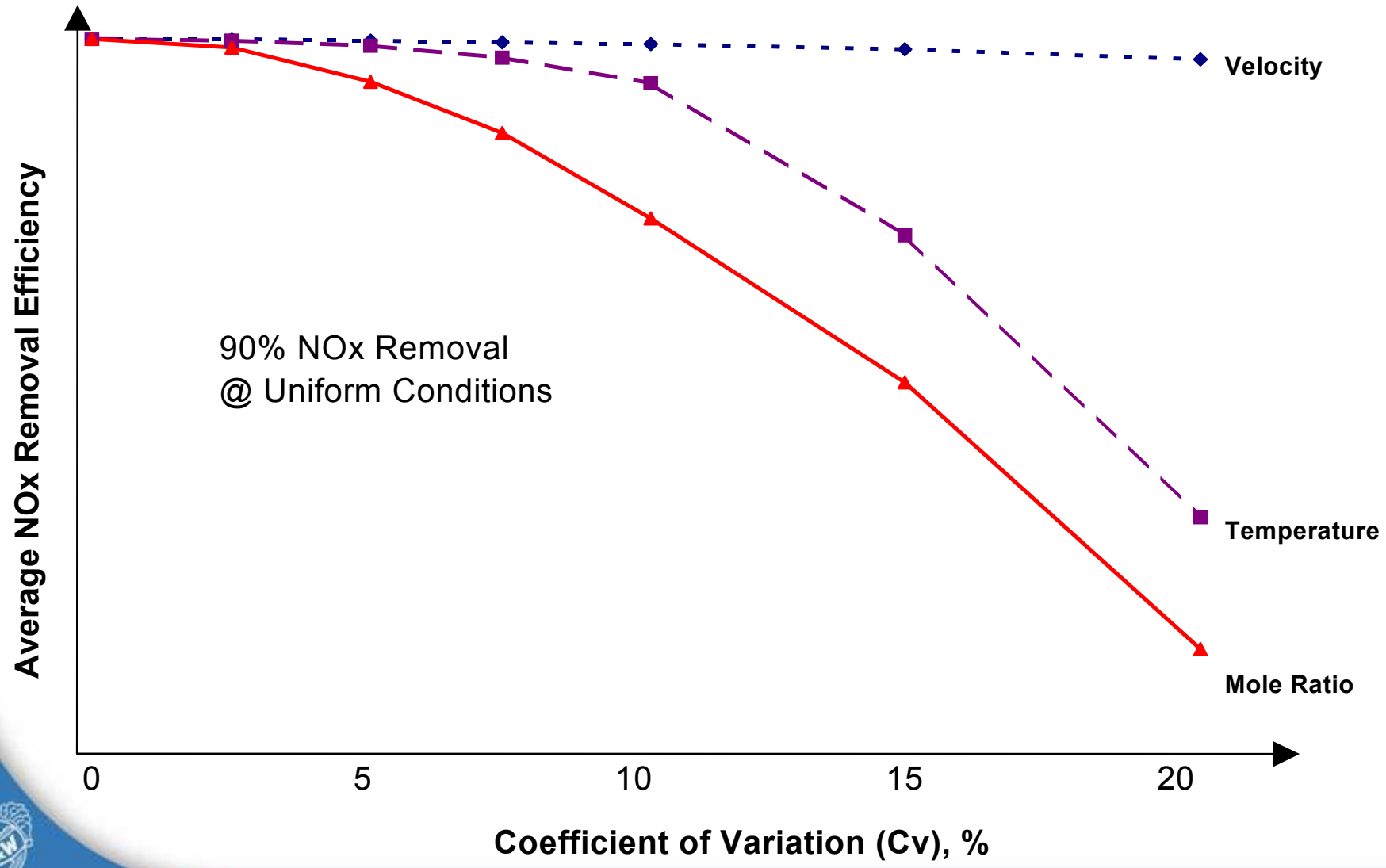
Relative Effect of Distributions on Reactor Efficiency @ 70% DeNOx



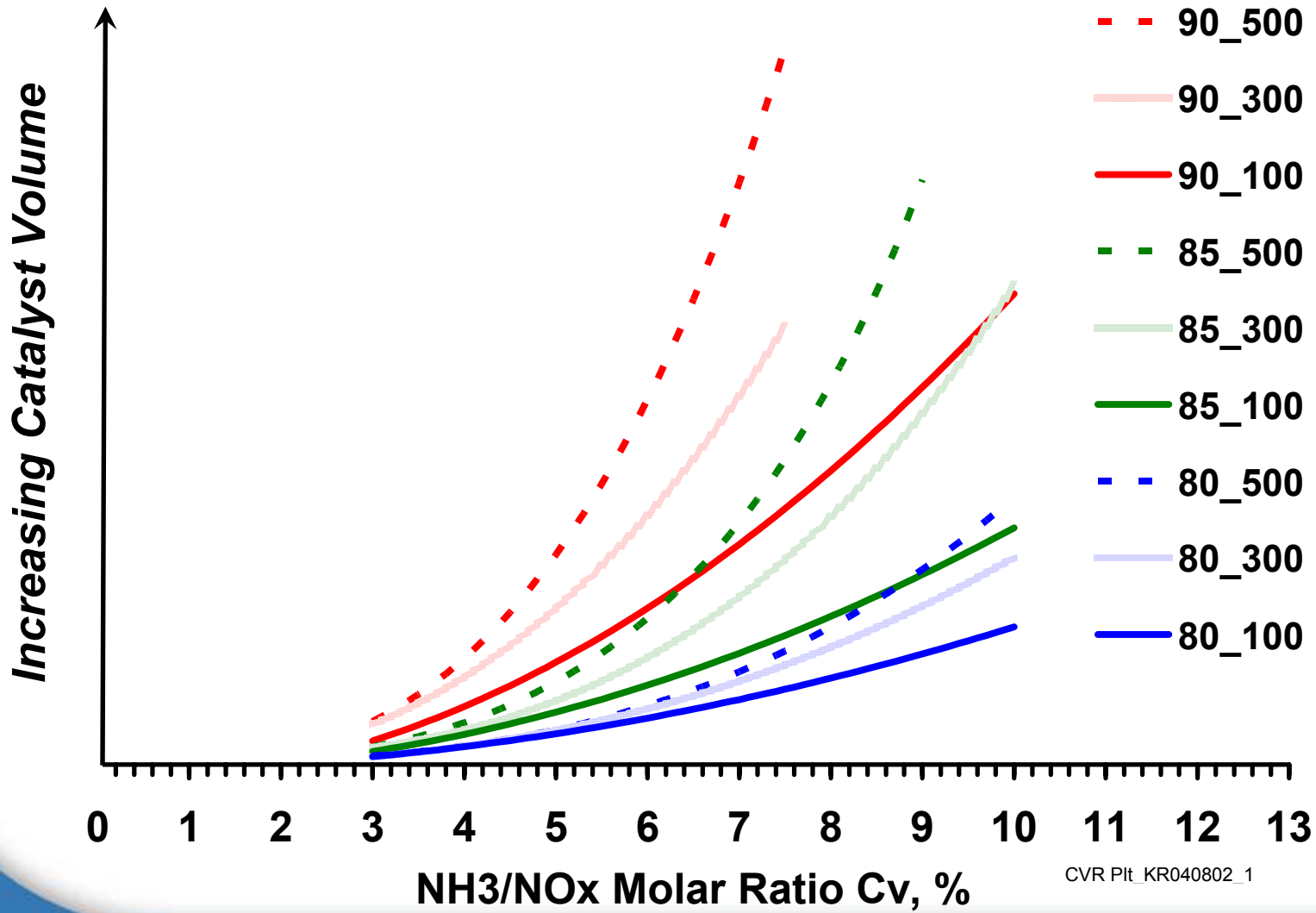
70% NOx Removal
@ Uniform Conditions



Relative Effect of Distributions on Reactor Efficiency @ 90% DeNOx



Relative Catalyst Volume vs Inlet NH_3/NO_x Cv and NO_x Removal (@ 2 ppm Ammonia Slip)

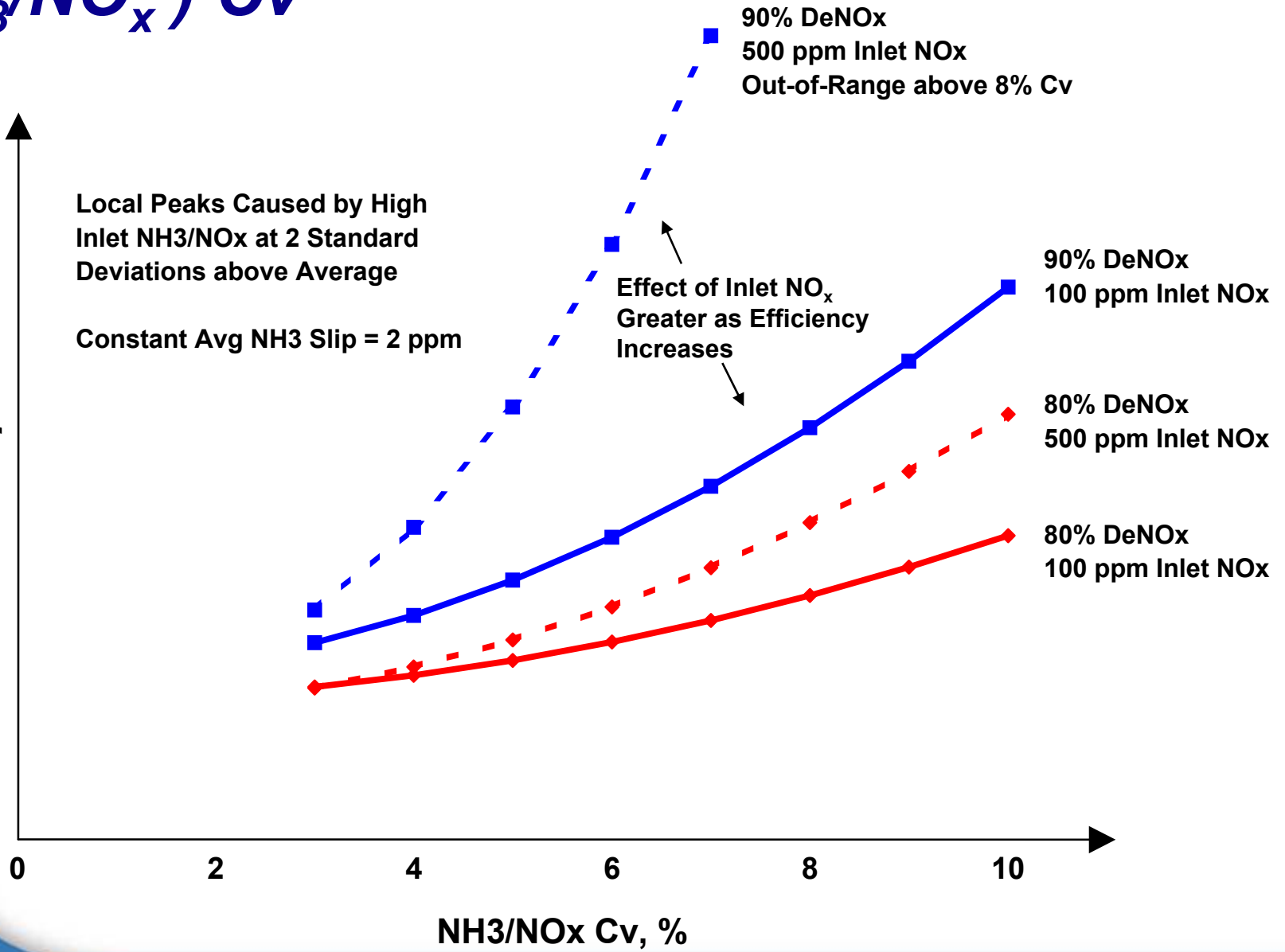


CVR Pit_KR040802_1

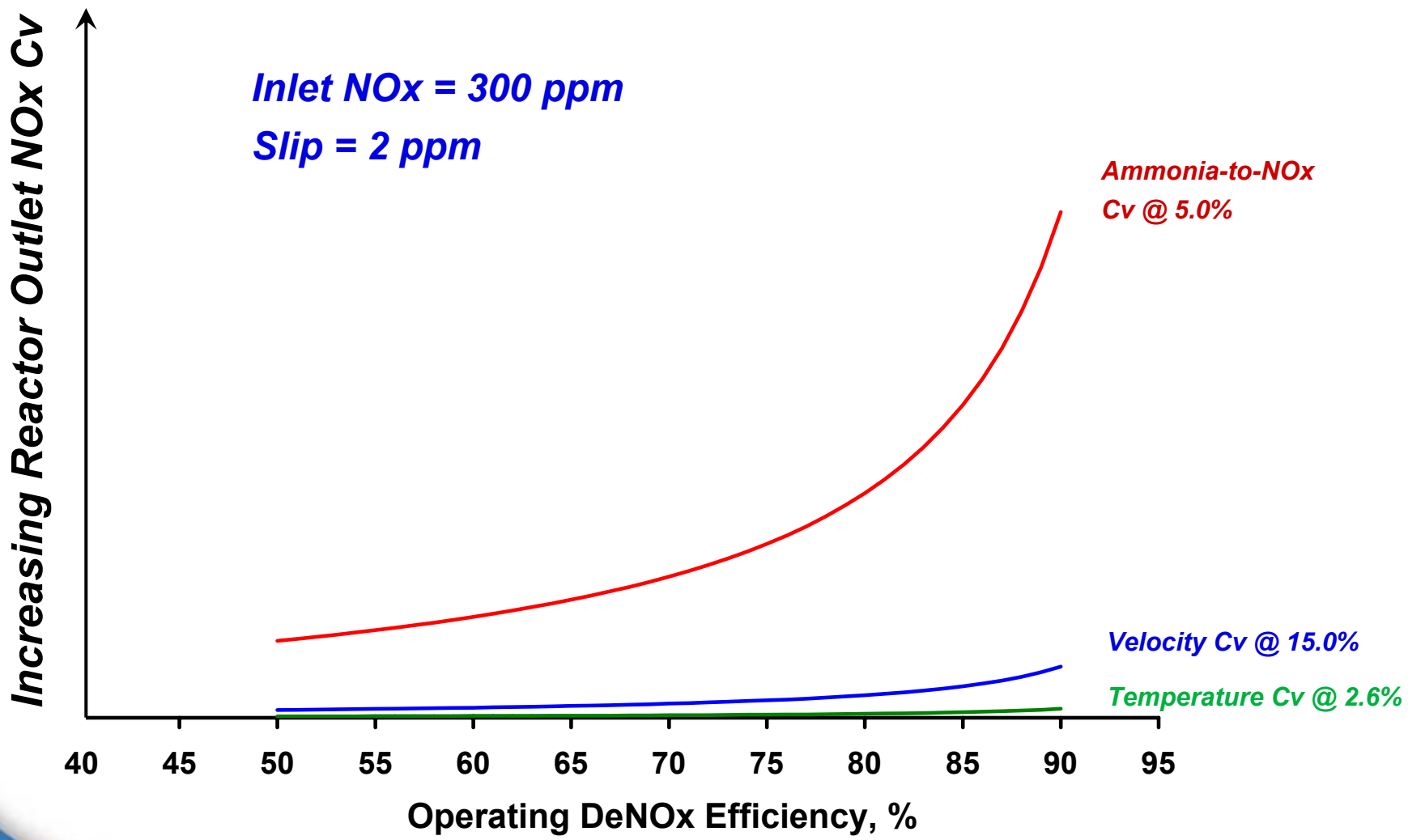


Local Peak Ammonia Slip vs Molar Ratio (NH_3/NO_x) Cv

Increasing Reactor Outlet Local Peak Slip



Relative Influence of Inlet Distributions on Reactor Outlet NOx Cv



Consider the following Example

DeNO_x Efficiency: 90 %
Inlet NO_x: 270 ppm
Slip: 1 ppm

$$\begin{aligned}\text{Average Mole Ratio} &= 0.90 + 1/270 \\ &= 0.9037 \text{ NH}_3/\text{NO}_{x \text{ IN}}\end{aligned}$$

$$\begin{aligned}\text{Excess Reagent} &= (0.9037 - 0.90)/0.90 \\ &= 0.0041 \text{ NH}_3/\text{NO}_{x \text{ REMOVED}}\end{aligned}$$

At an Inlet NH_3/NO_x $C_v \cong 5\%$

Maximums could easily range between $+2\sigma$ and $+3\sigma$

Or $2 \times 5 = +10\%$ to $3 \times 5 = +15\%$

Or $1.1 \times 0.9037 = 0.994 \text{ NH}_3/\text{NO}_x$ to $1.15 \times 0.9037 = 1.039 \text{ NH}_3/\text{NO}_x$

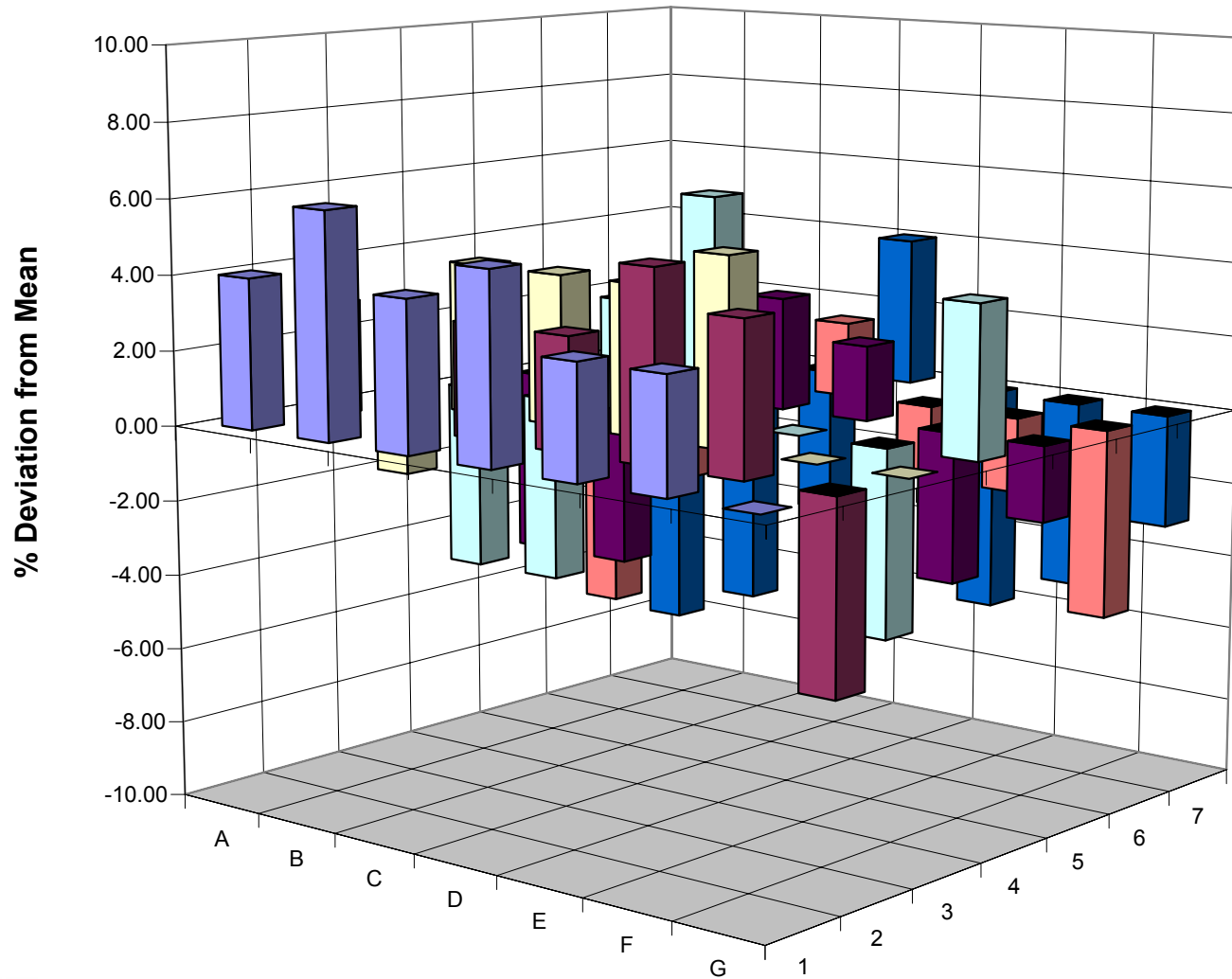
Need Much More Catalyst to approach 100% @ 99.4% efficiency not easily achieved – thus higher local slip

An Infinite Amount of Catalyst will Not Allow Excess Ammonia > 1.0 to be Consumed (NO_x has been Depleted)



Assume a Typical Reactor Gas Flow Profile

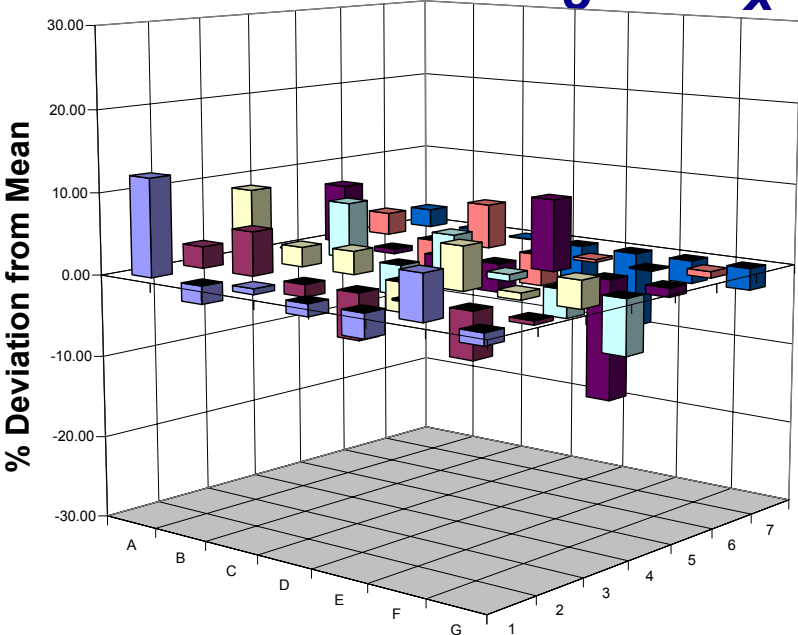
Flow Cv \cong 4%



Then Consider Two Possible Inlet NH_3/NO_x Distributions

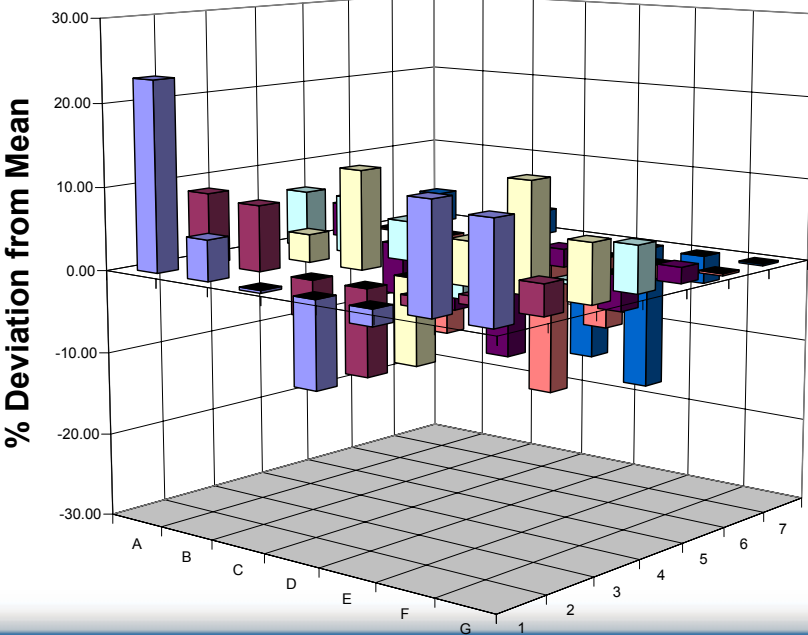
One @ $C_v \cong 5\%$

Avg Slip $\cong 1.0$ PPM



Another @ $C_v \cong 8.5\%$

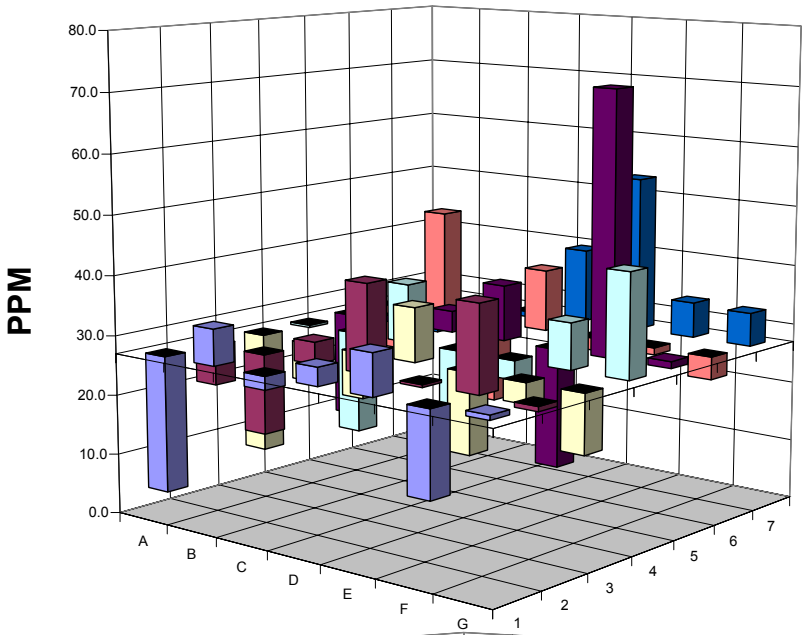
Avg Slip Increases to $\cong 2.4$ PPM to maintain 90% removal



Resultant Outlet NOx Distributions

When Inlet NH_3/NO_x
 $C_v \cong 5\%$

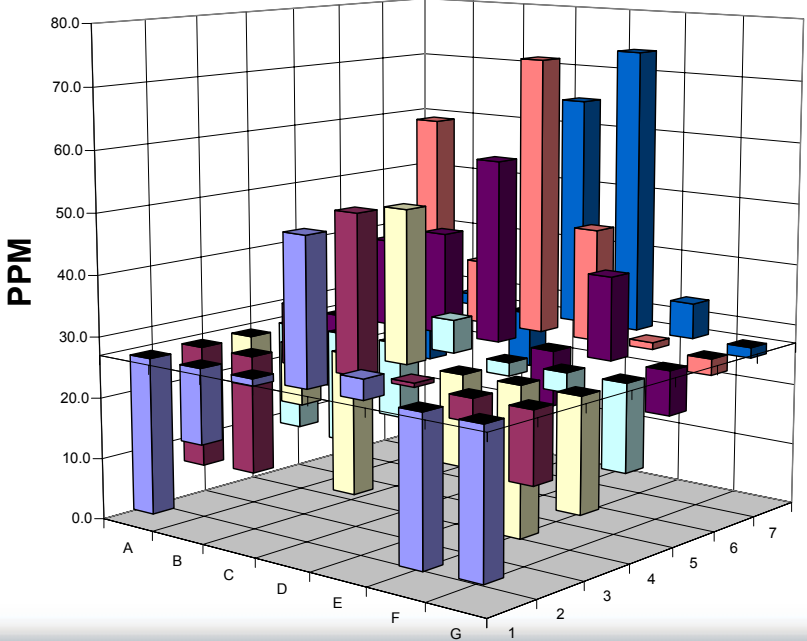
Avg Slip $\cong 1.0$ PPM



$C_v \cong 46\%$

When Inlet NH_3/NO_x
 $C_v \cong 8.5\%$

Avg Slip Increases to $\cong 2.4$ PPM
to maintain 90% removal



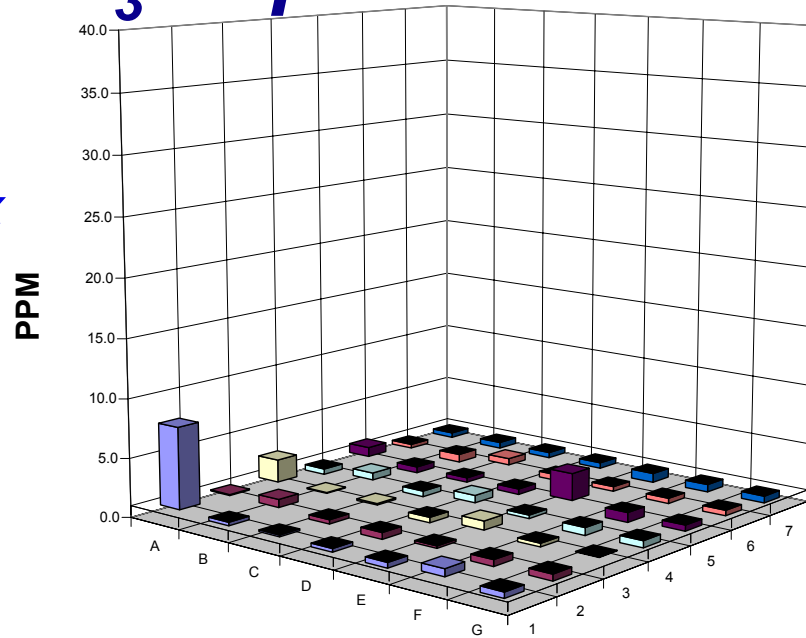
$C_v \cong 69\%$



Resultant Outlet NH_3 Slip Distributions

When Inlet NH_3/NO_x
 $C_v \cong 5\%$

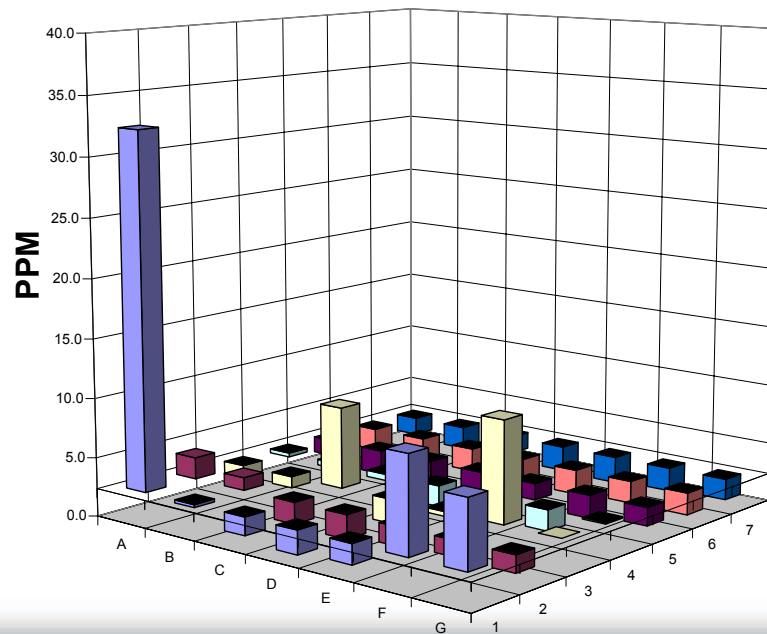
Avg Slip $\cong 1.0$ PPM



$C_v \cong 120\%$

When Inlet NH_3/NO_x
 $C_v \cong 8.5\%$

Avg Slip Increases to $\cong 2.4$ PPM
to maintain 90% removal



$C_v \cong 220\%$



Distributions other than NH_3/NO_x

Velocity Distributions

- Less Critical to Performance
- Typical Concern - Deposition & Erosion
- $Cv \leq 15\%$ For Catalyst Approach Generally Acceptable

Temperature Distributions

- Typically Less Critical to Performance
- Sintering & BiSulfate Formation Concerns
- Min/Max $\pm 20F$ to $\pm 50F$ Generally Acceptable



NH_3/NO_x Molar Ratio Distributions

- **Less Critical Below 70% DeNO_x Efficiency**
- **Becoming Rapidly More Important Above 80%**
- **90% Removal of 300 ppm Inlet NO_x @ 2 ppm Slip**
(Not Practical/Possible with NH_3/NO_x Cv = 10%)
- **Critical for 90% DeNO_x and Above**
- **Cv < 3% for 95% DeNO_x**
- **Excess Reagent Reduces Sensitivity [$slip/inlet\ NO_x$]**
(Gas Fired - High Slip → Coal Fired - Low Slip)



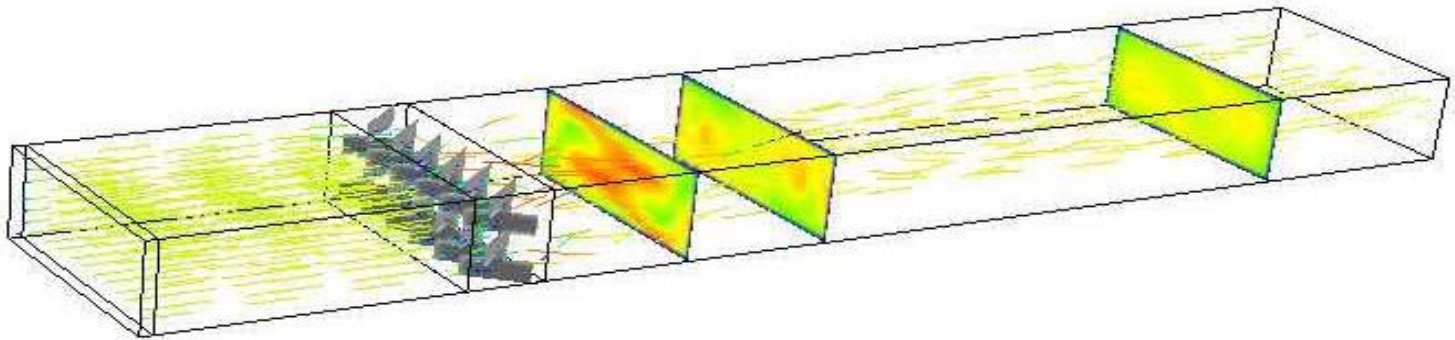
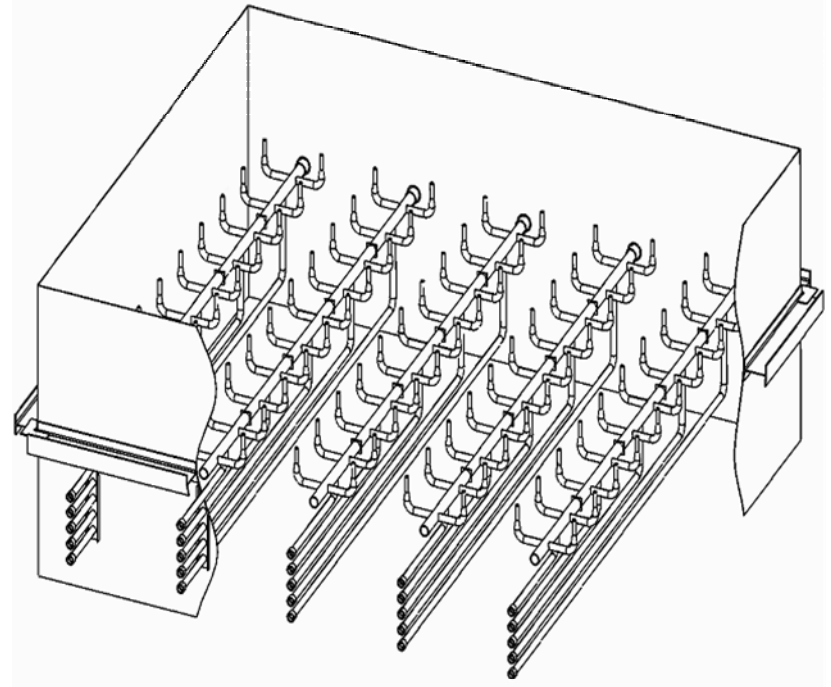
High Efficiency ($\geq 90\%$) = More Stringent Requirements

- Increased AIG Flow Uniformity
 - Increased Dispersion @ AIG
 - Increased Mixing Energy
 - Increased Flue Length
- Interrelated**
- Sacrifice of Velocity Profiles to Improve NH_3/NO_x Profile
 - Blending of Peak Slip Downstream of Reactor
 - Tolerance to Mixing Error Rapidly Reduced for High DeNO_x Removal Efficiency (Cv drift 5% → 8% is a problem)

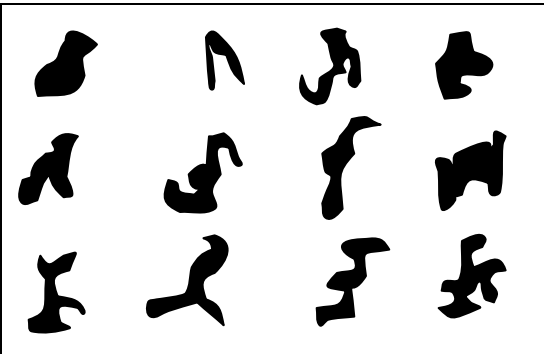


SCR Ammonia Injection & Gas Mixing Technology

- **Why Mix ?**
- **Technology Fundamentals**
- **AIG & Mixer Design**
- **Field Performance**



Representation of Blending



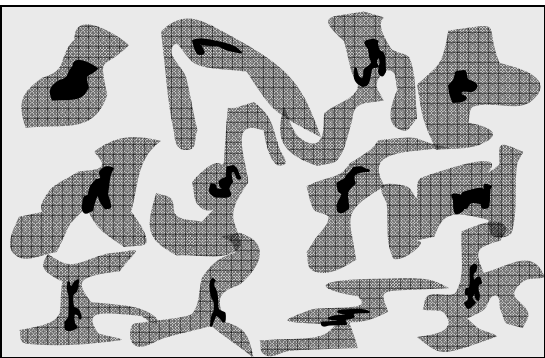
Decreasing Scale
of Segregation



Decreasing
Intensity of
Segregation



Decreasing
Intensity of
Segregation



AIG & Mixing Fundamentals

Mixing is Dominated by Three Primary Factors

- 1. Original Distribution** – How well ammonia is deposited over the space or profile of an initial NO_x distribution (Scale of Segregation)
- 2. Stretching and Folding** - How larger regions of varying concentrations are being thinned and spread across the area via macroscopic turbulence (Scale of Segregation)
- 3. Molecular Diffusion** – Occurring simultaneously throughout and necessary for the final an approach to complete homogeneity – influenced & facilitated by the increased surface area brought about by **1** & **2** (Intensity of Segregation)



AIG & Mixing Fundamentals

Aspects of Initial Ammonia Dosing

- 1. Flow Dosing** – *The relative matching of regional or local ammonia flow to the regional or local flue gas flow - (Fairly stable flow profile contours through the plane of ammonia injection typically allow for stable flow dosing)*
- 2. NOx Dosing** - *The relative matching of regional or local ammonia flow to the regional or local NOx Concentration - (NOx profile contours are often not as stable with regard to the positioning of high a low concentration regions and can thus be difficult to adjust to).*



AIG & Mixing Fundamentals

Aspects of Initial Ammonia Dosing – Cont'd

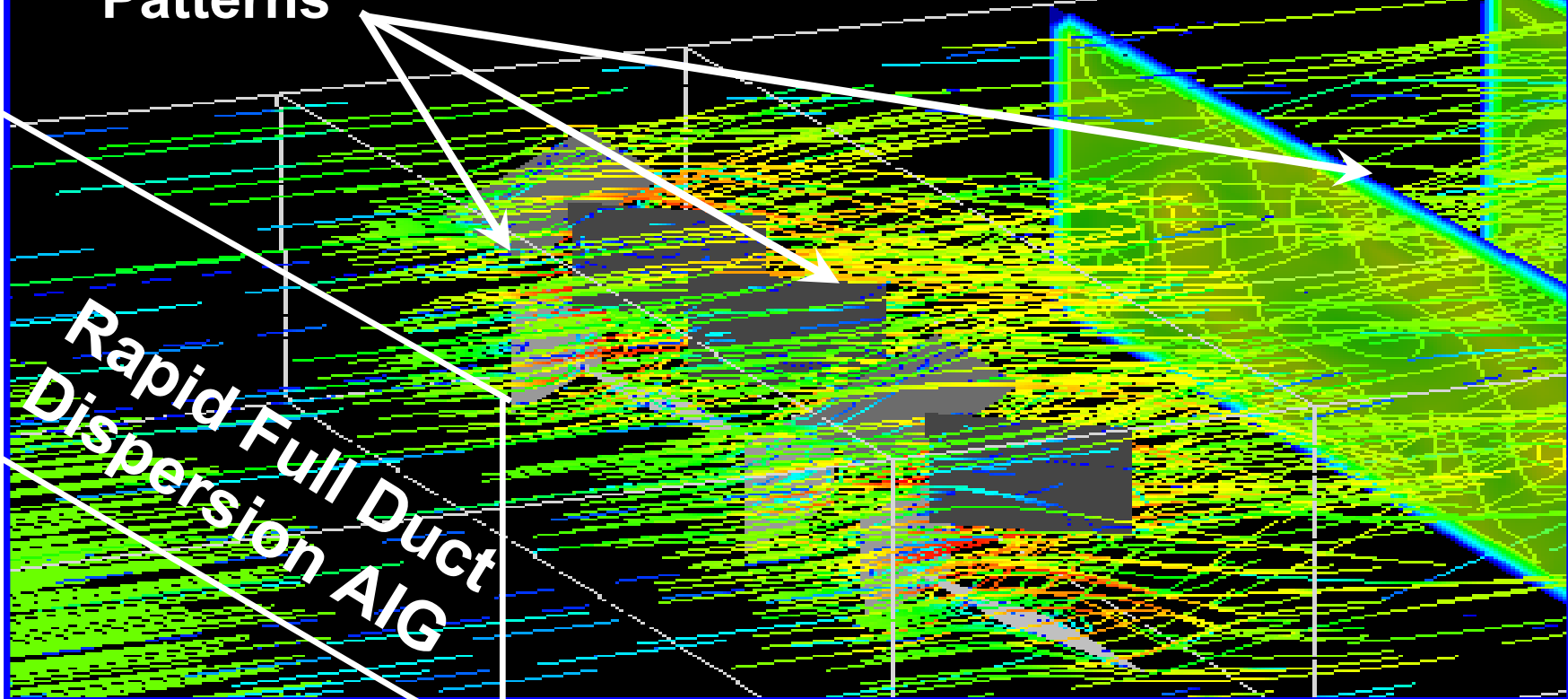
3. Spatial Dosing – Defined by the spacing of the injection points and thus the injection point quantity: (Initial Scale of Ammonia Segregation)

- 1. Increasing the number improves the final blend to a point of diminishing return.***
- 2. Too few reduces system effectiveness and efficiency.***
- 3. Too few can over-sensitize placement of injection points relative to mixer vane elements.***



B&W Mixing Approach

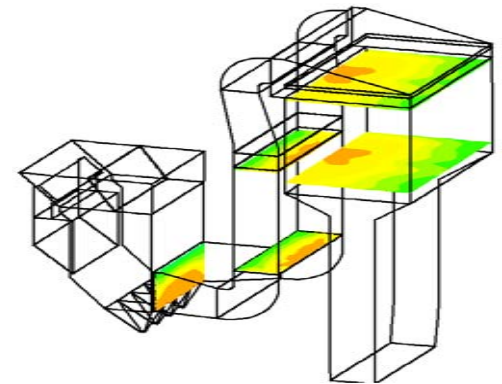
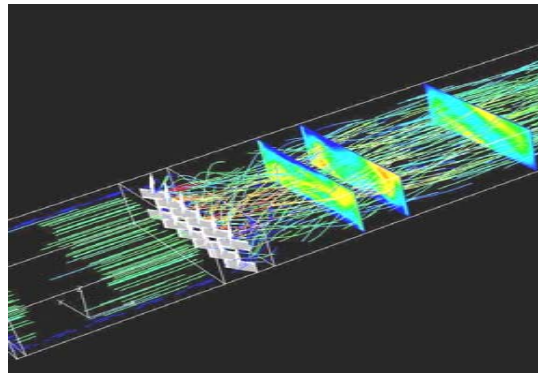
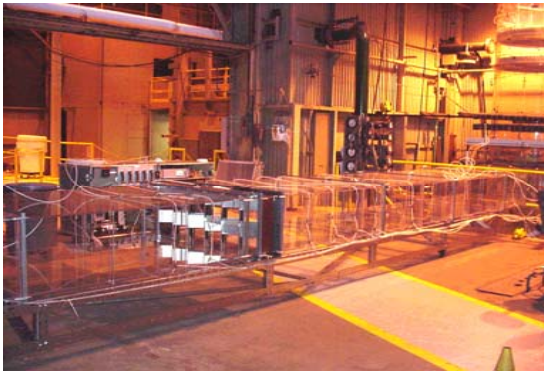
**Efficient Use of Duct Length with Rapid Shear,
Controlled Turbulence and Duct Macro Flow
Patterns**



Mixer Development

Test Stands

- *From Simple to Complicated – Size, Cost, Testing & Run Times*
- *More Complicated for Analysis of Arrangement Performance (the performance of devices in complex arrangements)*



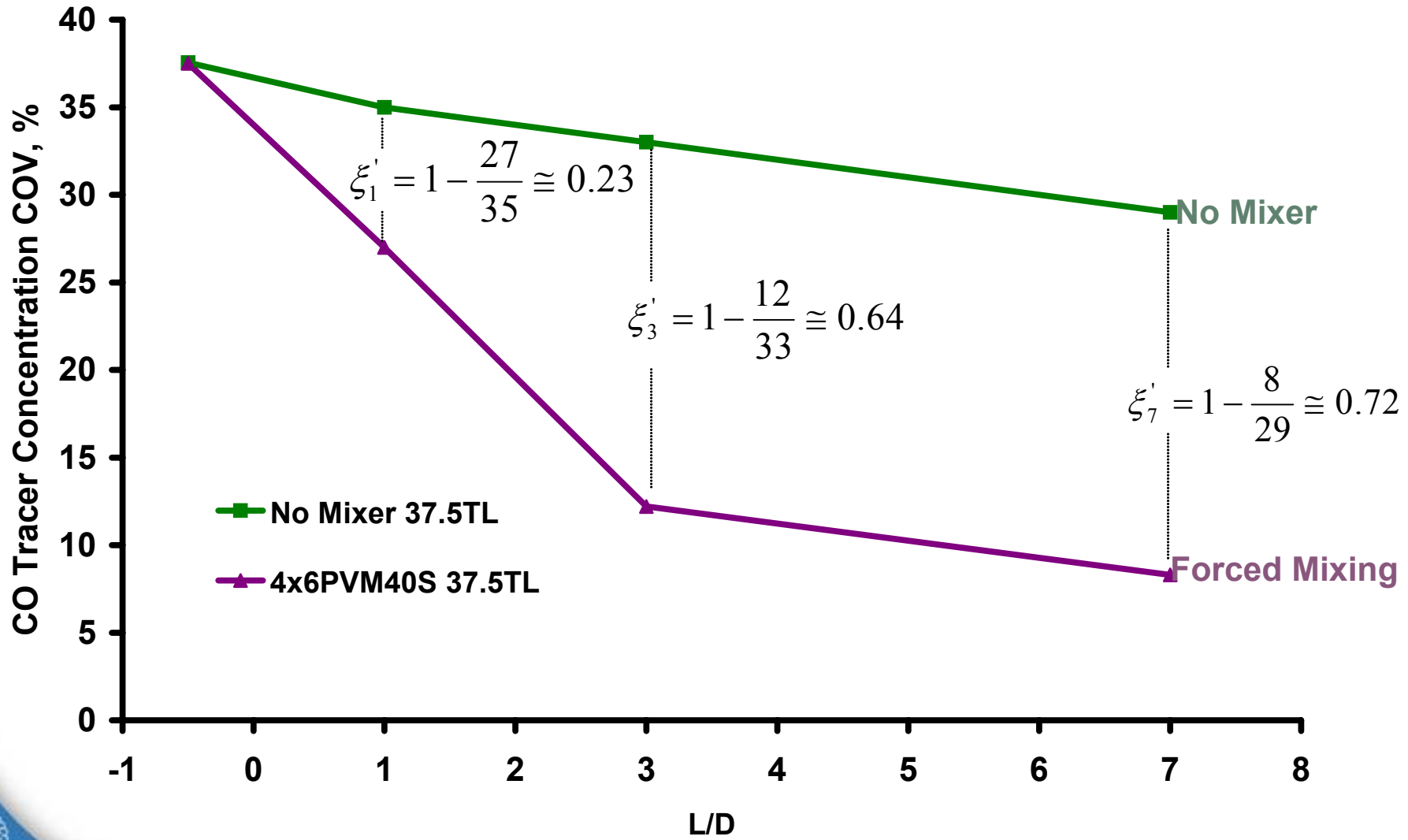
Predictive Formula

- *Structured Array of Test Programs*
- *Initial Application & Optimization*

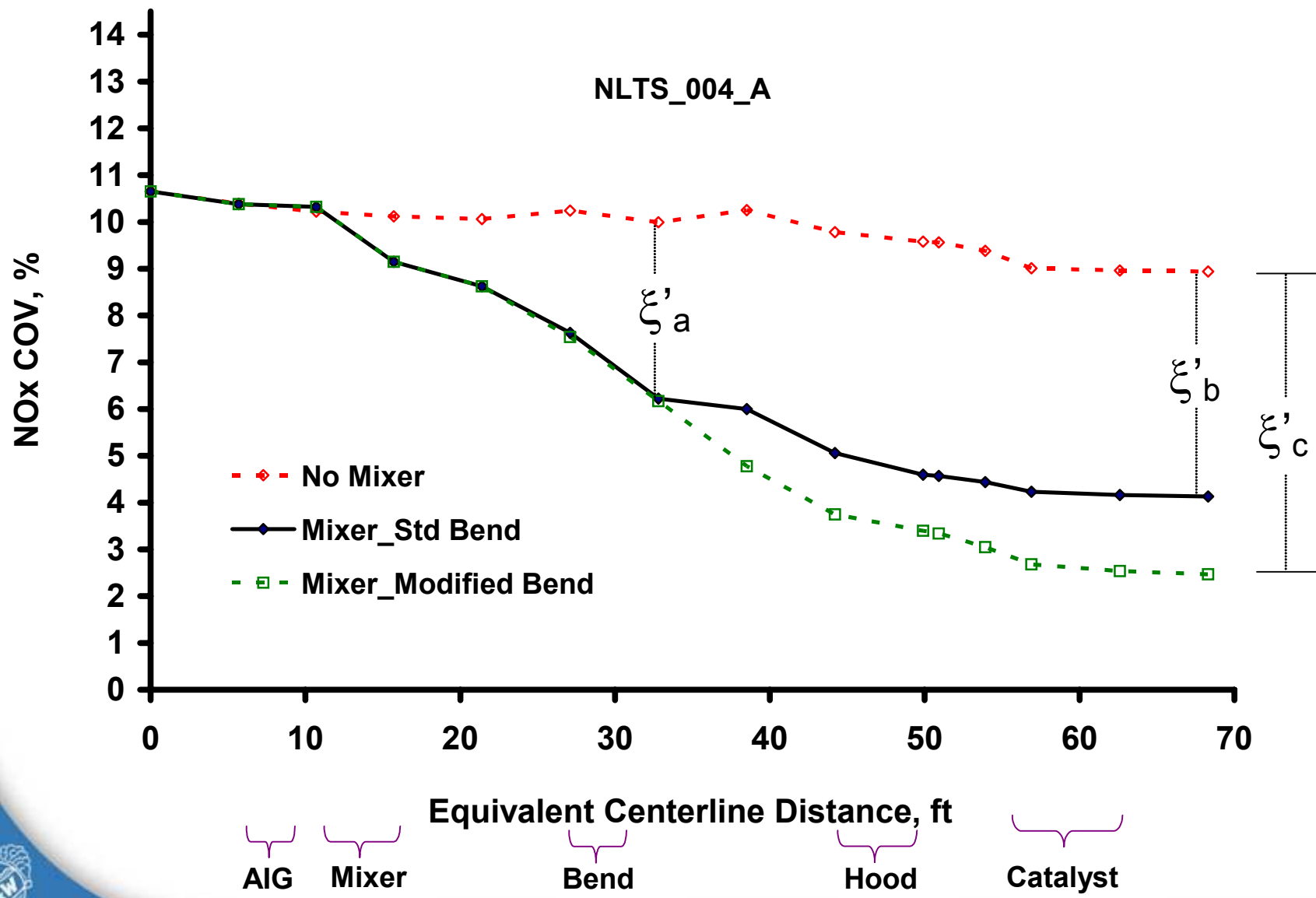
Field Performance



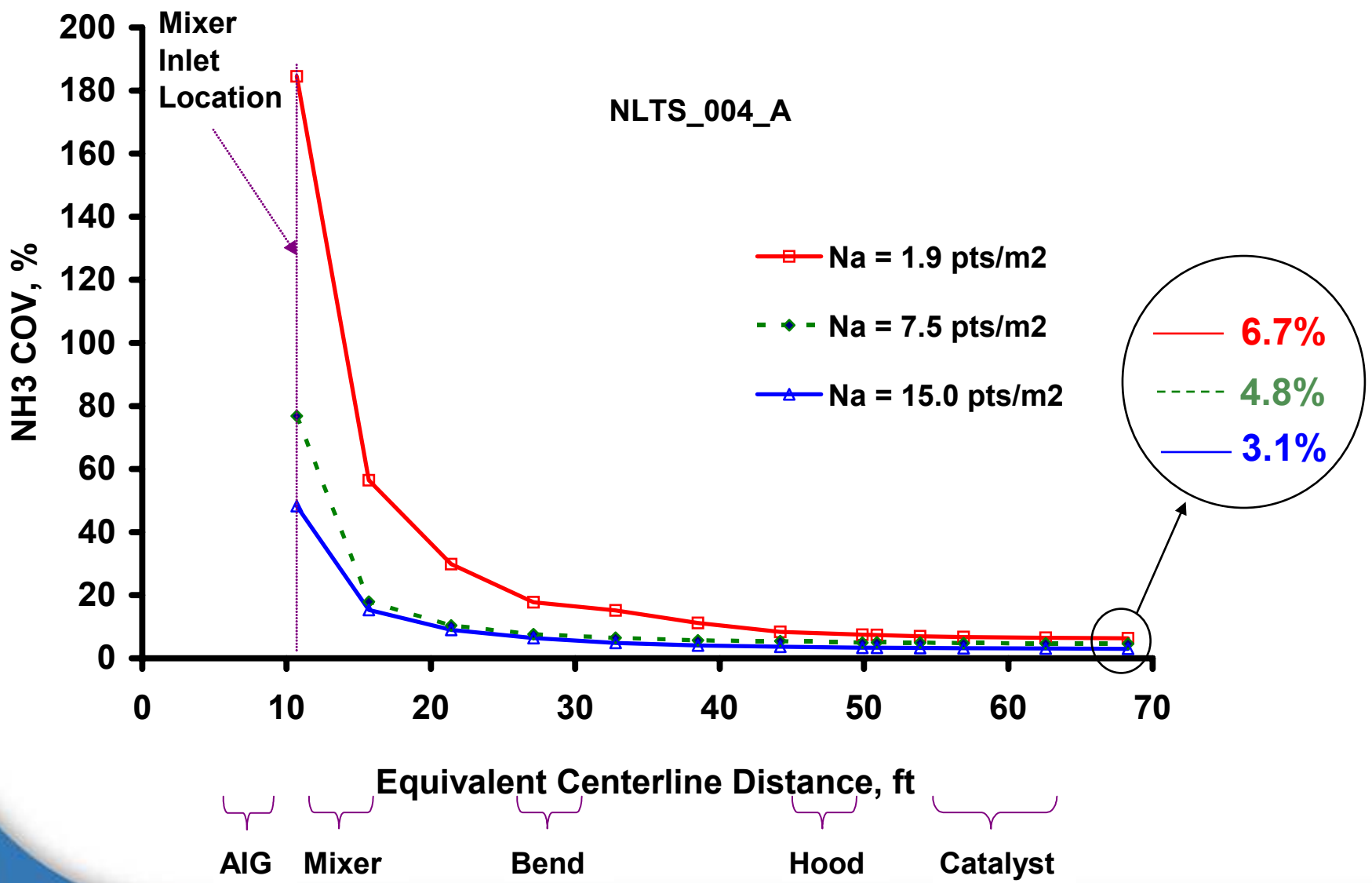
Mixing Effectiveness



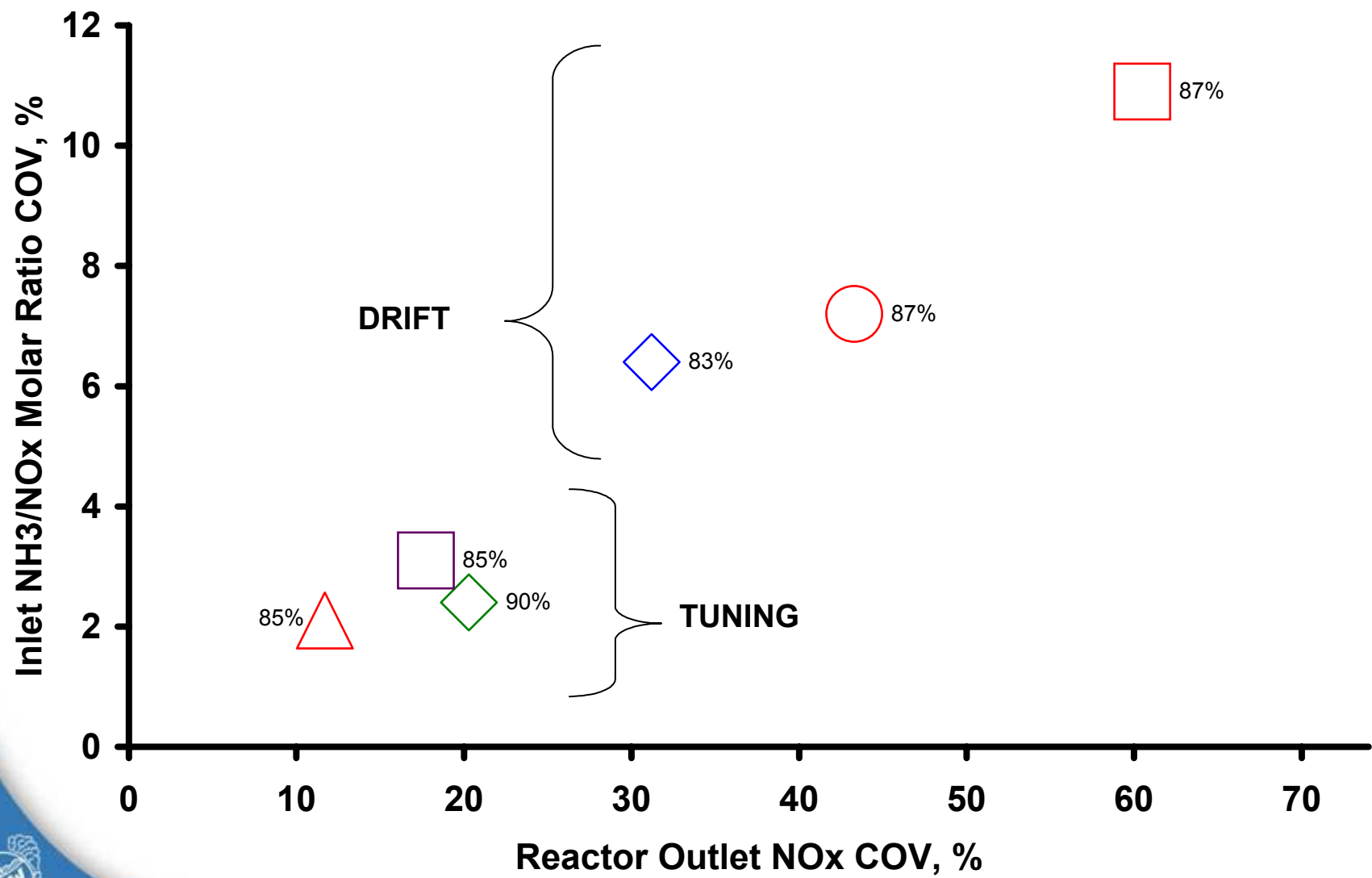
Influence of Bend Design



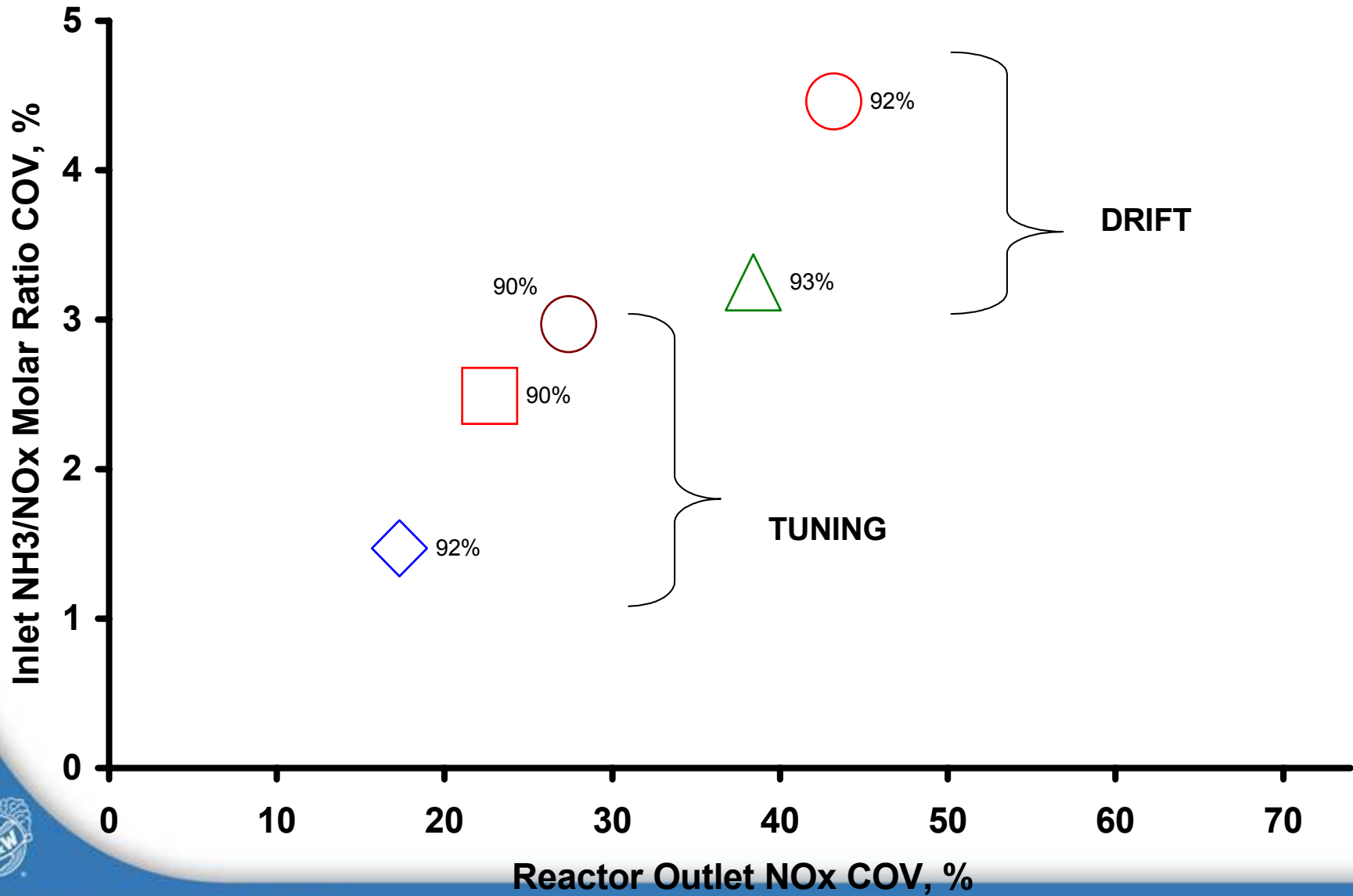
Influence of Injection Point Quantity



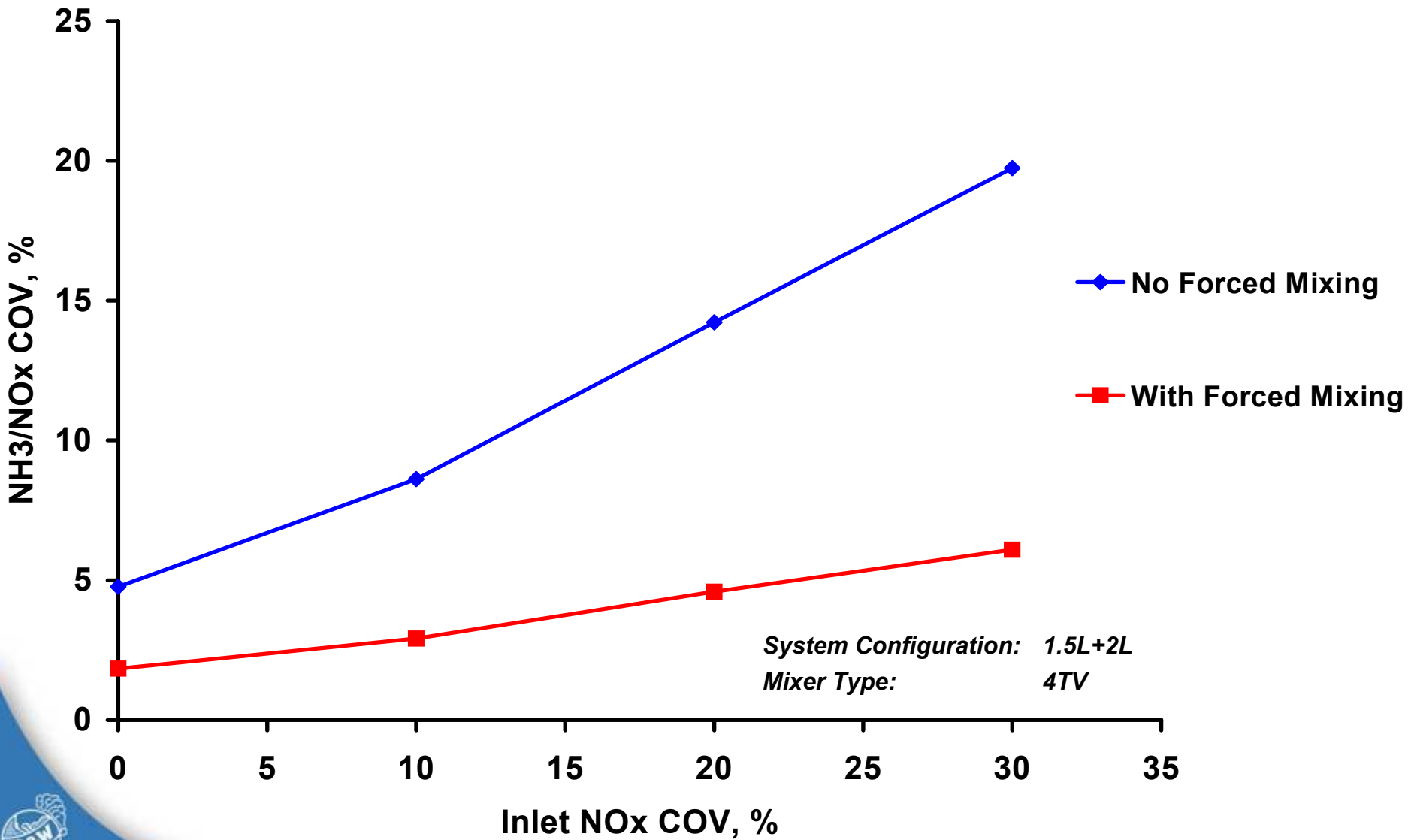
Operating Unit Molar Ratio Drift (w/o Static Mixing)



Operating Unit Molar Ratio Drift (with Static Mixing)



CFD Based Sensitivity Analysis



Design Considerations

Forced Mixing for Stable Uniformity

Stability

- *W/O Forced Mixing: Molar Ratio COV 2% → 8% → 15%*
- *With Forced Mixing: Molar Ratio COV 2% → 5%*

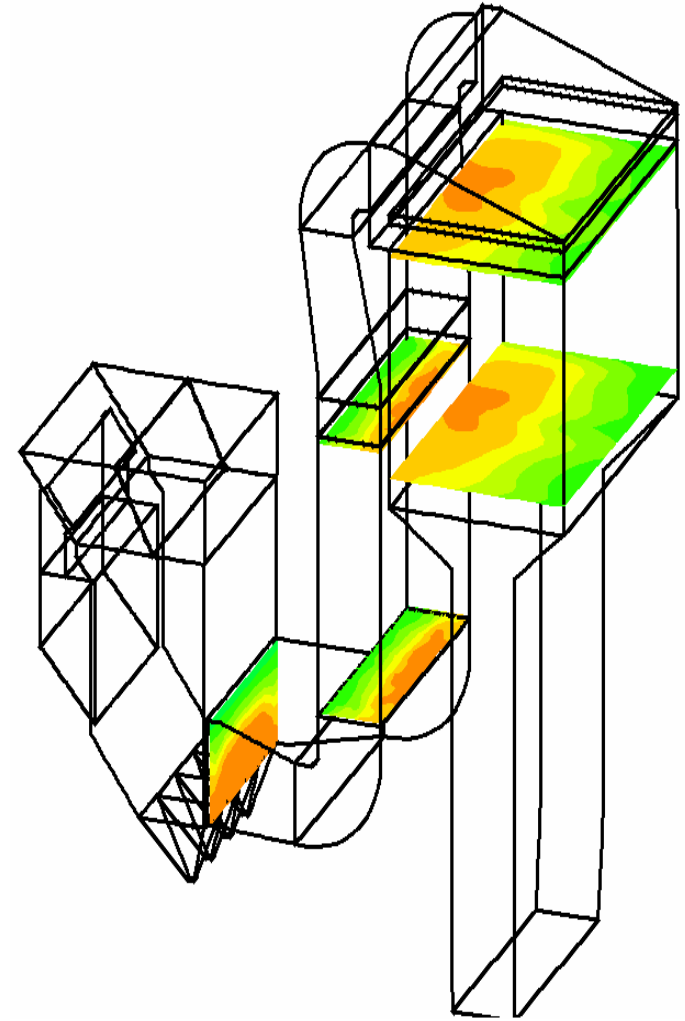
Important Optimization Parameters

- *Initial Dosing (AIG Design, NOx profile, Flow Profile)*
- *Injection Nozzle Quantity*
- *Directivity of Mixing Effectiveness*
- *System Length vs Energy Efficiency*
- *Arrangement Design (Dampers, Exp/Con, Bends, Hoods, etc.)*

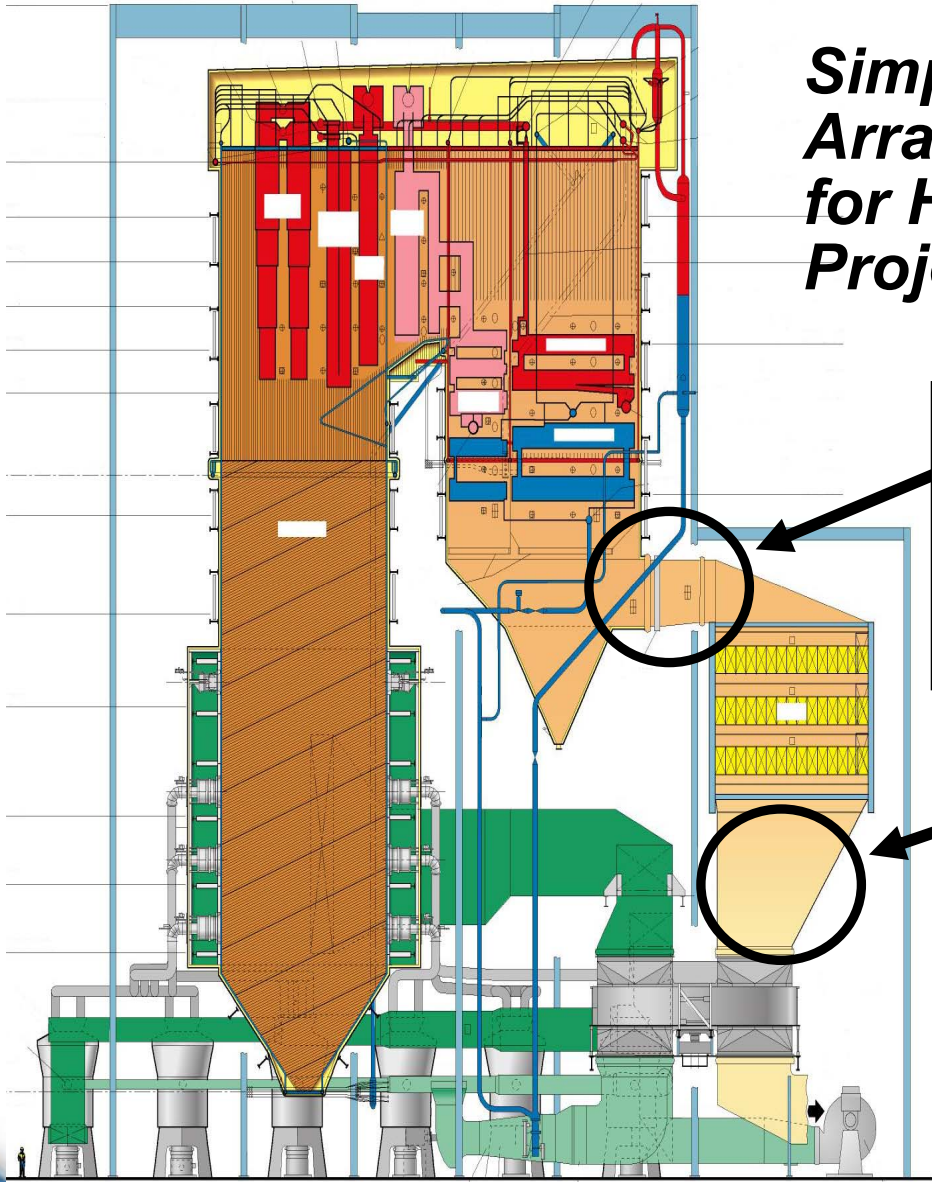


Design Considerations – Cont'd

- ***NOx removal duty (Inlet loading, % removal, allowable slip)***
- ***NOx & Temperature Profiles***
- ***Allowable draft loss***
- ***Straight flue lengths available***
- ***Bends & overall flue geometry***
- ***AIG inlet gas flow profile***
- ***Quantity of injection points***
- ***Mixer Placement***
- ***Flow correction prior to catalyst***



Poor Arrangements for High Removal



Simple Close-Coupled Arrangements Will Not Work for High NOx Removal SCR Projects

Insufficient distance to inject and blend for very low and stable molar ratio maldistributions

Short opportunity to blend peak local slip concentrations prior to AH



Arrangements for Promotion of Mixing

All mixing considered complete prior to flow straightening into the catalyst

Permanent sample grid Location

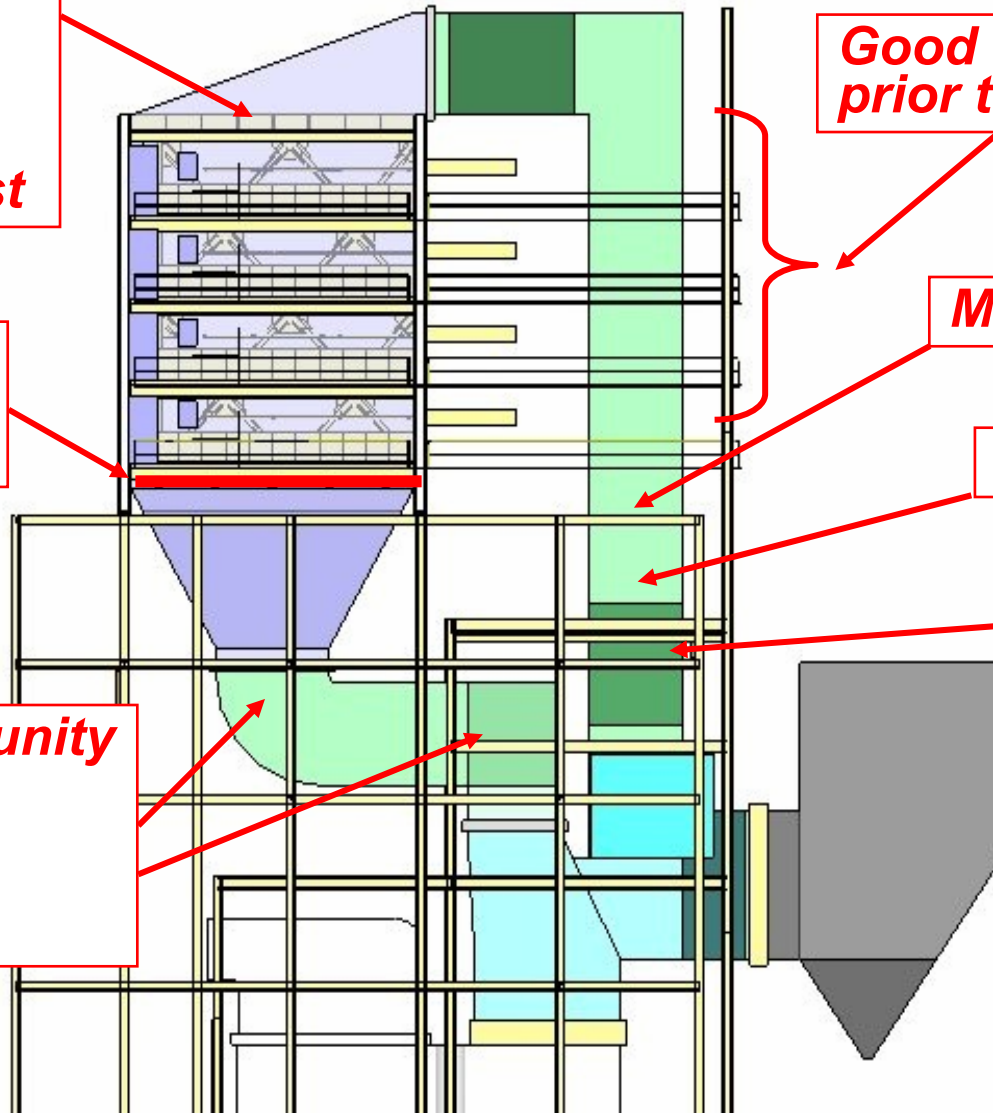
Greater opportunity for blending of peak local slip concentrations prior to the AH

Good mixing distance prior to bend

Mixer Location

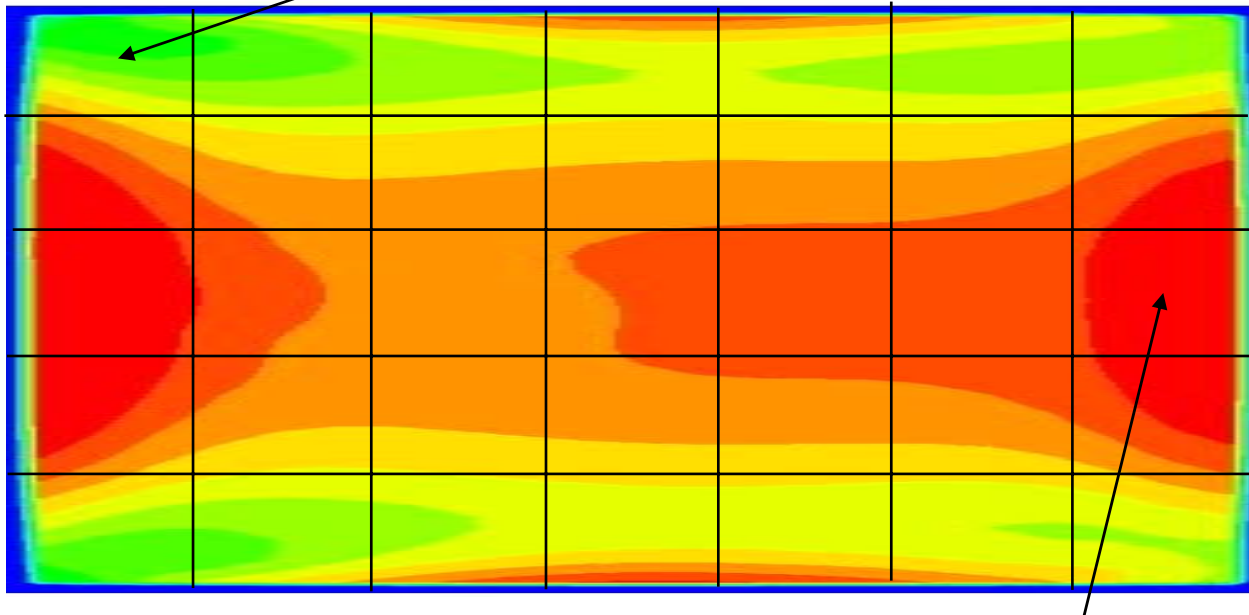
AIG Location

Flow correction 'as required' prior to the AIG (Often perforated plate and/or vanes)



AIG Field Tuning

Decrease ammonia flow in region of lower gas flow through the AIG for improved initial ammonia dosing



Increase ammonia flow in region of higher gas flow through the AIG for improved initial ammonia dosing

When units are designed with static mixers, this simple initial tuning trial, based on model study results for the flow profile through the AIG, is often sufficient to obtain an acceptable blend.



AI_G Field Tuning

Reactor Outlet Distribution

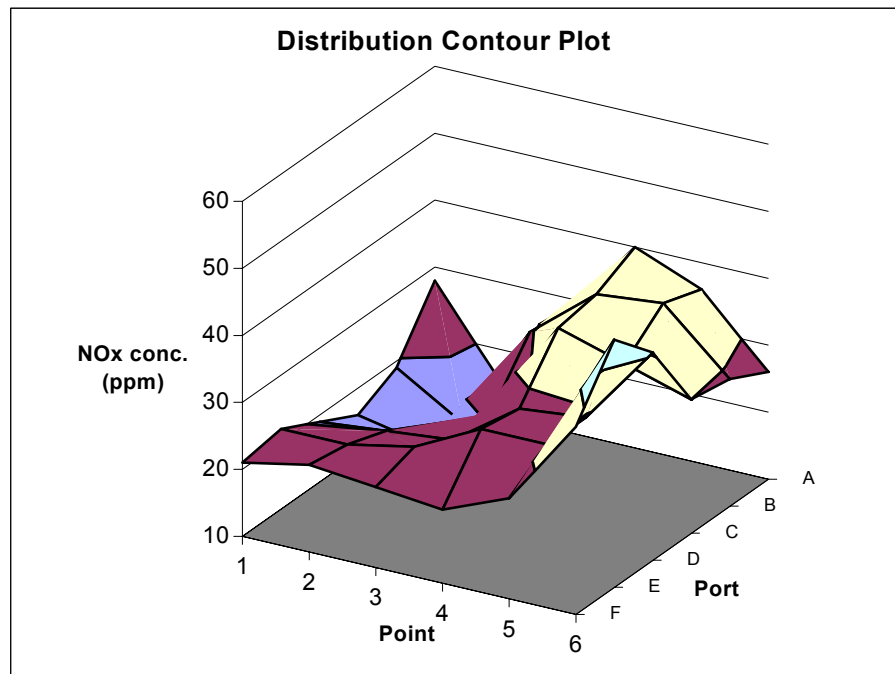
Initial Load	275 MW
Final Load	275 MW
NH ₃ Flow	350 lb/hr
% Reduction	90.0%

port/point	1	2	3	4	5	6
A	28	15	28	40	36	26
B	19	13	29	37	38	29
C	16	14	21	36	33	30
D	19	20	21	28	29	41
E	22	22	24	29	29	47
F	21	23	22	21	25	38

Std. Dev.
8.27

%RMS
30.72

Average (ppm)
26.92



***AI**G Field Tuning*

Given:

270 ppm Inlet NO_x

0.50 ppm ammonia slip

$$**Md = 0.90 + 0.50/270 = 0.9019**$$

Outlet NO_x Cv Target \cong 44% - 46% @ inlet NH₃/NO_x Cv \cong 5%

NO_x Cv is 30.7% Achieved \rightarrow Solving for the inlet NH₃/NO_x Cv @ outlet NO_x Cv is 30.7% yields an inlet NH₃/NO_x Cv \cong 3%



Field Uniformity Performance

Field Site →	A	B	C	D	E
Mixer Design	Other	Other	B&W	B&W	B&W
Removal Efficiency, %	87%	86%	92%	93%	89%
SCR Outlet NO _x COV	18%	23%	16%	10%	24%
SCR Inlet NH ₃ /NO _x COV	2.5%	3.8%	1.9%	1.2%	3.2%
Relative Mix Length	1.5	3.3	1.0	2.7	2.8
Relative Shock Loss	2.0	1.0	2.7	3.3	1.3





a McDermott company

The Babcock & Wilcox Company

Generating Powerful SolutionsSM

1-800-BABCOCK
www.babcock.com

