SCR Performance Optimization Through Advancements in Aftertreatment Packaging

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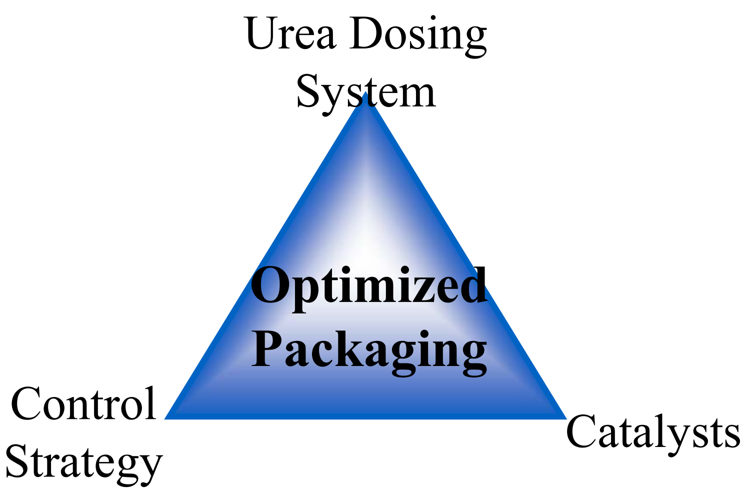
Outline

Optimization Through Aftertreatment Packaging

- Urea Doser Integration
  - Urea deposit formation & chemistry
  - Eliminating deposit formation
- Urea Preparation
  - Mixer design & simulation
  - Urea solution vaporization
  - Flow distribution
  - Urea distribution & mixing
- Single & Dual Wall Packaging
  - NO_X reduction impact
  - Skin temperature
- Summary

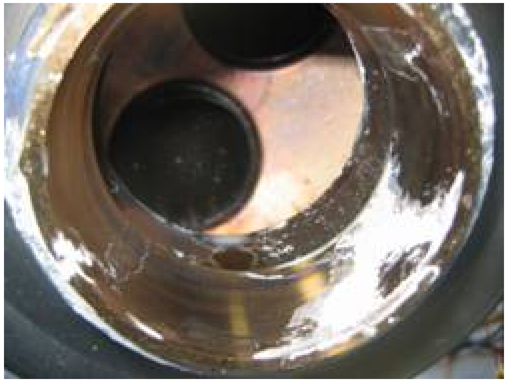


Doser Integration
What Are Deposits?

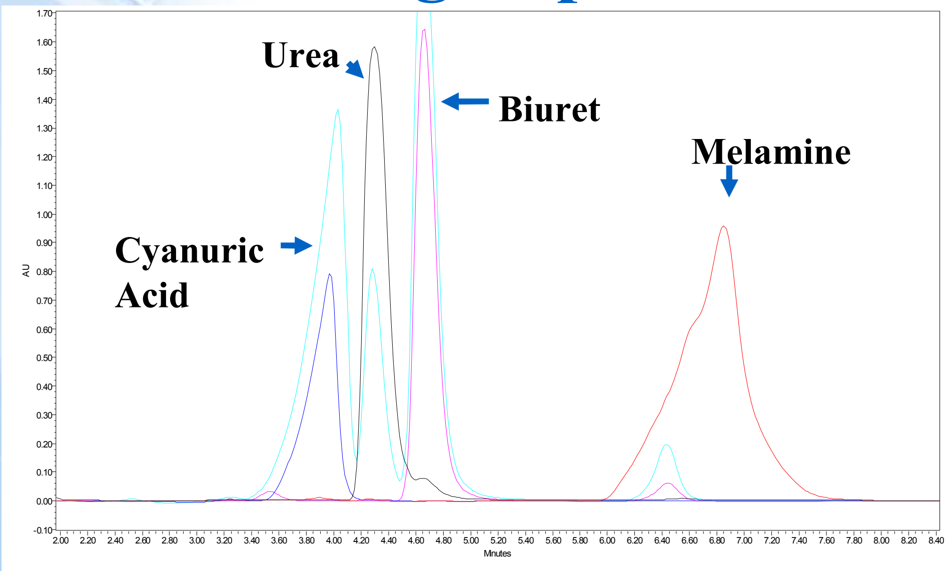
Step 1 (Vaporization): Water evaporates from spray droplet
Step 2 (Decomposition): Urea thermolysis & hydrolysis reaction

$$CO(NH_2)_2 \xrightarrow{\Delta} NH_3 + HNCO$$
$$HNCO + H_2O \rightarrow NH_3 + CO_2$$

Incomplete decomposition results in deposit formation



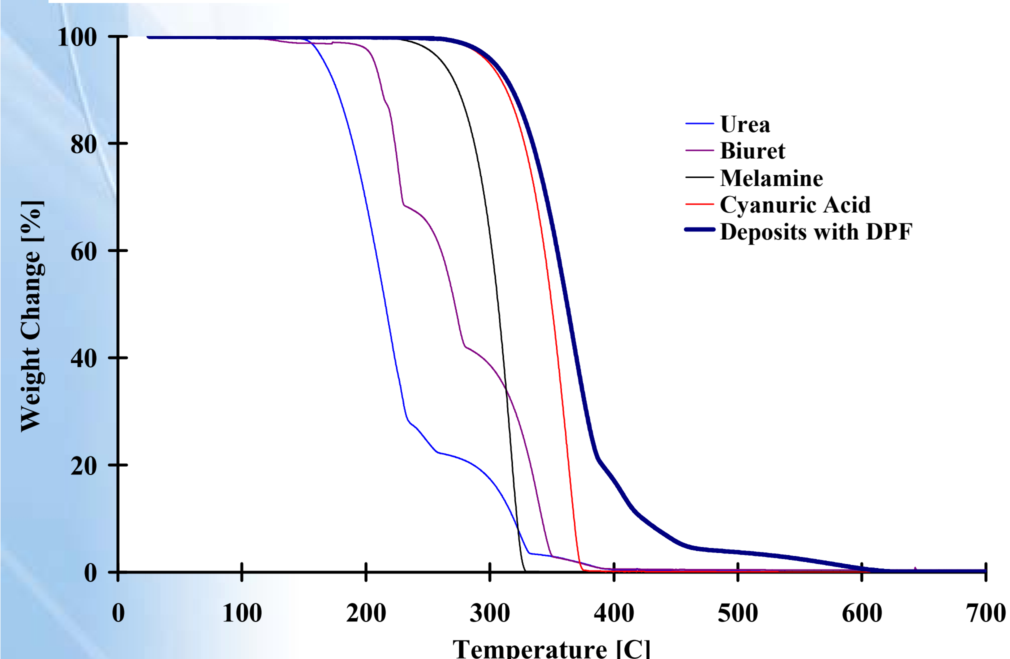
Doser Integration
Understanding Deposit Chemistry



High Performance Liquid Chromatography

Confirms composition of collected deposits:

- **Urea**
- Melamine
- **Cyanuric acid**
- Biuret



Thermogravimetric Analysis

- Deposit decomposition requires significant energy & time
- Prevention through proper **doser integration & urea preparation**

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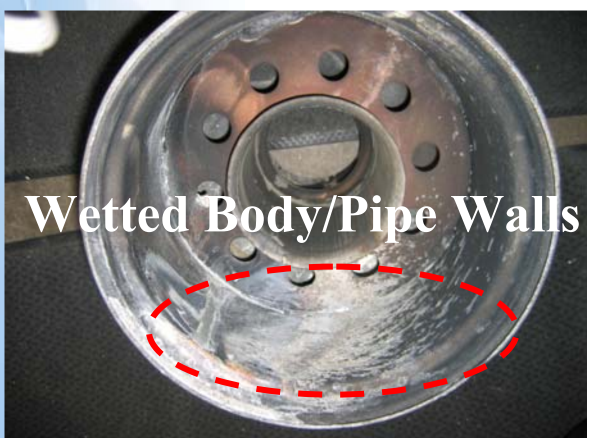
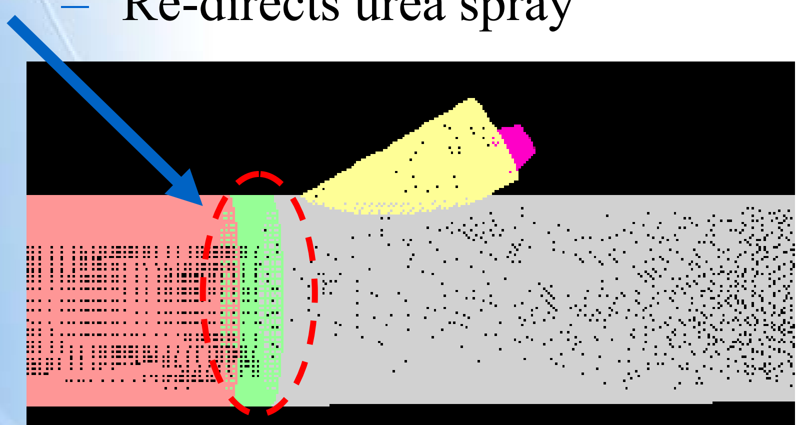
Urea Doser Integration
Deposit Formation & Root Cause

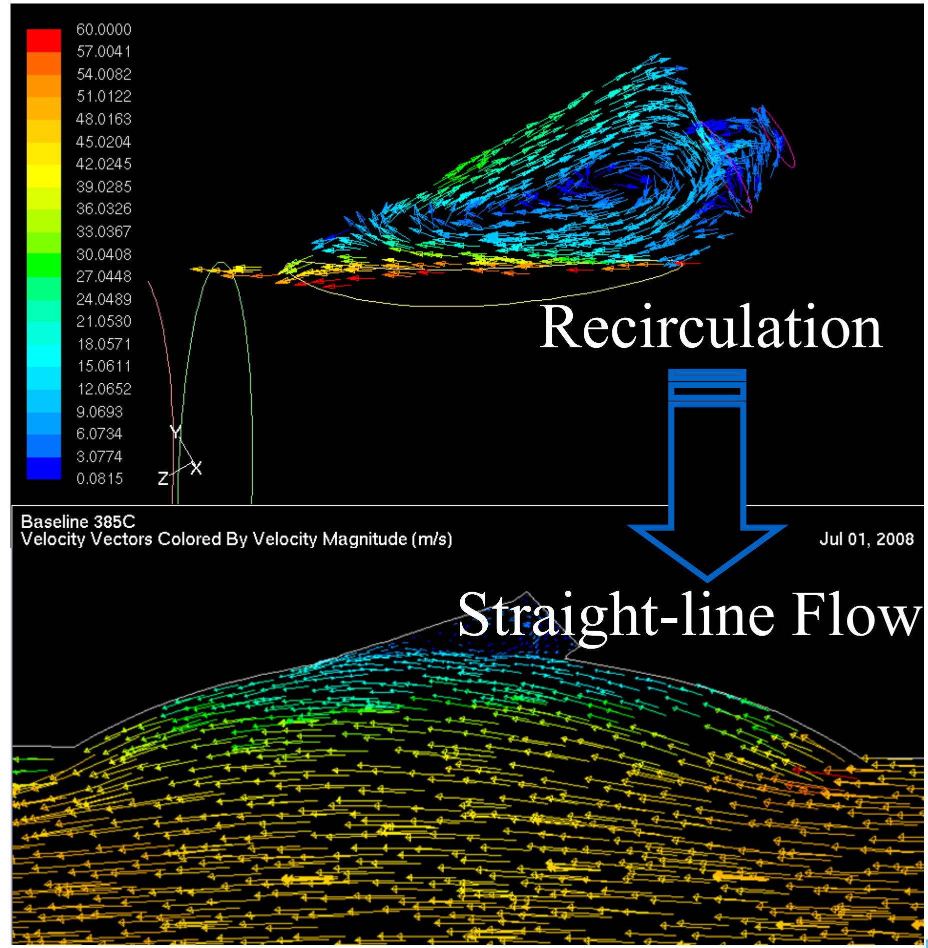


- Deposits form in three areas:
  - Injector location (spray tip/boss)
    - Cool tip/boss temperatures, direct spray impingement, <u>spray recirculation</u>
  - Interior wetted walls
    - Direct spray impingement on cool wall surface
  - Catalyst surface
    - "Wet" urea contacting catalyst surface (poor urea mixing/preparation)

Urea Doser Integration
Eliminating Deposits

- Eliminated wall wetting at injection location and pipe walls (CFD)
- Eliminated flow recirculation zone (CFD)
- Incorporate Wire-mesh "accumulator"
  - Direct spray impingement
  - Eliminates wall wetting
  - Re-directs urea spray





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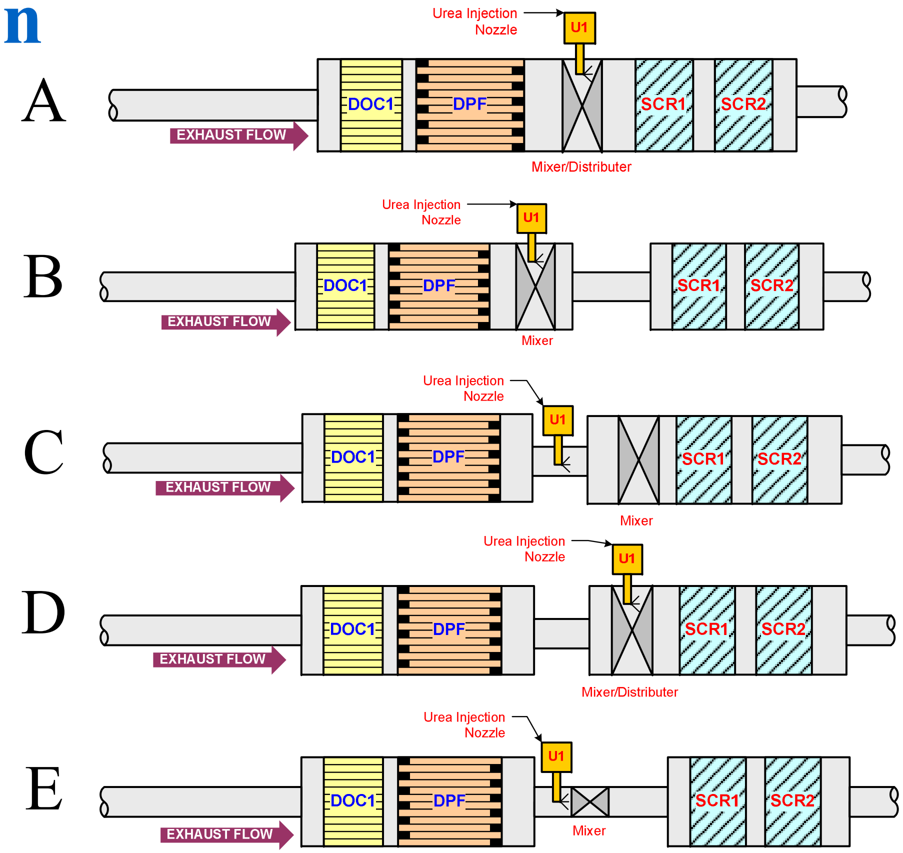
Urea Preparation
Mixer Design and Simulation

- **What is the "best" mixer type?**
  - In-pipe mixers
  - In-body mixers
  - Multiple injection locations
  - Multiple mixer variations
- **Water injection used to simulate urea**



- **Model Outputs:**
  - % Vaporization
  - H_2O vapor uniformity (γ_{H2O})
  - Velocity uniformity (γ_{Vel})
  - Backpressure penalty

- **Simulation/Test Modes:**
  - 332g/s @ 500˚C exh (high flow)
  - 151g/s @ 290˚C exh (low flow)

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Urea Preparation

Mixer Design and Simulation

		BP (kPa)	γ_{H2O} High Flow	γ_{H2O} Low Flow	γ_{Vel} High Flow	γ_{Vel} Low Flow
In-Body	A – Continuous Body & On-Mixer Doser	2.2	0.77	0.90	0.95	0.98
	B – DPF Outlet Mixer & On-Mixer Doser	2.0	0.97	0.98	0.96	0.99
	C – SCR Inlet Mixer & On-Pipe Doser	2.6	0.87	0.92	0.94	0.97
	D – SCR Inlet Mixer & On-Mixer Doser	1.6	0.82	0.93	0.94	0.98
In-Pipe	E – In Pipe Vortex & On-Pipe Doser	1.9	Incomplete vaporization at SCR face 0.96	0.87	0.97	0.99

- Ideal mixer determined to be in-body design
  - Low backpressure penalty
  - Maximum mixing/vaporization
  - Maximum injection location flexibility

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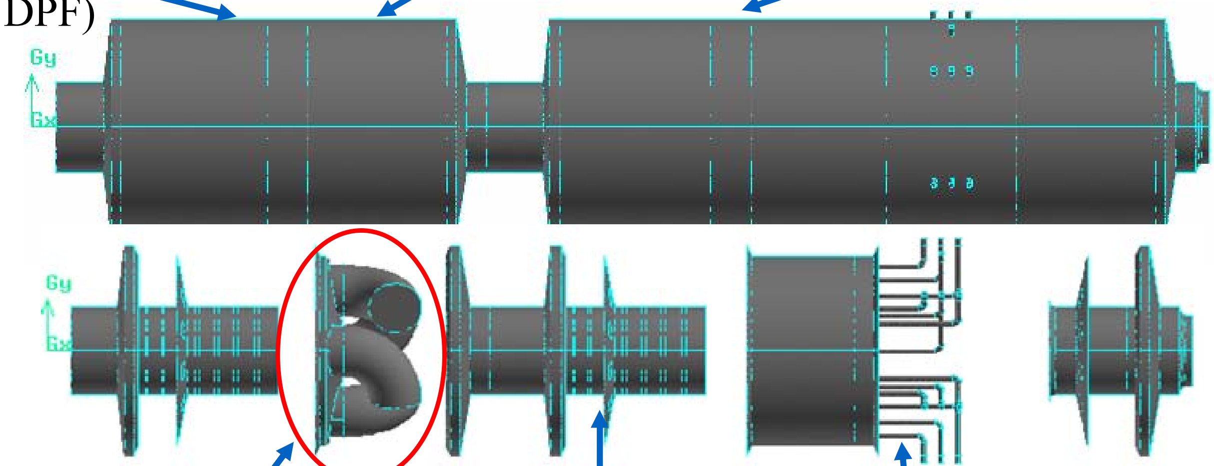
Urea Preparation
Simulation Validation

Single 10.5" x 6" SCR promotes ammonia slip for distribution measurement

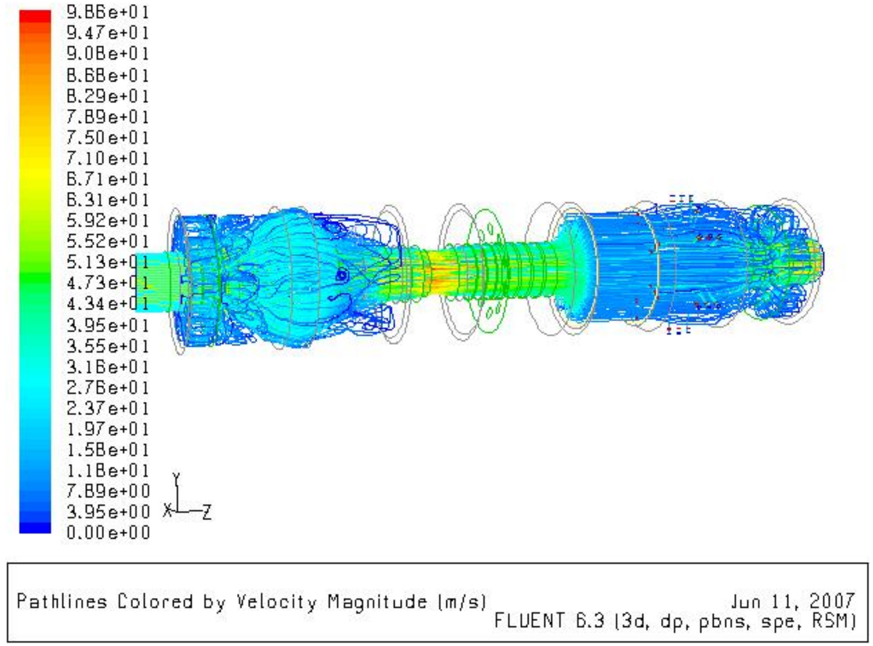


- In-body mixer refined via simulation
- Simulation results compared against engine test:
  - 15 liter, Cummins ISX 500
  - 342 g/s @ ~477 C 1,616 ml/hr injection
  - 190 g/s @ ~429 C 638 ml/hr injection
  - 224 g/s @ ~204 C 1,741 ml/hr injection
- Baseline (no mixer) compared to with-mixer case

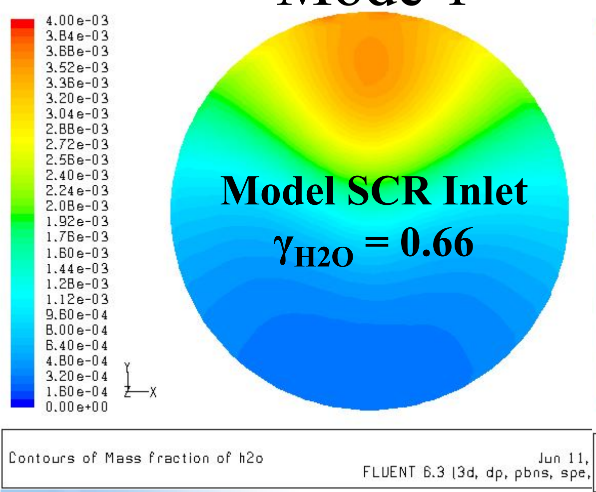
Urea Preparation
Simulation Validation

Baseline Simulation Results

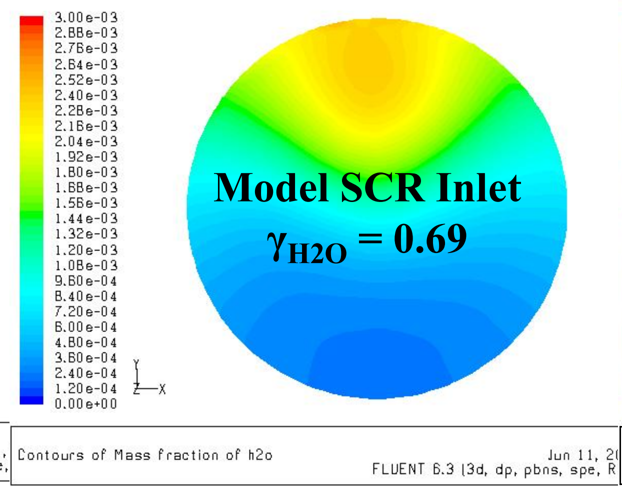
- Linear flow with some turbulence (limited vaporization time)
- > 75% of urea impacts core face as liquid
- Poor reactant distribution at the SCR core face



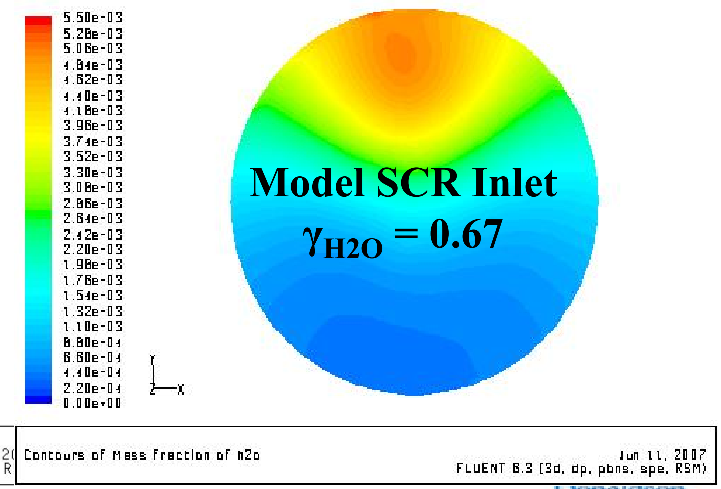
Mode 1



Mode 2



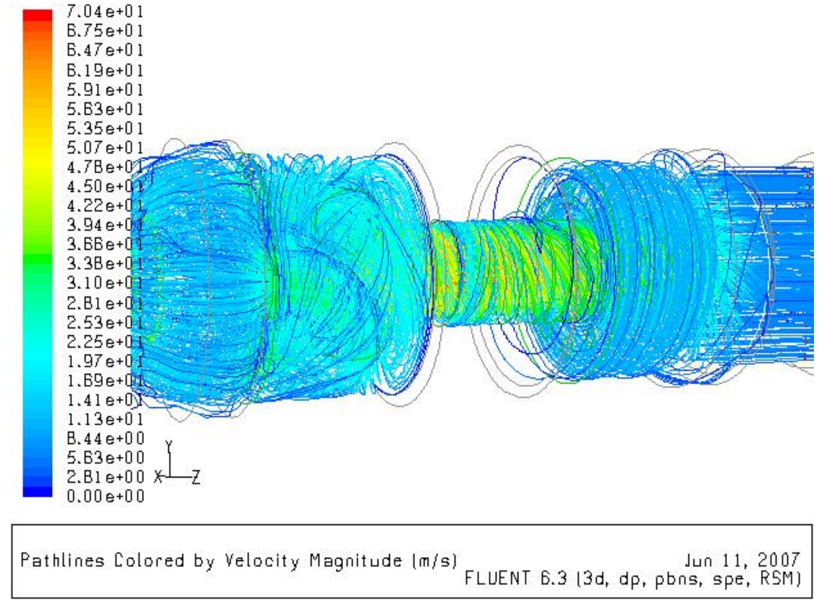
Mode 3



Urea Preparation
Simulation Validation

Mixer Simulation Results

- Strong vortex = increase vaporization time
- No liquid urea escapes
- Uniform distribution



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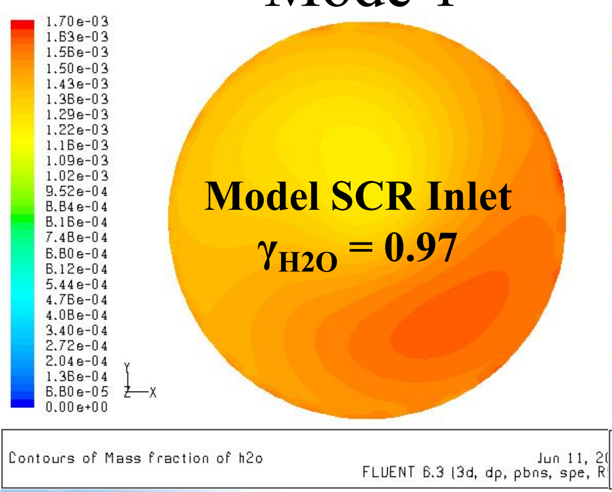

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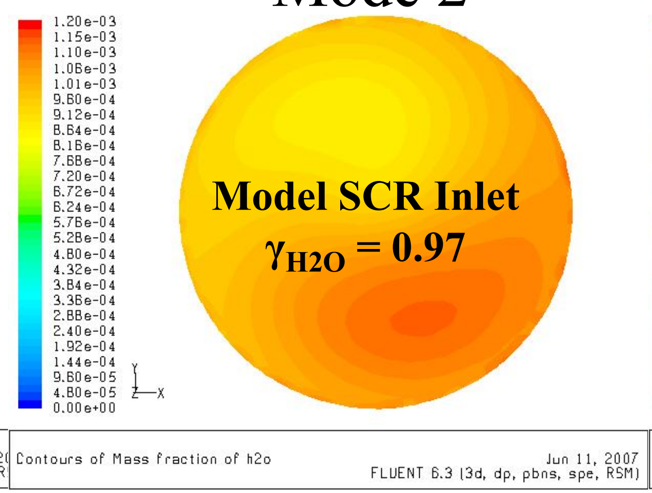
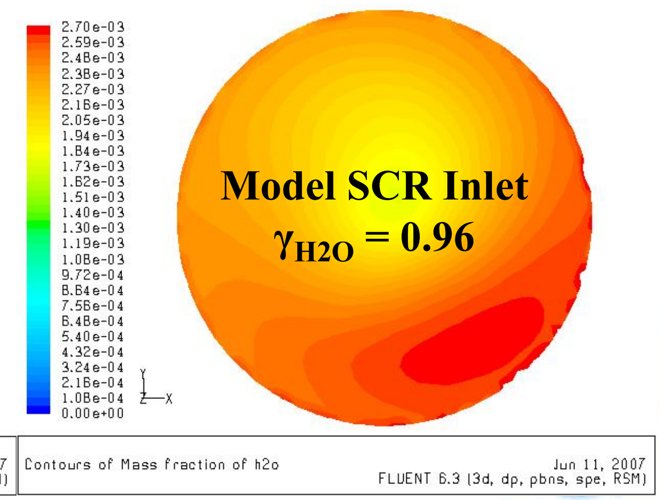
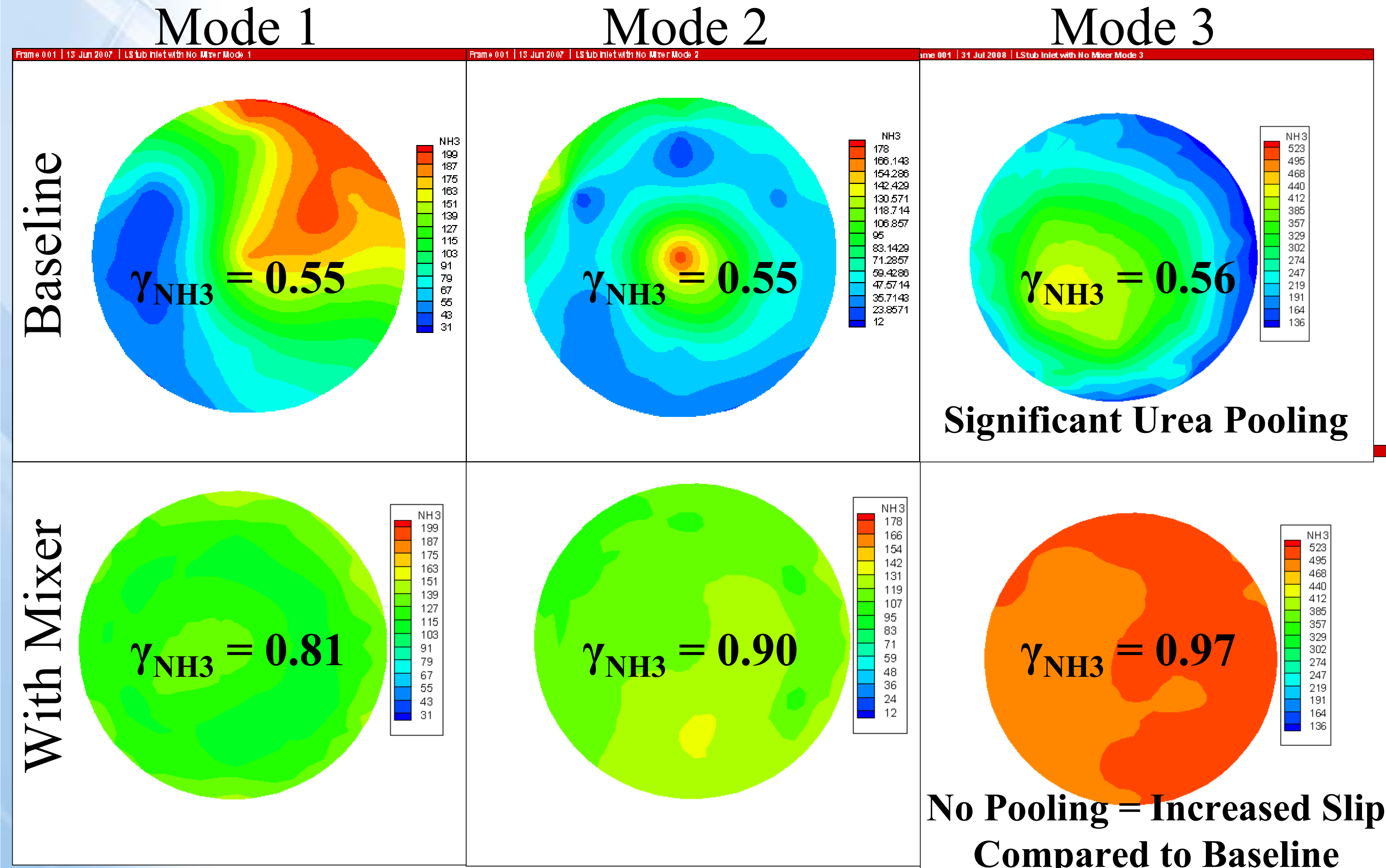


Mode 3



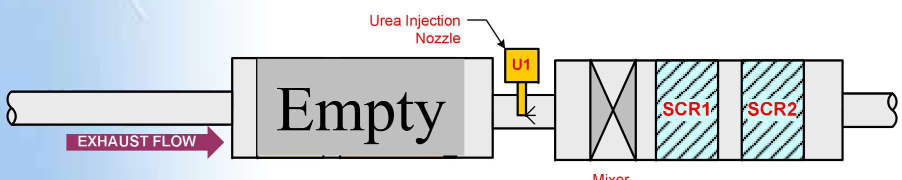
Urea Preparation

Measured Ammonia Slip Distribution



Urea Preparation
On-Engine Performance Evaluation

- 2004 CAT C7
- 600 HP eddy-current dynamometer
- Pseudo FTP cycle
  - Cold start transient (duration: 20 min)
  - 20 min hot soak
  - Hot start transient (duration: 20 min)
- 3 steady-state SET modes
  - 1901 RPM, 175 ft-lb (B25)
  - 1901 RPM, 525 ft-lb (B75)
  - 2240 RPM, 611 ft-lb (C100)
- Alpha = $NH_3:NO_X = 1.0$ while exhaust > 200˚C



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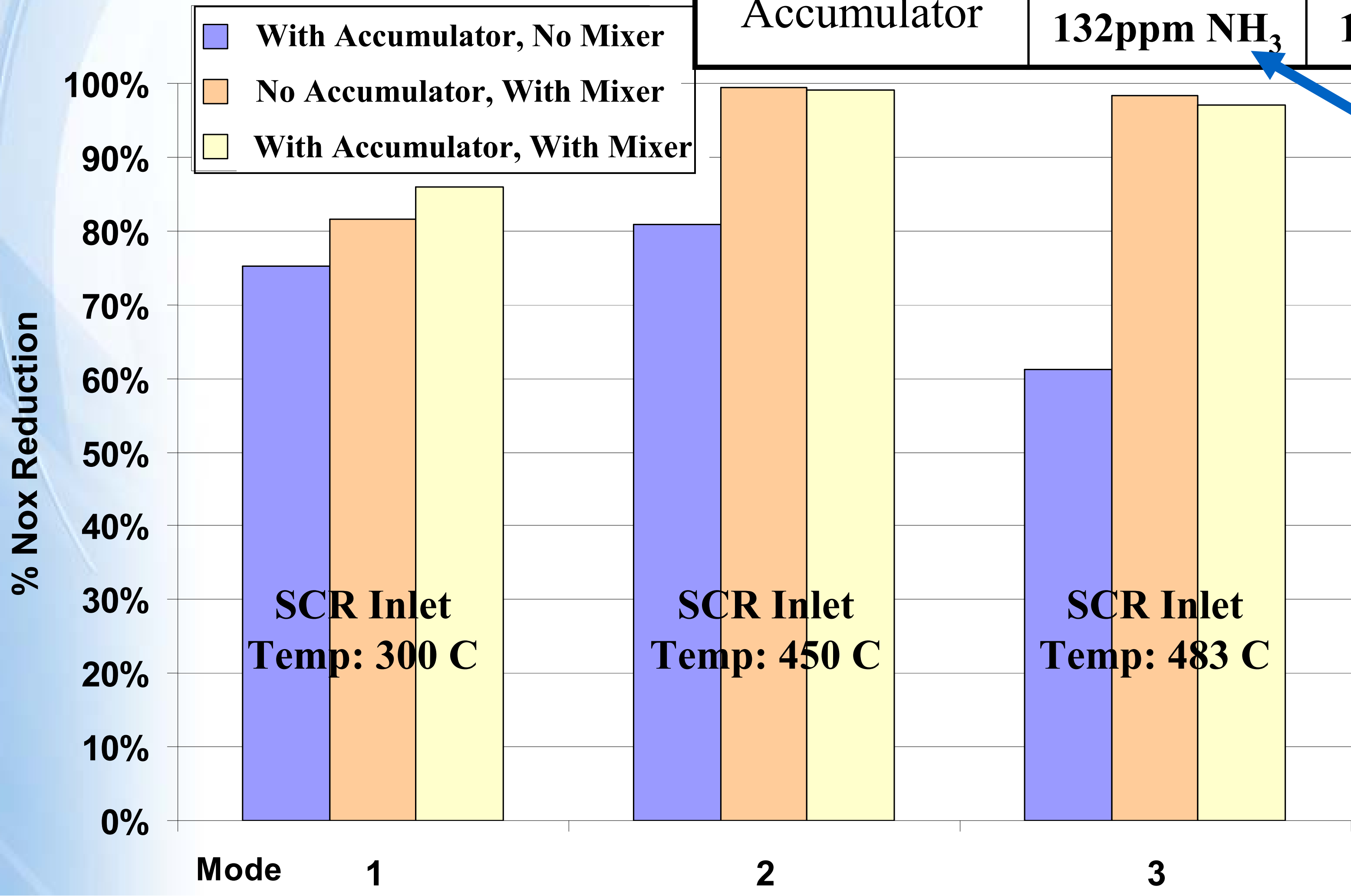
Urea Preparation
On-Engine Performance Evaluation

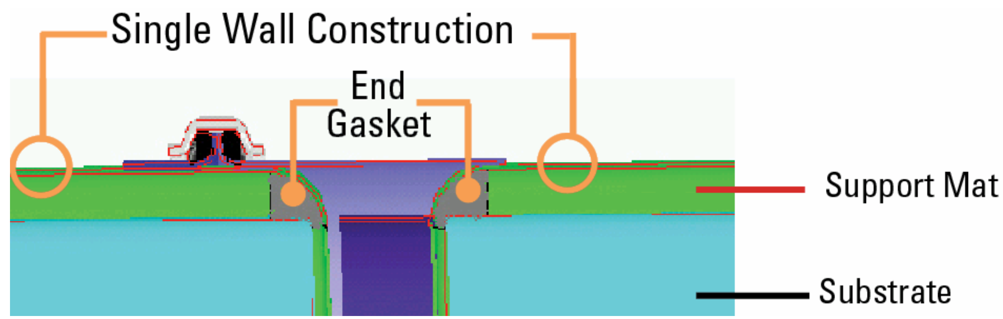
FTP NOx Red	No Mixer	With Mixer
No Accumulator	**47.2 %** **442ppm NH_3**	**74.9 %** **15ppm NH_3**
With Accumulator	**62.5 %** **132ppm NH_3**	**81.9 %** **15ppm NH_3**

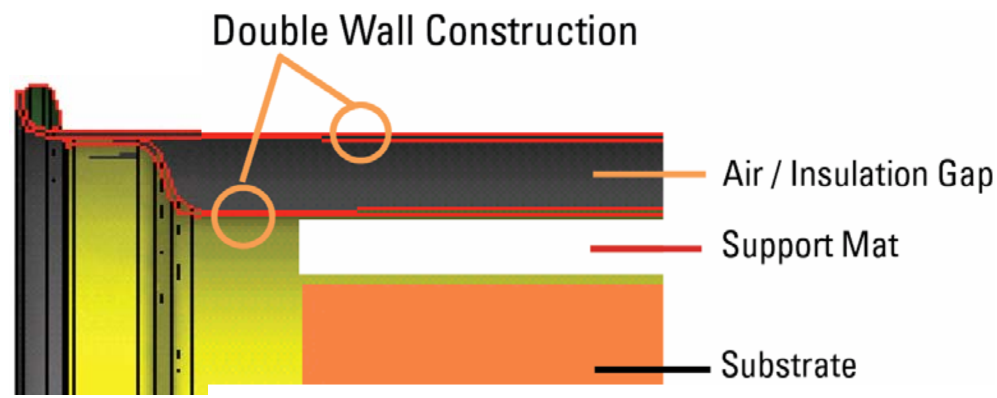
Cycle Peak Slip

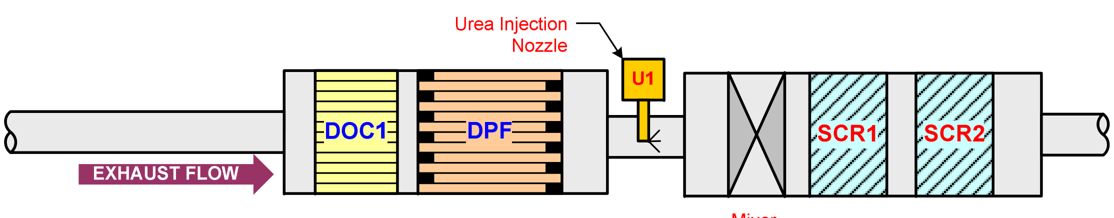


Packaging Style
Dual or Single Wall?

- Single or dual wall drivers:
  - Skin temperature: dual wall has lower skin temperature
  - Heat retention: improved cold start NOx reduction
  - Cost: dual wall is higher cost
- Performance tested
  - Cold start + hot start FTP
  - Steady state, ~ 480˚C exhaust gas temperature







Test System

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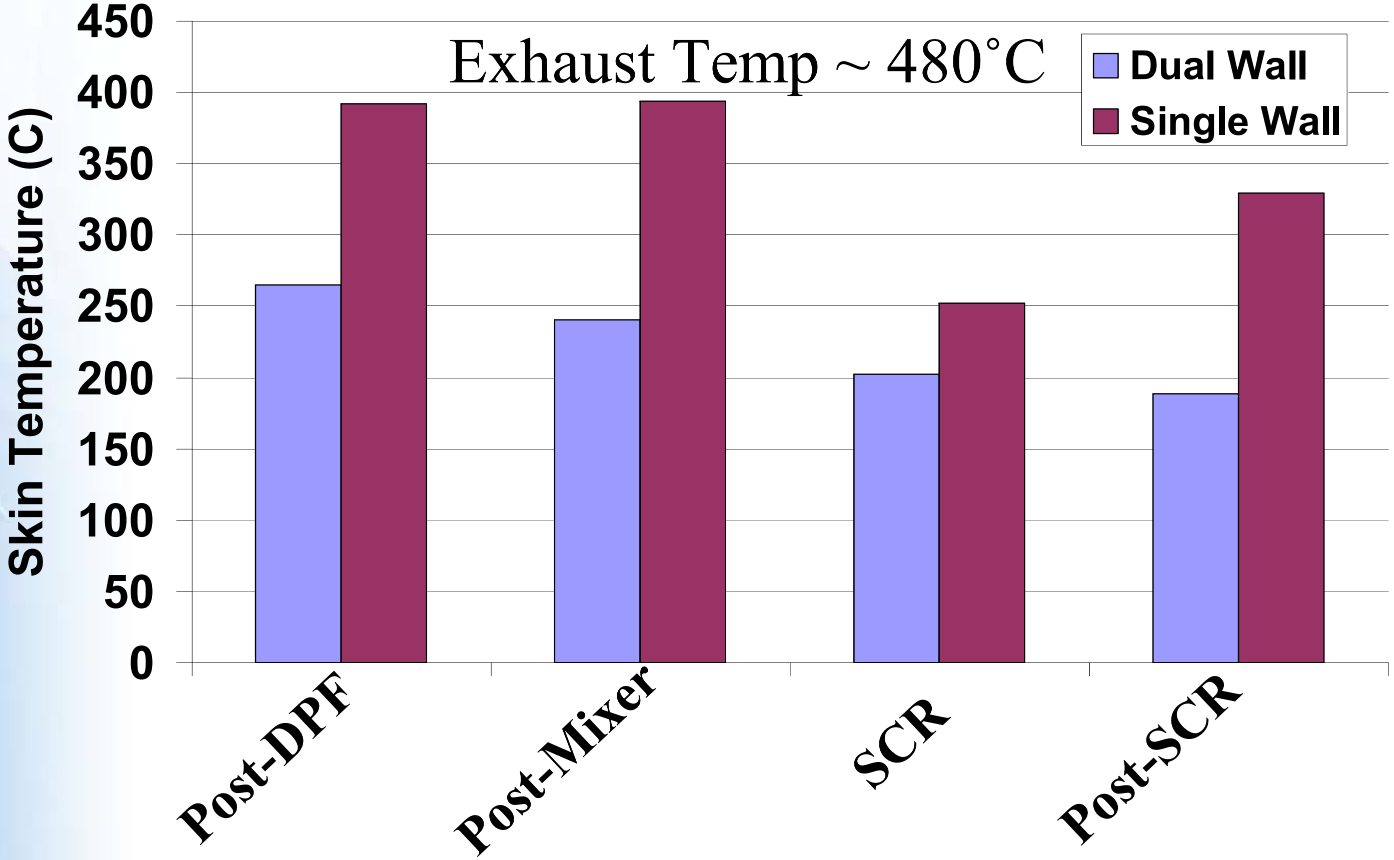
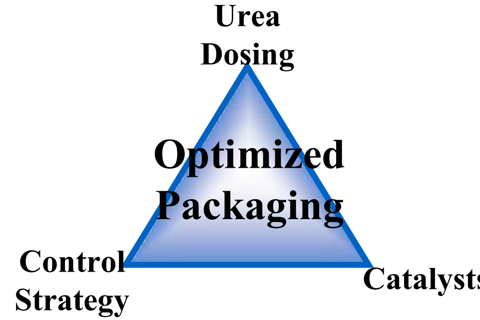
Test Cell Evaluation

Impact of Dual Walled Packaging – NO_X Reduction

FTP %NOx Reduction	
Dual Wall (System)	77.2%
Single Wall (SCR only)	75.7%



Summary



- Doser integration priorities
  - Zero wall wetting
  - Zero recirculation
  - In-pipe accumulator reduces deposits
- Urea preparation significantly impacts system performance
  - In-pipe mixers require long pipe lengths for full vaporization
  - In-body swirl mixer provides the best performance:
    - 100% vaporization
    - excellent flow distribution
    - 6” package space, doser flexibility
  - Combination of in-body mixer with in-pipe accumulator offers performance and deposit advantages
- Single or dual wall packaging?
  - Little to no impact on NOx reduction over cold + hot FTP
  - Skin temperature, cost - primary drivers
  - Impact on deposit formation needs to be evaluated

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