Diesel Catalyst Aging: Findings from Engine and Vehicle Tests

Presented at the Southwest Research Institute

Symposium on Diesel Catalyst Accelerated Aging, Feb 22 2008

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Eaton Aftertreatment

Presentation Outline

1. Eaton's Diesel Aftertreatment System

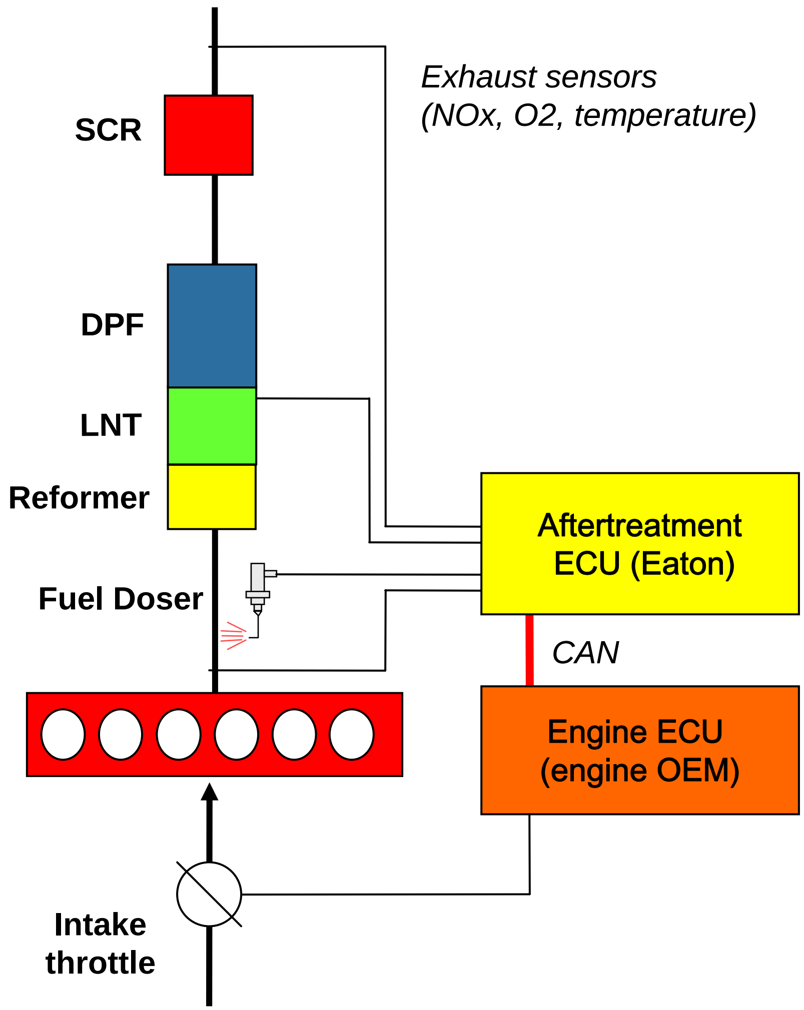
2. Fuel Reformer Catalyst
    1. Model-based temperature control
    2. On-road test data
    3. Summary

3. LNT Catalyst DeSulfation
    1. Results of 150 cycle desulfation
    2. Time-at-temperature variability
    3. Summary

Each summary includes Eaton current best-practice for catalyst oven aging

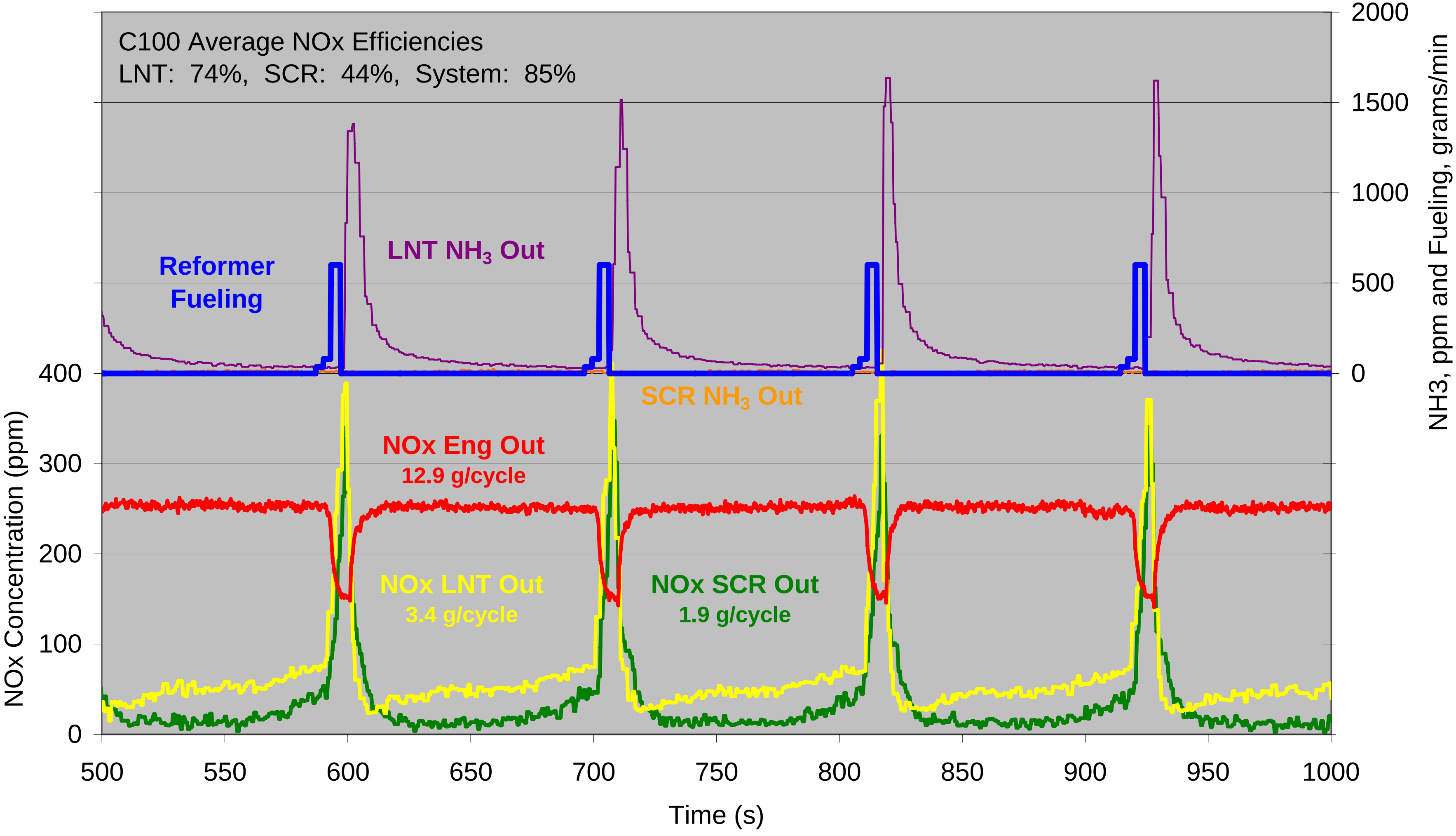
Eaton Aftertreatment System

- **Reformer → LNT → DPF → SCR**
  - Primary NOx reduction via LNT
  - Secondary NOx reduction via SCR
  - NH_3 generated at LNT via regen
    - No on-board tank or 2nd fluid
- **Rich operation during LNT regeneration**
  - Intake throttle to 'less lean' engine operation (O_2 approx 5%)
  - Fuel dosing to achieve rich exhaust
- **3 Key Processes for System Function**
  - LNT regeneration
  - DPF regeneration
  - LNT desulfation



System Operation: Typical NOx Performance

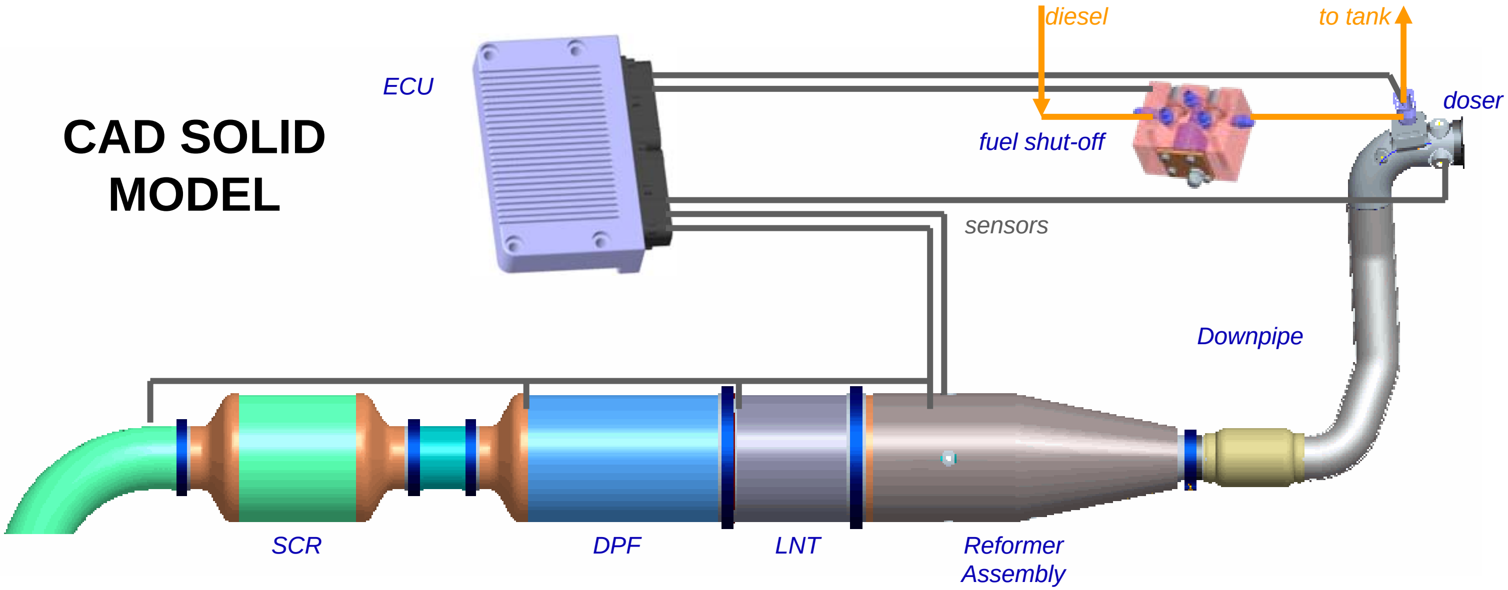
14L engine, US'04 engine-out NOx, C100 engine condition



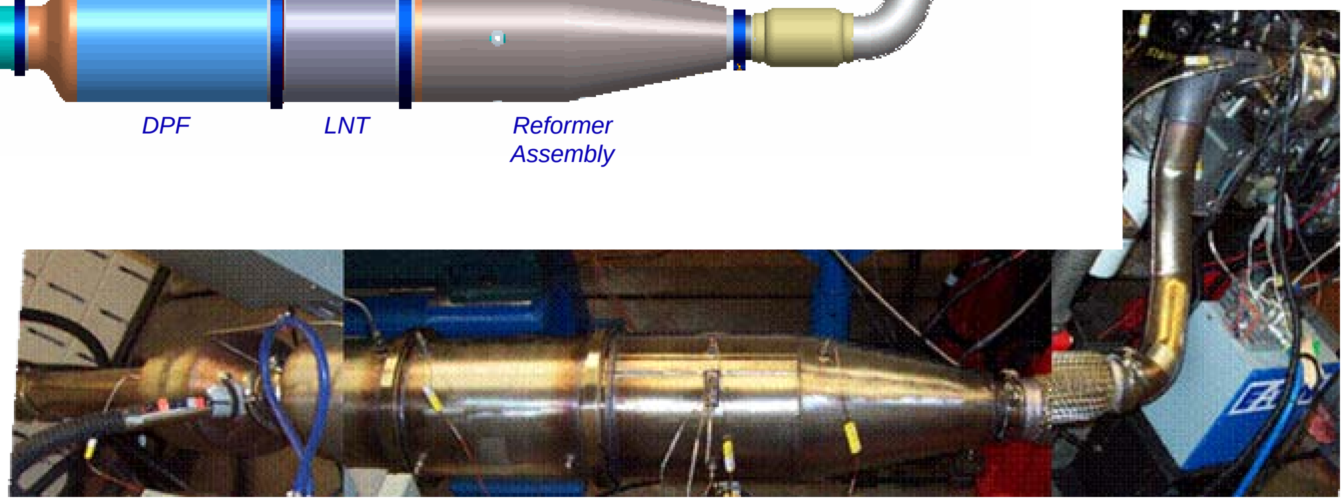
System Prototype

NOx & PM targeted at 2010, tier-4b standards

CAD SOLID MODEL



Engine Test Cell Photo



System currently installed in dyno cells and vehicles for durability evaluation

Notes on this presentation

- The is is not a comprehensive presentation
  - Not a full review of catalyst durability
  - Not a full review of Eaton's system or efforts
  - No discussion of DPF or SCR
    - although both are important
  - No in-depth discussion of surface chemistry
    - e.g., sintering, sulfur storage, etc.

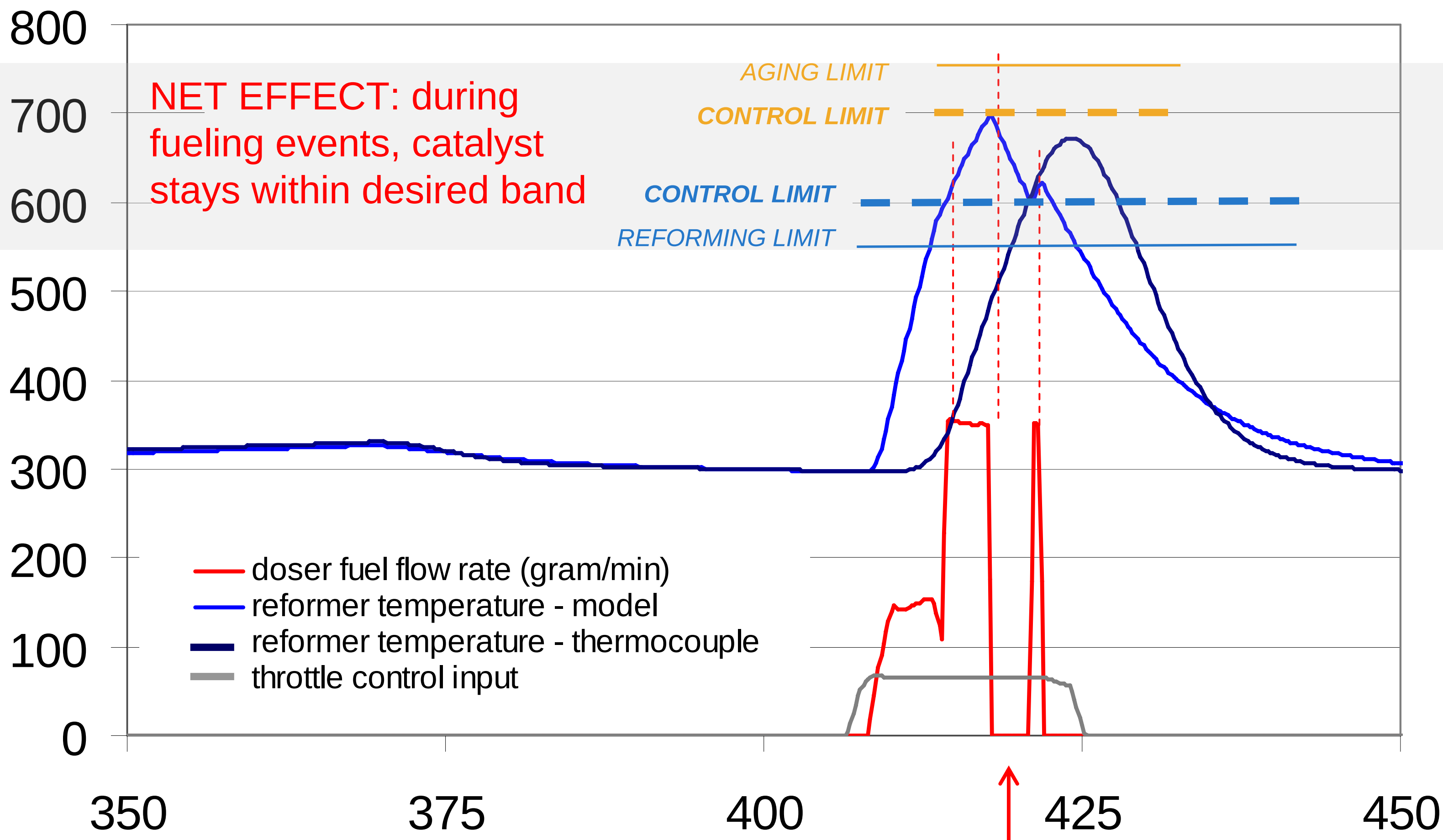
- Strong focus on temperature exposure / history in real-world application
  - Key question: what is the real-world aging profile of key catalysts?

- The objective is to share ideas and data that may be helpful in defining industry tests for diesel catalyst aging

Fuel Reformer Catalyst

A real-time model of reformer temperature is used to calculate fueling rate

objective: achieve rich pulse <u>and controlled temperature conditions</u> during regeneration

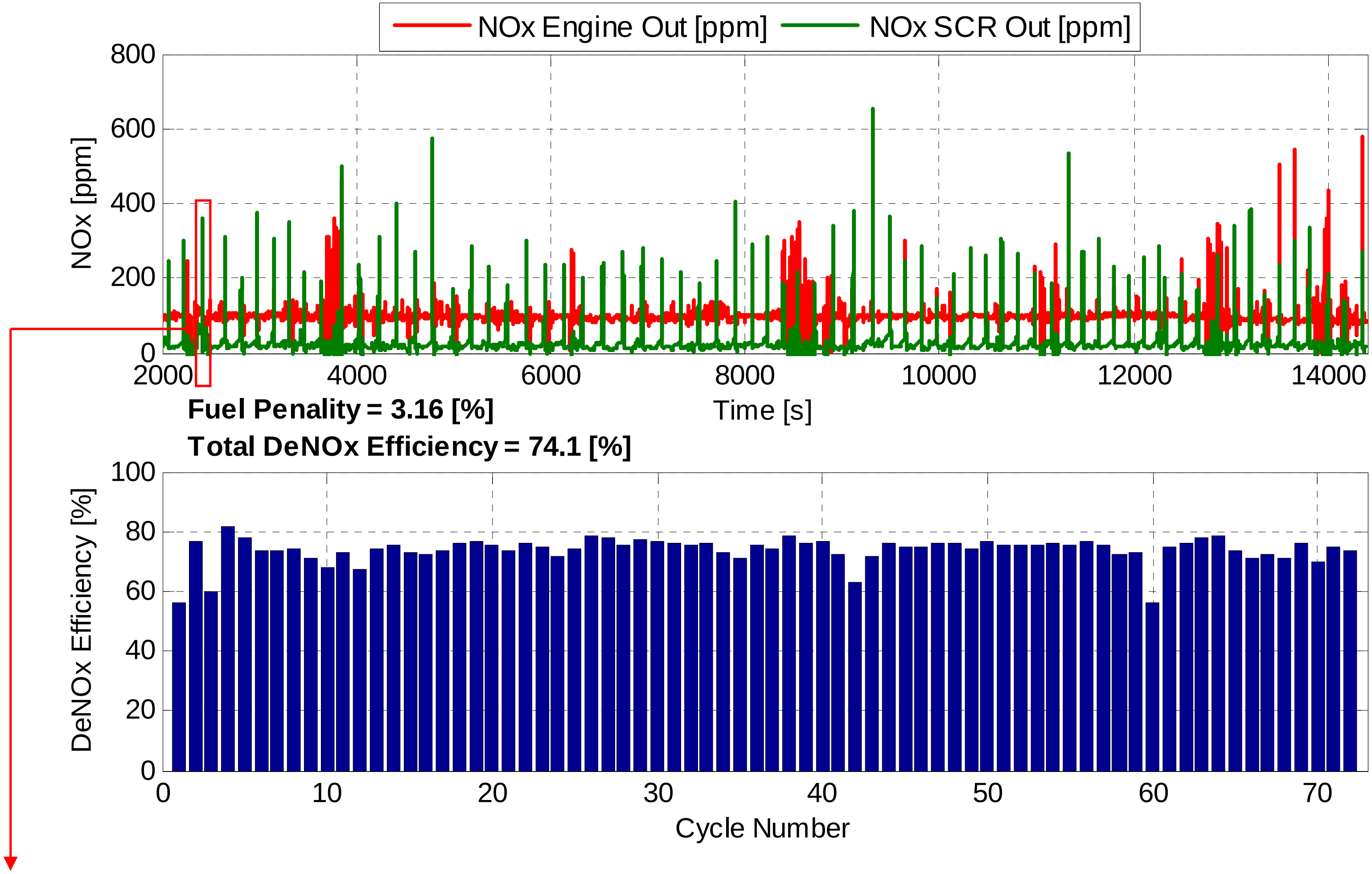


High-temperature limit sometimes leads to double-rich pulse with cooling period in-between

Example of on-board test data:

NOx Conversion during on-road test

(June 2007, I-94, 3.5 hours operation, 73 regenerations)

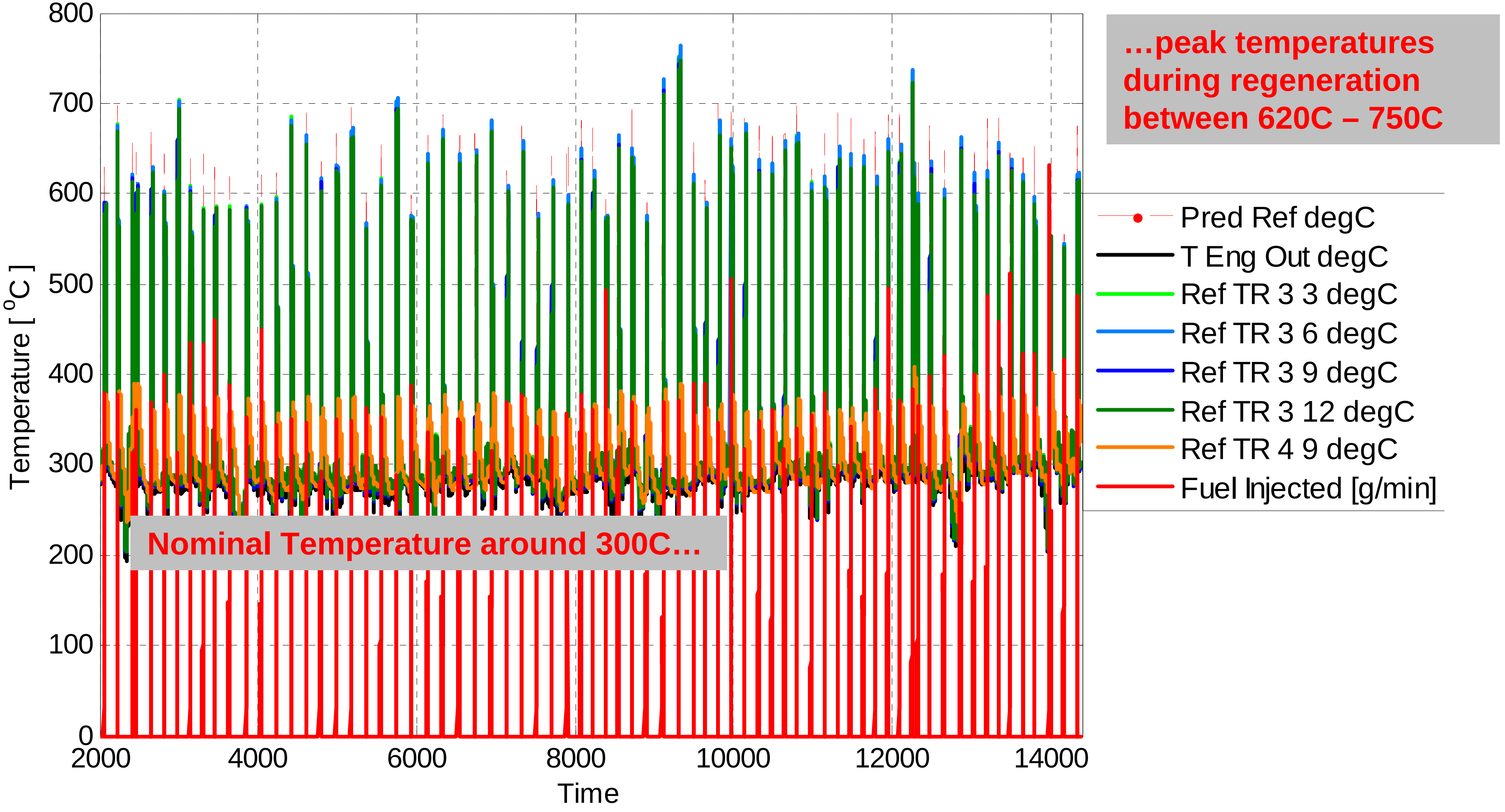


Each regeneration event represents rich fueling and associated reformer exotherm…

Example of on-board test data:

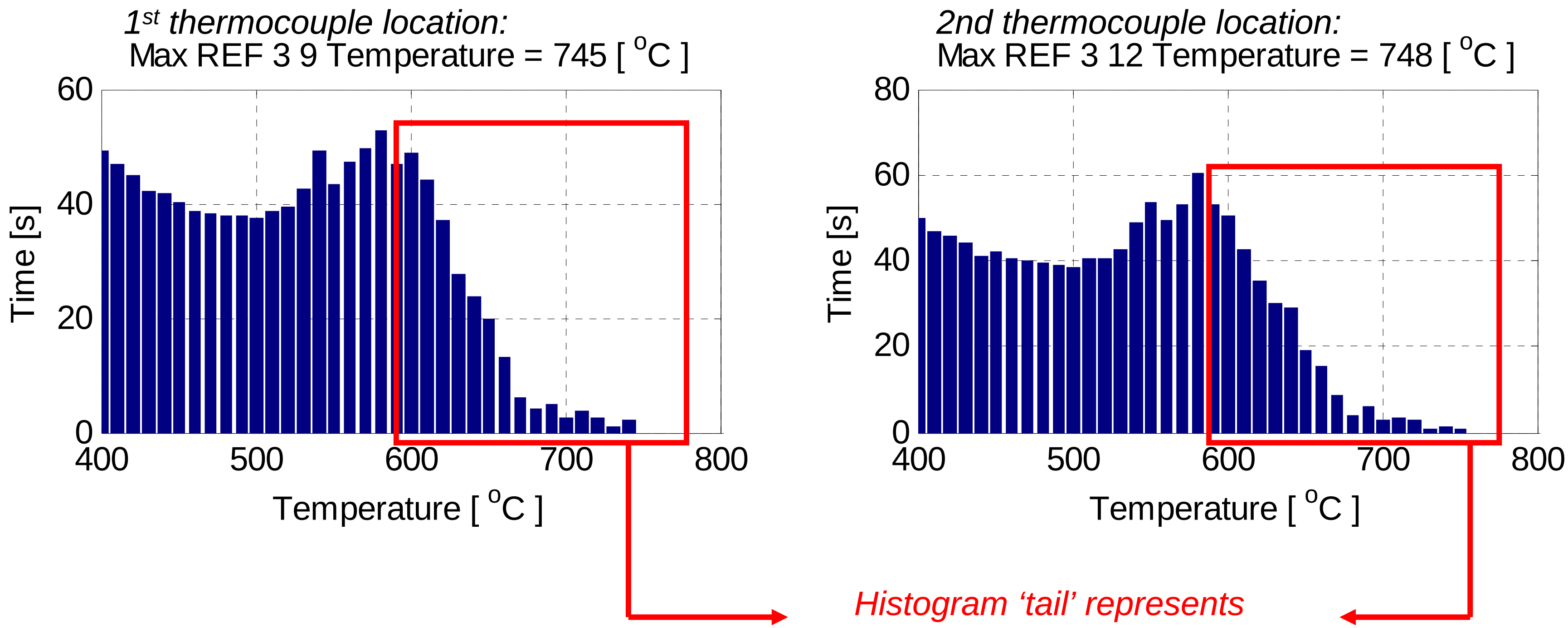
Reformer temperatures during on-road test

(June 2007, I-94, 3.5 hours operation, 73 regenerations)



Time-at-Temperature Histograms

from 3.5-hour on-board test
(same data as previous slide, in a new format)



Histogram 'tail' represents high-temperature exposure during regeneration exotherm

- Time-at-temperature histogram shows fuel reformer catalyst temperature stays under 750C through entire 3.5 hour test
- From this data, we can develop temperature process control metrics

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Development of a Bench Aging Protocol: Fuel Reformer Catalyst

- Temperature exposure is dominated by real-time model-based controls
  - Objective: keep reformer catalyst inside proper temperature range
  - Limit set to 750C for this catalyst material
  - Vehicle test example shows 0% exposure over 750C in 3.5 hours of operation

- Current Bench Aging Protocol
  - 750C temperature
  - 500 hours exposure
    - Derived from simple estimate of exotherm time in-service
  - Periodic lean/rich cycling throughout aging process

- Key Questions
  - Can 500 hour test be accelerated?
  - What is the impact of poisons/contaminants on reformer performance?

LNT DeSulfation Process

How many desulfation cycles are required to represent ‘useful life’?

a sketch calculation:

- 185,000 mile useful life (EPA-MD)
- 6mi/gal fuel economy (assumption)
- 0.5g/L desulfation loading target (rough estimate based on bench data)
- 10.5L LNT catalyst volume (current system prototype)
- 13ppm sulfur fuel
  - 10ppm sulfur fuel average, plus
  - 3ppm sulfur contribution from oil (on fuel-equivalent basis)

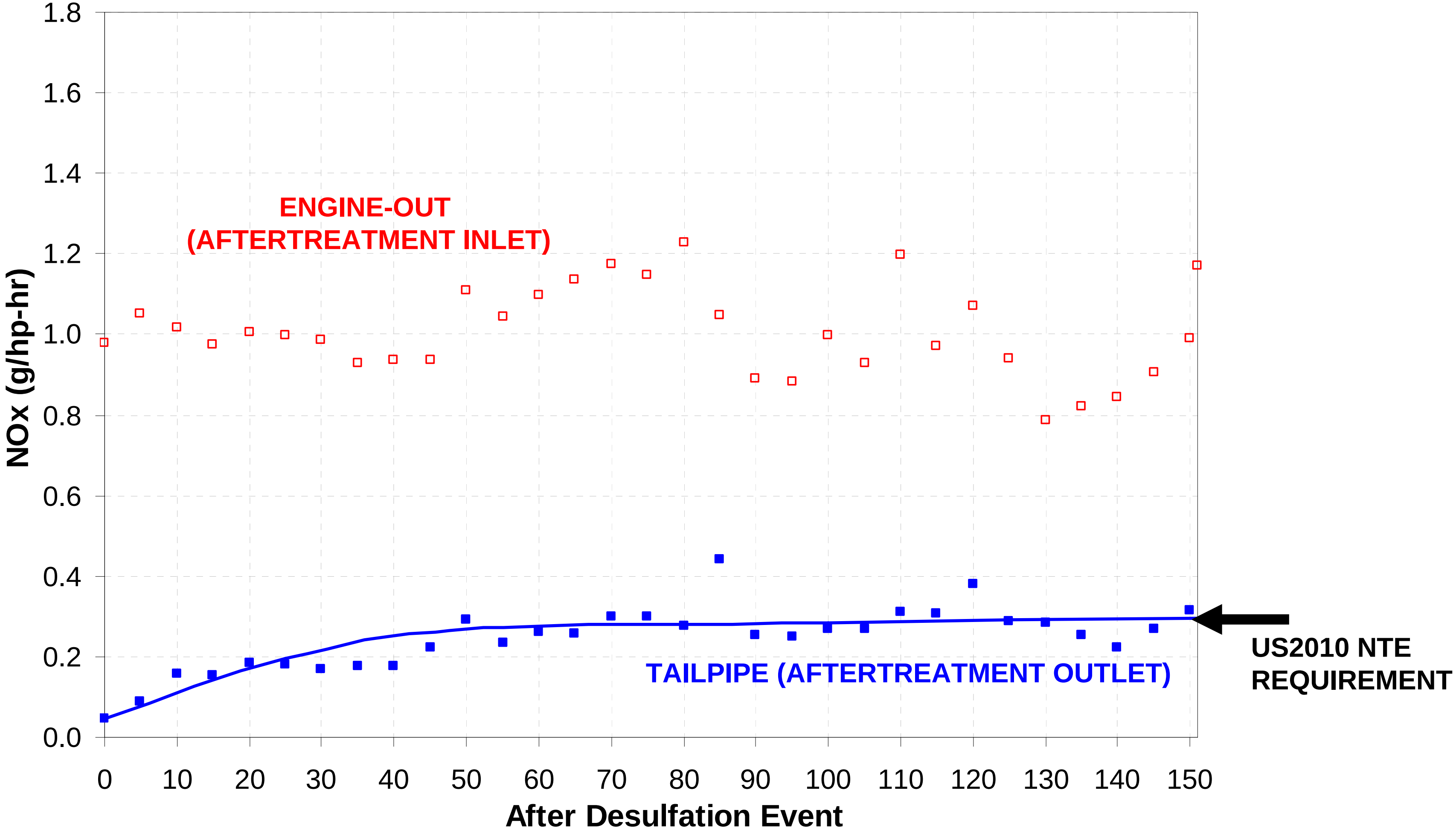
- TOTAL NUMBER OF DESULFATIONS REQUIRED: 244
  - This number can be argued up or down, depending on assumptions

- Eaton Internal Bogey for Desulfation Cycling: 200 – 300 cycles

- Eaton has completed 150 cycles of desulfation aging
  - Selected results shown at DOE DEER conference 2007
  - More to be published with SAE this summer

150-cycle Desulfation Data:

At medium-load conditions (B50), after 150 cycles, system NOx reduction performance is consistent with EPA-2010 NTE



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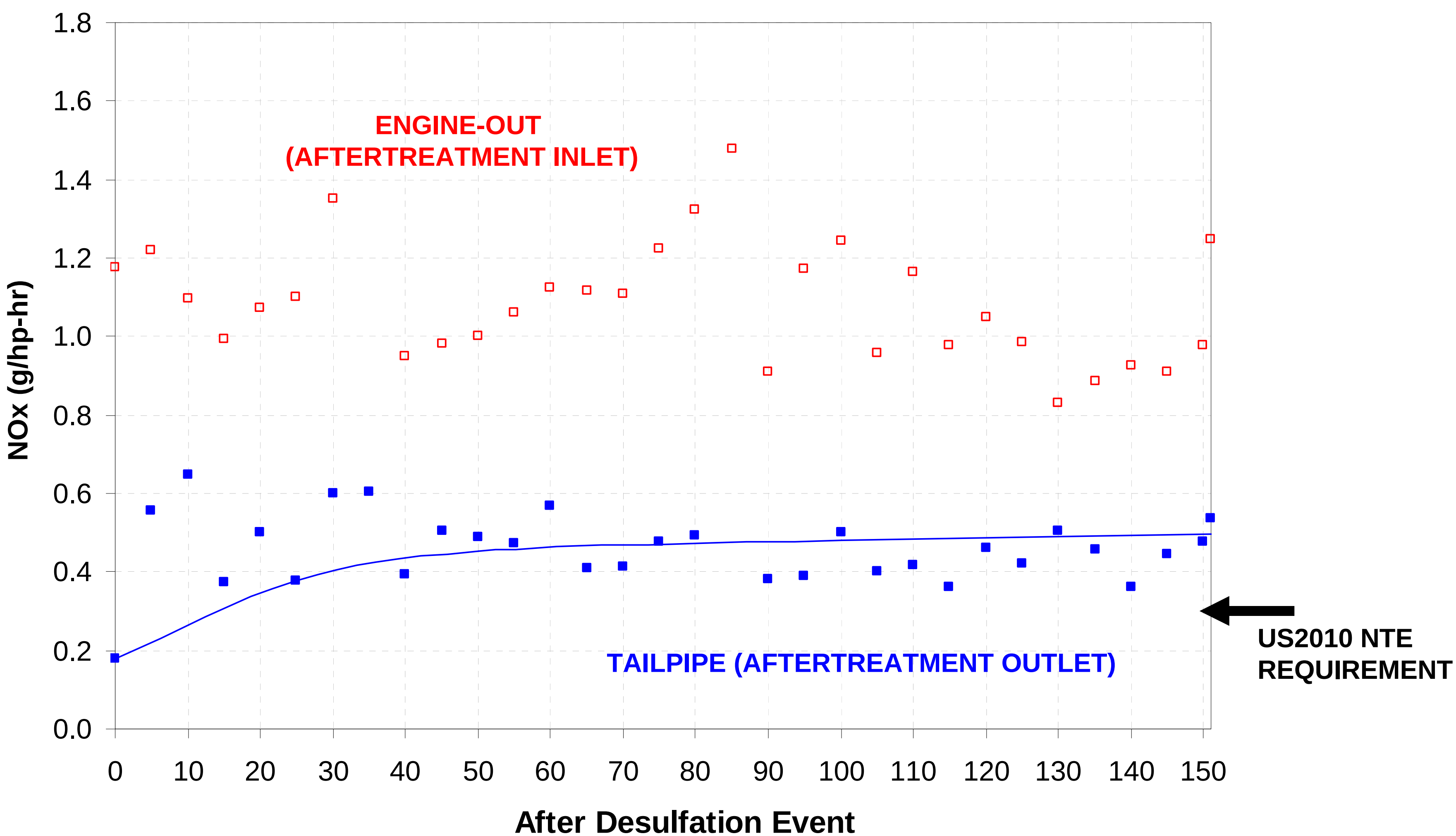
150-cycle Desulfation Data:

At high-load conditions (B100), after 150 cycles, system NOx reduction performance does not achieve EPA-2010 NTE:



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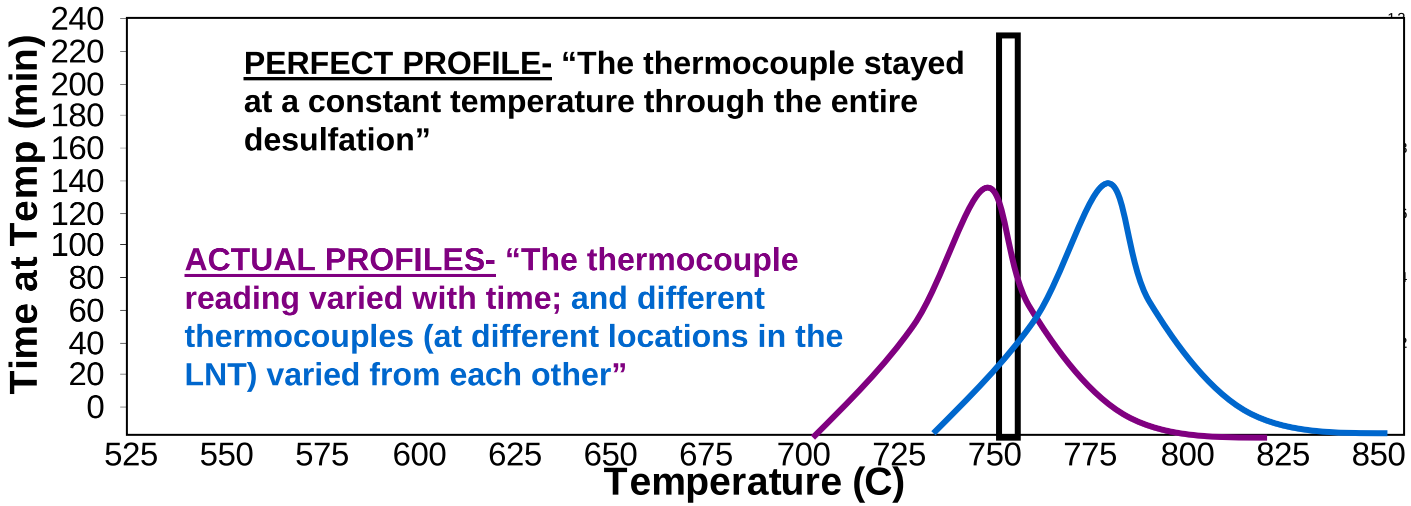
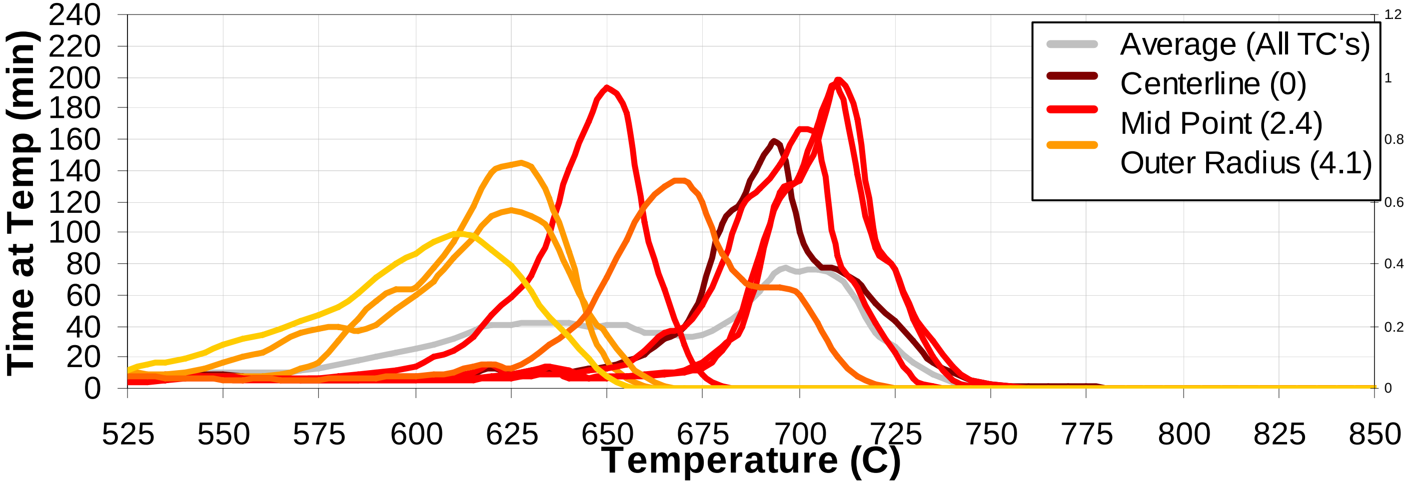
LNT Time-at-Temperature Histograms from 150-cycle test show large spatial variation within the LNT:

each thermocouple measurement from all 150 cycles included (approx 500,000 data points)



- Conclusion: temperature distribution improvements are required to reach the next level of desulfation performance
- Design improvements were made to reduce spatial temperature distribution
    - Insulation, mixing, dosing, etc.

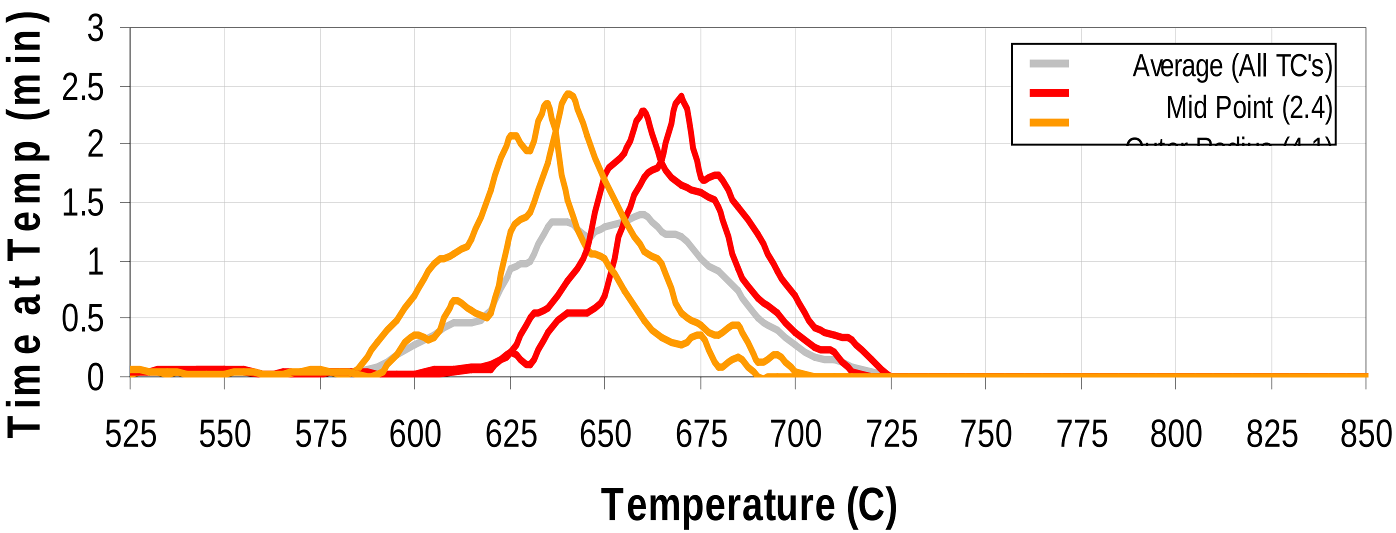
Temperature variability can be improved via design improvements:



BEFORE TEMPERATURE IMPROVEMENTS

peak-to-peak Δ= 100C

(from 150 cycle test)



AFTER TEMPERATURE IMPROVEMENTS

peak-to-peak Δ=40C

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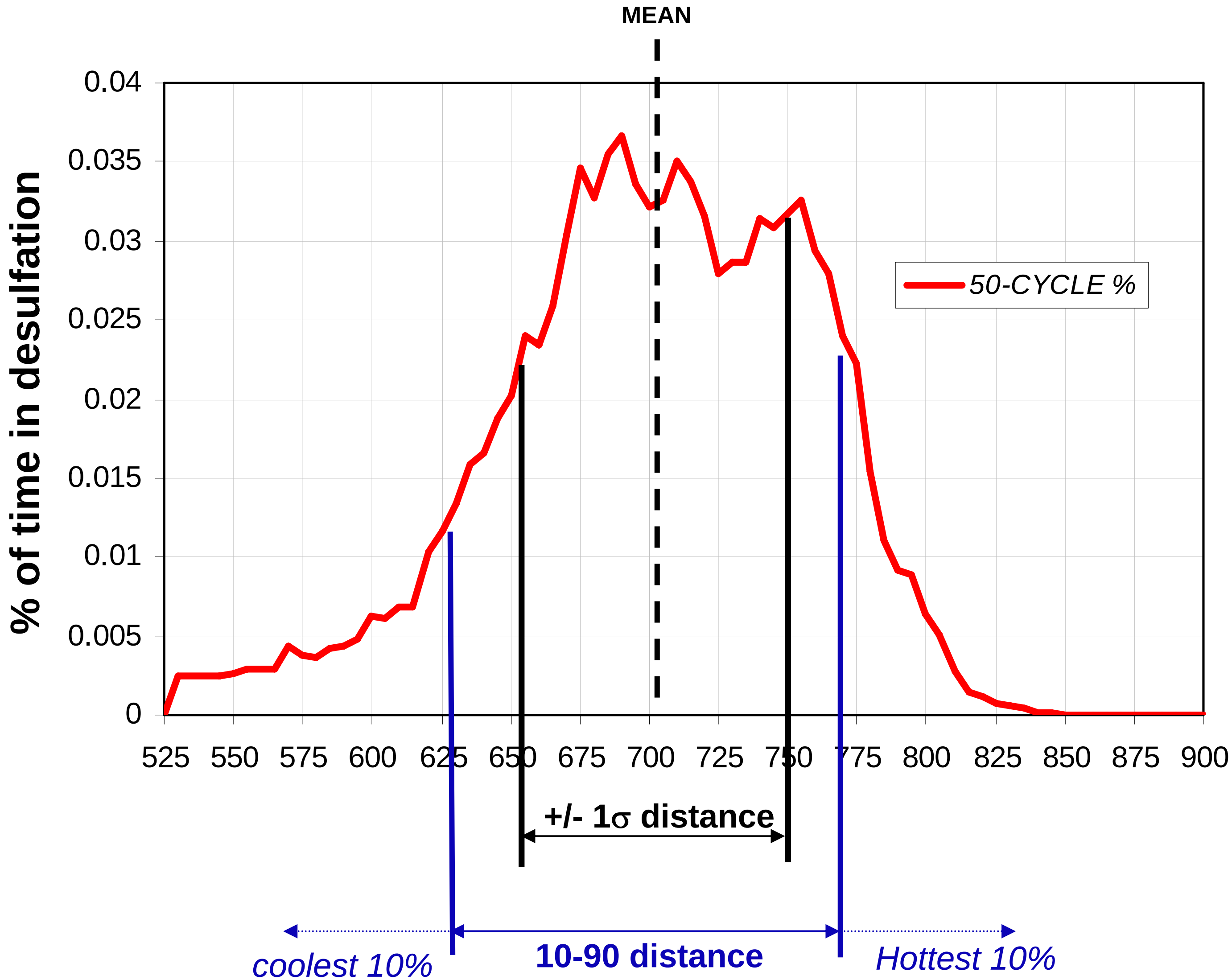
Process Metrics can be used to quantify improvements over time:



+/- 1σ distance:
Temperature range covering the middle 63.2% of all LNT exposure

10-90 distance:
Temperature Range covering the middle 80% of all LNT exposure

To be defined:
High-temperature sintering limit, and low-temperature sulfur removal floor for a given catalyst formulation

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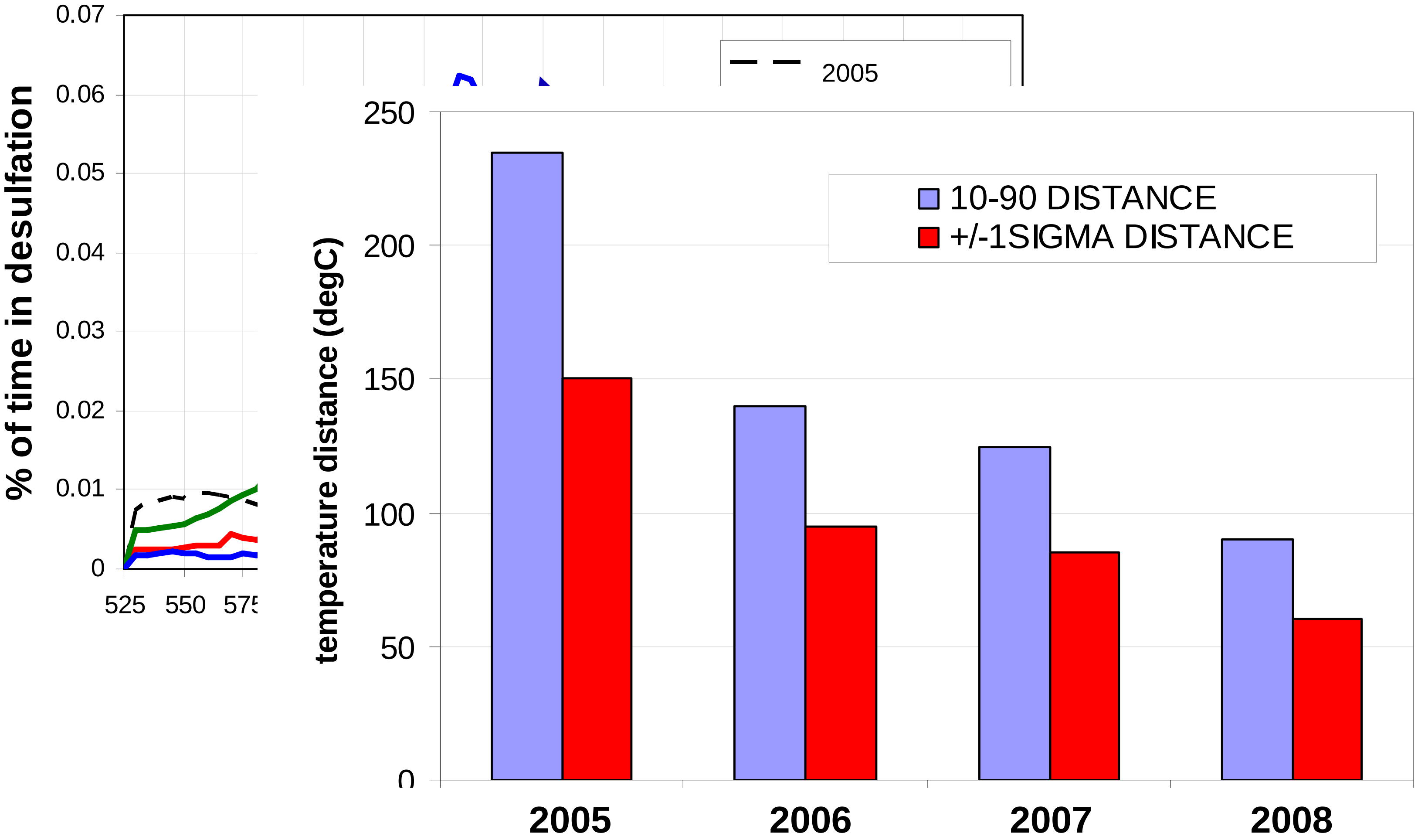
Process Metrics can be used to quantify improvements over time:



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Development of a Bench Aging Protocol: LNT Catalyst

- System performance is feasible for 2010 / tier-4b application
  - LNT still limited by traditional barrier of high-load NTE
  - Incremental next-steps needed to meet EPA at end-of-life condition

- Critical Parameter: Temperature Variability in Desulfation Process
  - Spatial temperature distribution identified as a problem in 150-cycle test
  - +/- 1σ interval has been reduced by 60% in last 3 years
    - From ~150C to ~60C

- Current LNT Oven-Aging Process:
  - 750C oven temperature
  - 10% steam
  - 50 hours exposure

- Open Questions
  - What is the impact of rich-time variation on desulfation effectiveness?
  - How can we decipher the impact of different physical effects?
    - Effect of residual stored sulfur after desulfation?
    - PGM sintering?
  - Is lean-rich cycling required in bench aging process?