Development of a NOx Adsorber System for Dodge Ram 2007 Heavy Duty Pickup Truck

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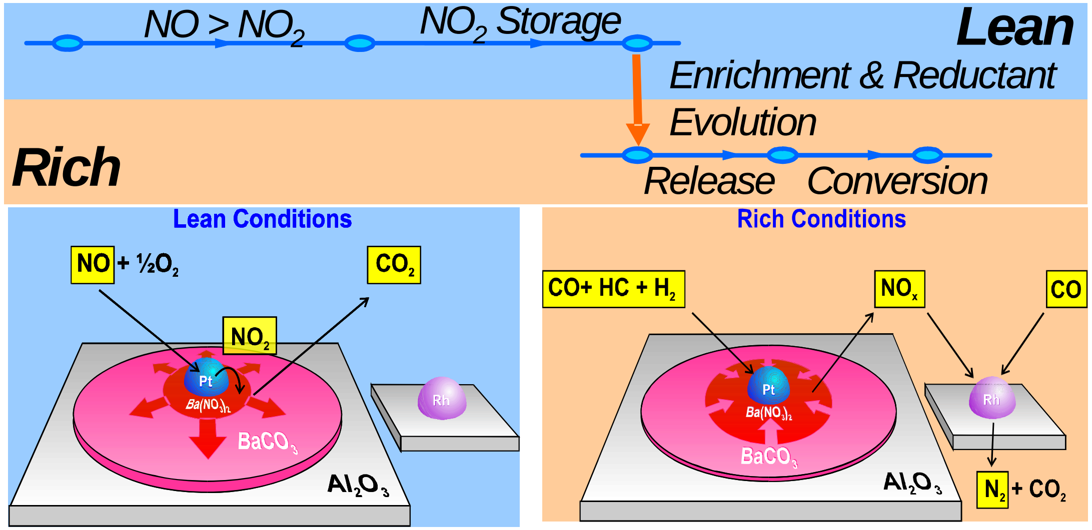
NOx Adsorber Technology

- Identified by the EPA 2007/2010 rulemaking process as a primary candidate for NOx emissions reduction
  - Major advancements in the *fundamental understanding* and *application* of the technology were required
- Fundamental challenges[1]:
  - Multi-component, multi-functional catalyst:
    - At least 3 components, with different functions
    - Both red-ox and acid-base catalyst chemistry
  - 5 sequentially-coupled process
  - Sulfur poisoning/removal



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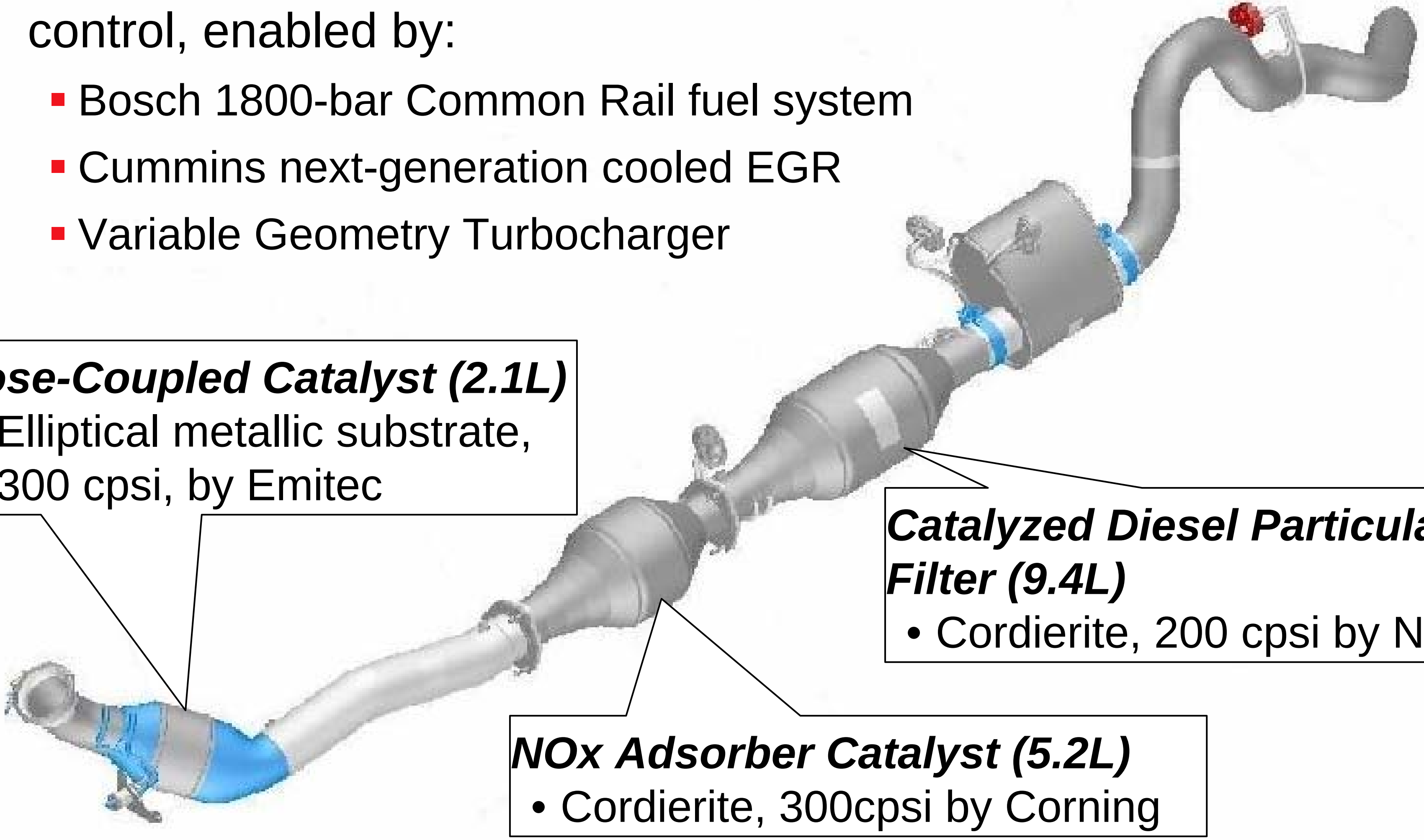
[1] Epling, Yezerets, Currier et al. "*Overview of the Fundamental Reactions and Degradation Mechanisms of NOx Storage/ Reduction Catalysts*". **Catalysis Reviews**; V46(2004), p.163-245

LEV II-ULEV Certified System with Cummins 6.7L Engine and A/T System

- In-cylinder source of reductants and heat for A/T system control, enabled by:
  - Bosch 1800-bar Common Rail fuel system
  - Cummins next-generation cooled EGR
  - Variable Geometry Turbocharger



Close-Coupled Catalyst (2.1L)
- Elliptical metallic substrate, 300 cpsi, by Emitec

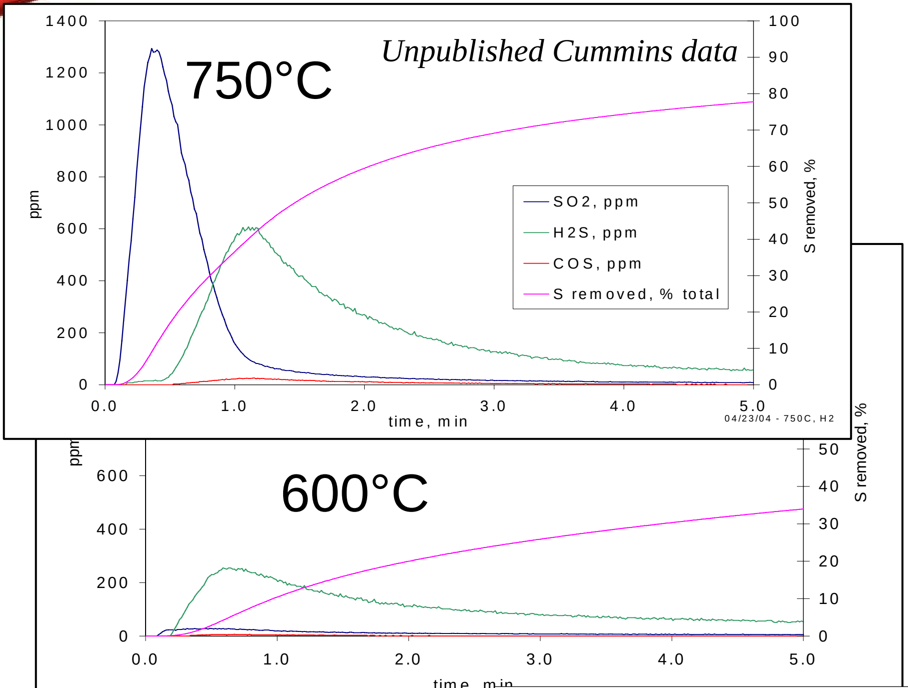
Catalyzed Diesel Particulate Filter (9.4L)
- Cordierite, 200 cpsi by NGK

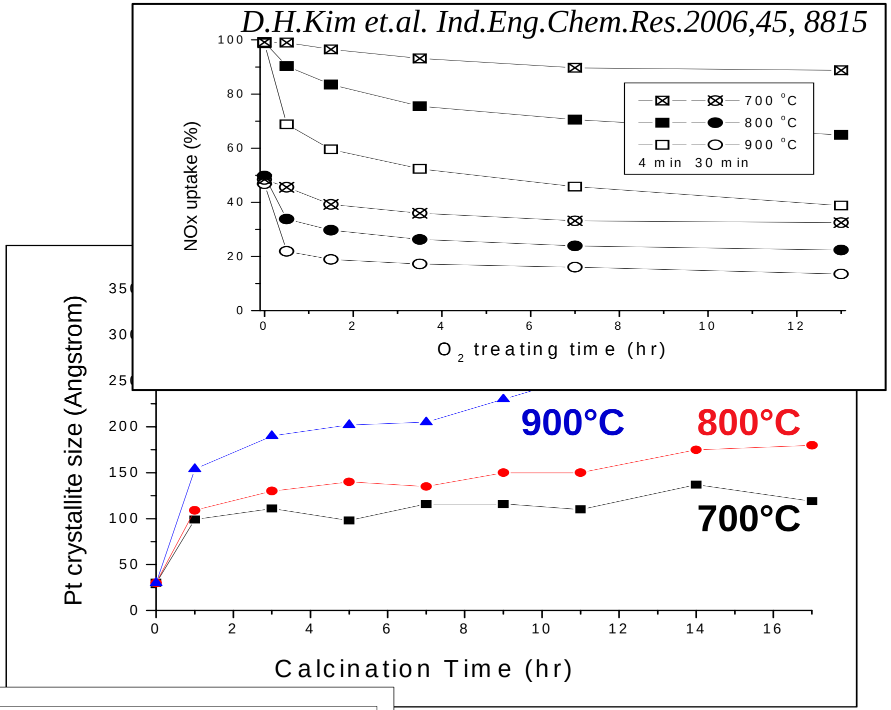
NOx Adsorber Catalyst (5.2L)
- Cordierite, 300cpsi by Corning

Several Major Application Challenges

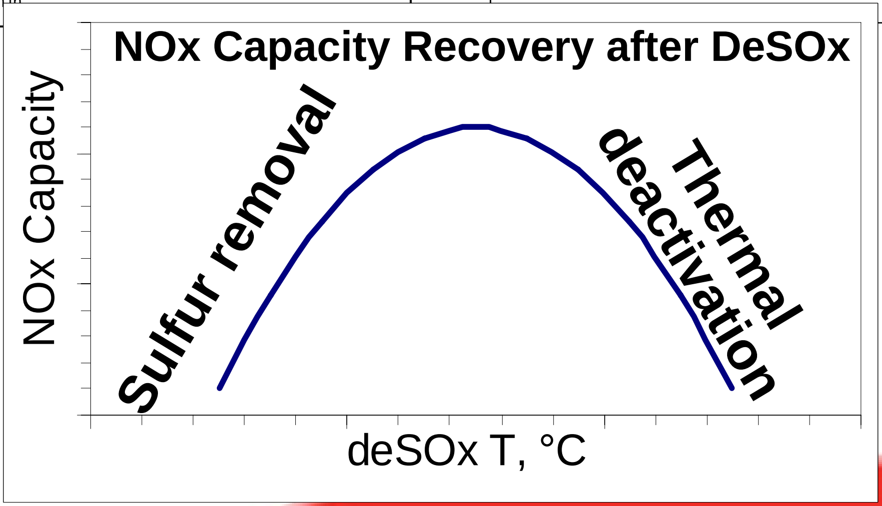
- How to make NAC survive deSOx-related aging?
  - Trade-off between deSOx efficiency and thermal degradation
  - Different forms of sulfur
  - Reductant quality
  - Distribution of temperature and species across the catalyst
- How to achieve maximum deNOx performance for a catalyst of a given age?
- Catalyst diagnostics
  - Laboratory and on-board

Tradeoff Between deSOx Efficiency and Thermal Deactivation





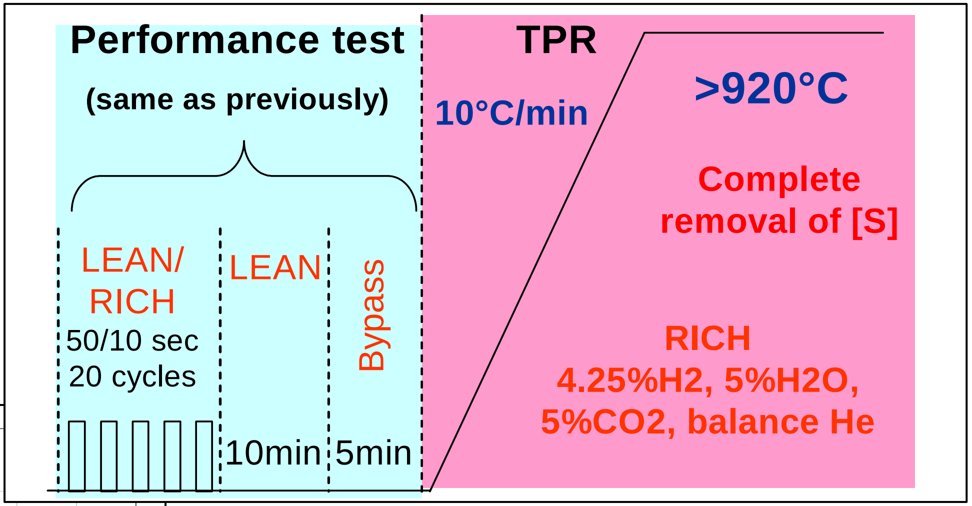
Comprehensive kinetic deSOx model developed by Cummins

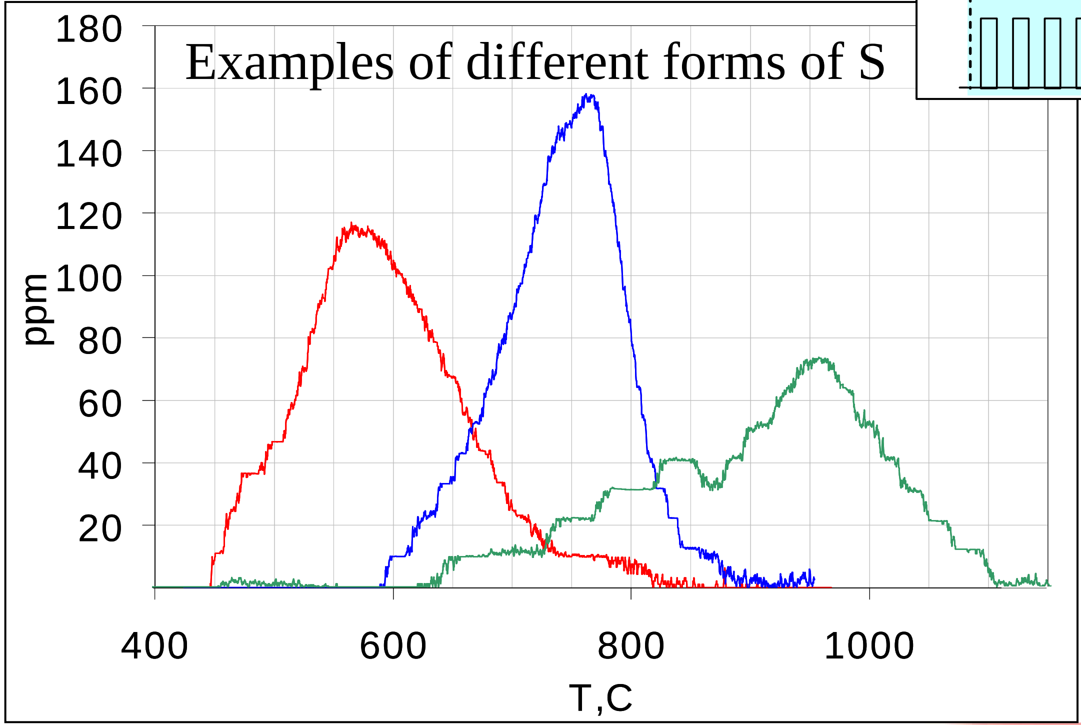


DeSOx-related degradation understanding from PNNL/ Cummins/ JM CRADA

Different Forms of Sulfur

- S can exist on NOx adsorber catalyst in different forms
  - Chemically uniform (sulfate)
  - Morphologically different (surface/bulk)

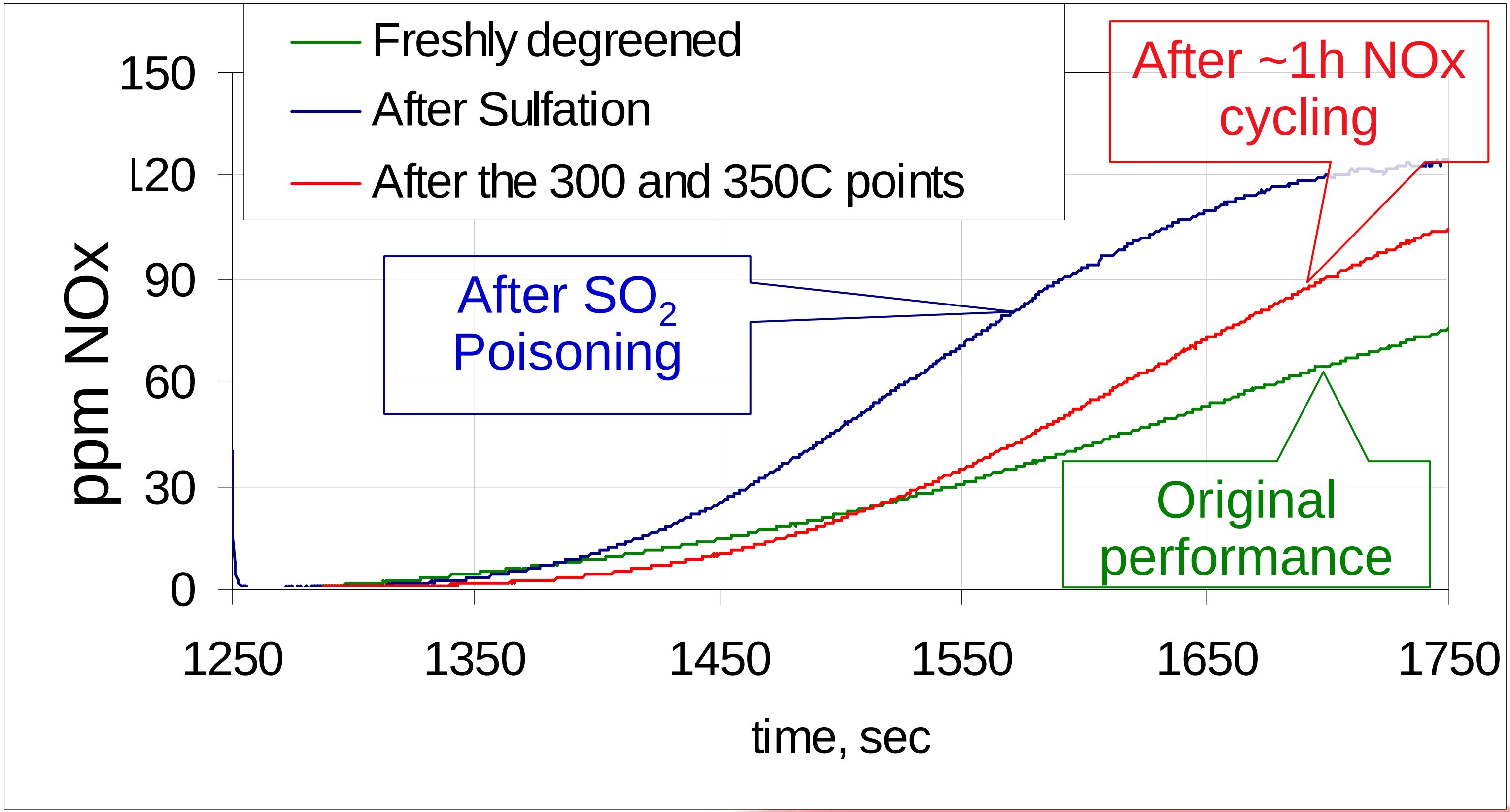



Examples of different forms of S

- [S] form depends on the formation conditions
  - Can be affected by subsequent re-distribution
- Different forms of [S] have different impact on NOx performance

Example: NOx Adsorber *"Memory"*

- Sulfated a "Degreened" LNT, Lost ~1/3 of NOx capacity
- Apparent re-distribution of sulfur after ~1 hour normal NOx operation in the 300-400°C range
    - No sulfur loss confirmed by subsequent temperature-programmed reduction

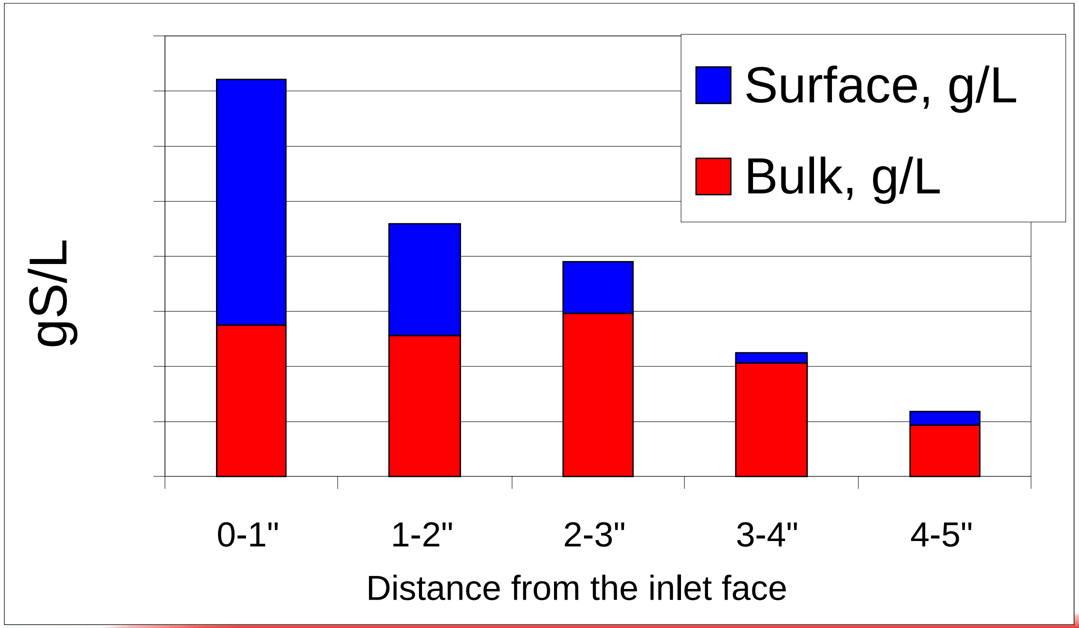


Different Forms of Sulfur/ Distribution Across catalyst

- Important to distinguish between forms of sulfur
  - No reason to attempt removing “bulk” sulfur –
    - Additional thermal exposure
    - Minimal advantage for the “dynamic” NOX capacity
- Inherently non-homogeneous species distribution in an integral device

Micro-core analysis:

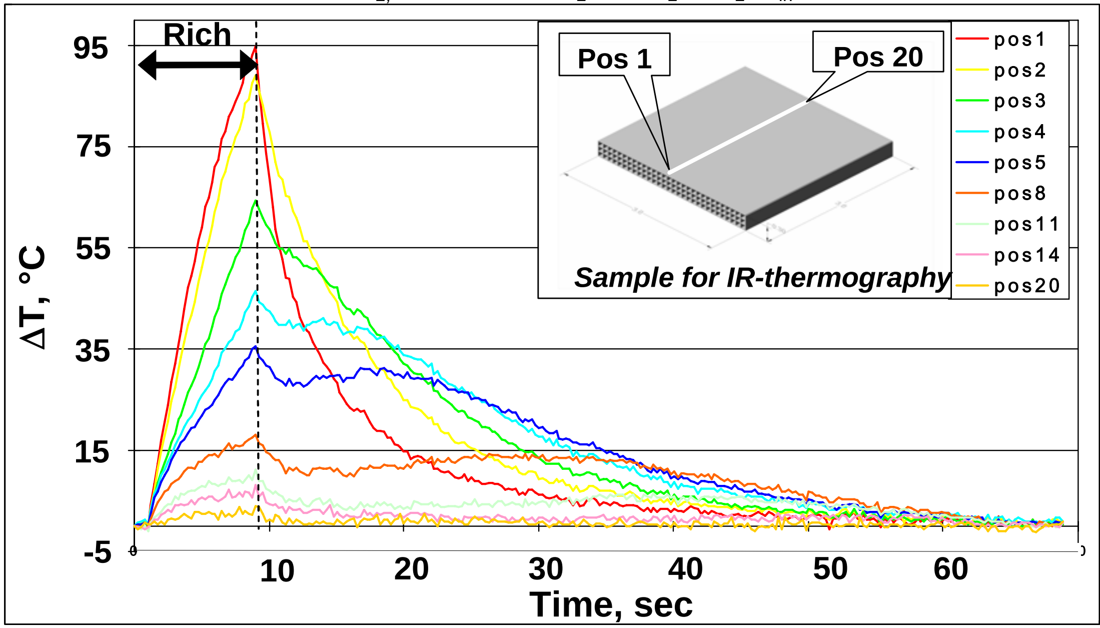
- *minimally invasive (<1cm³ sample)*
- *NOx performance, [S] amount and form*
- *multiple locations in the catalyst*



Importance of Spatially-Resolved Measurements

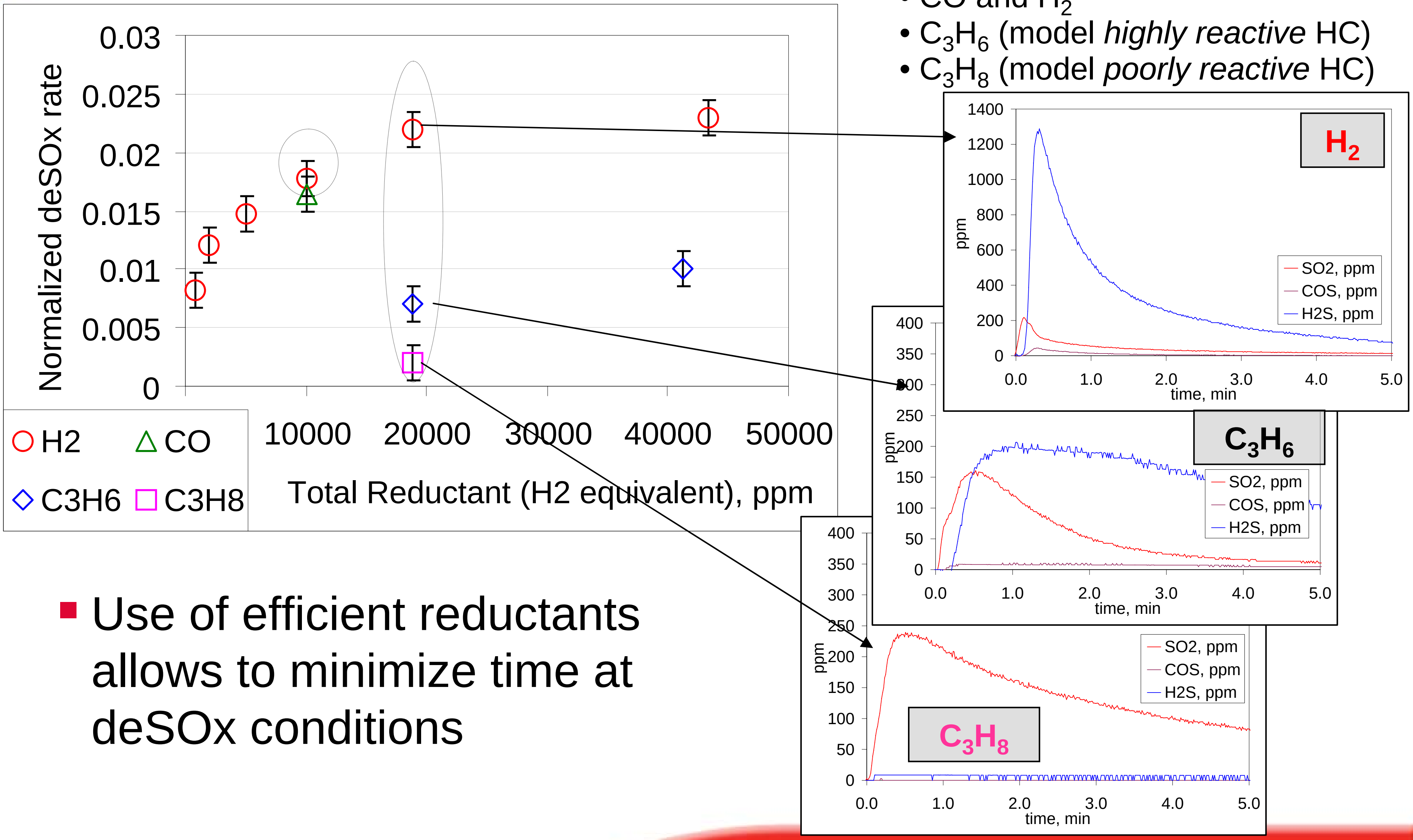
- Gradients in integral devices
  - Gas species
  - Temperature
  - Surface species
- Pioneering role of NTRC(FEERC)/Cummins CRADA
  - SPACI-MS
  - P-Thermography
- Additional work sponsored by Cummins at U. Waterloo
  - IR thermography
  - SpaRC

Rich: *2% O_2, 4%CO, 5%CO_2, 5% H_2O, N_2,* T_{in}*=300°C*



Reductant Quality

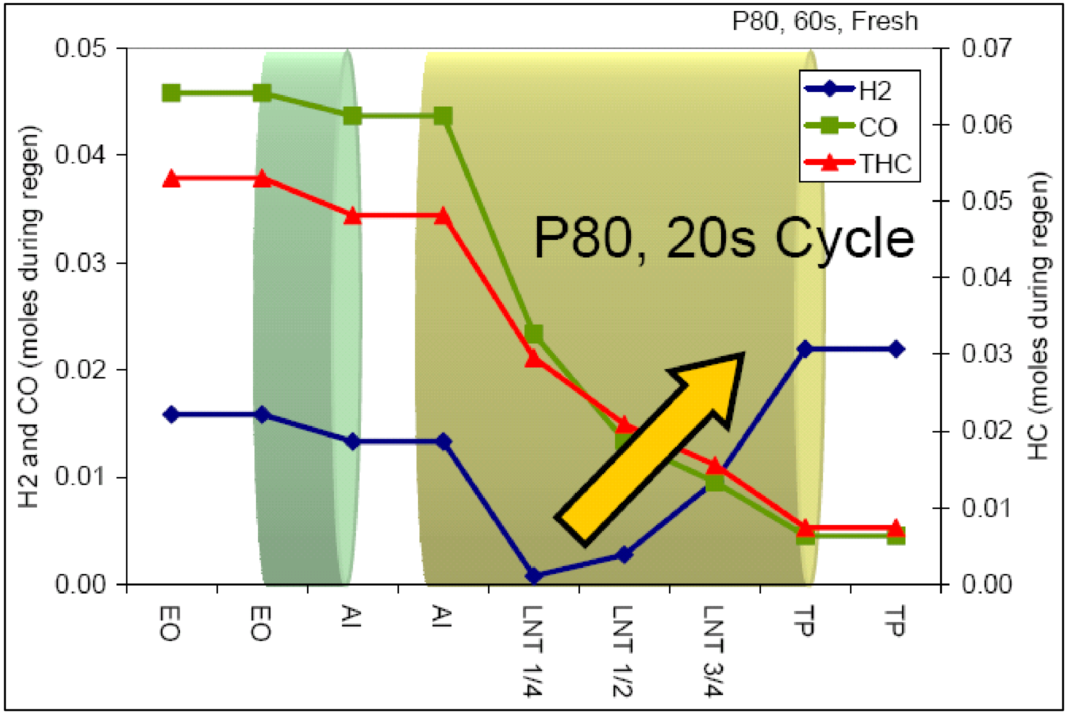
- CO and H_2
- C_3H_6 (model *highly reactive* HC)
- C_3H_8 (model *poorly reactive* HC)



- Use of efficient reductants allows to minimize time at deSOx conditions

Reductant Quality

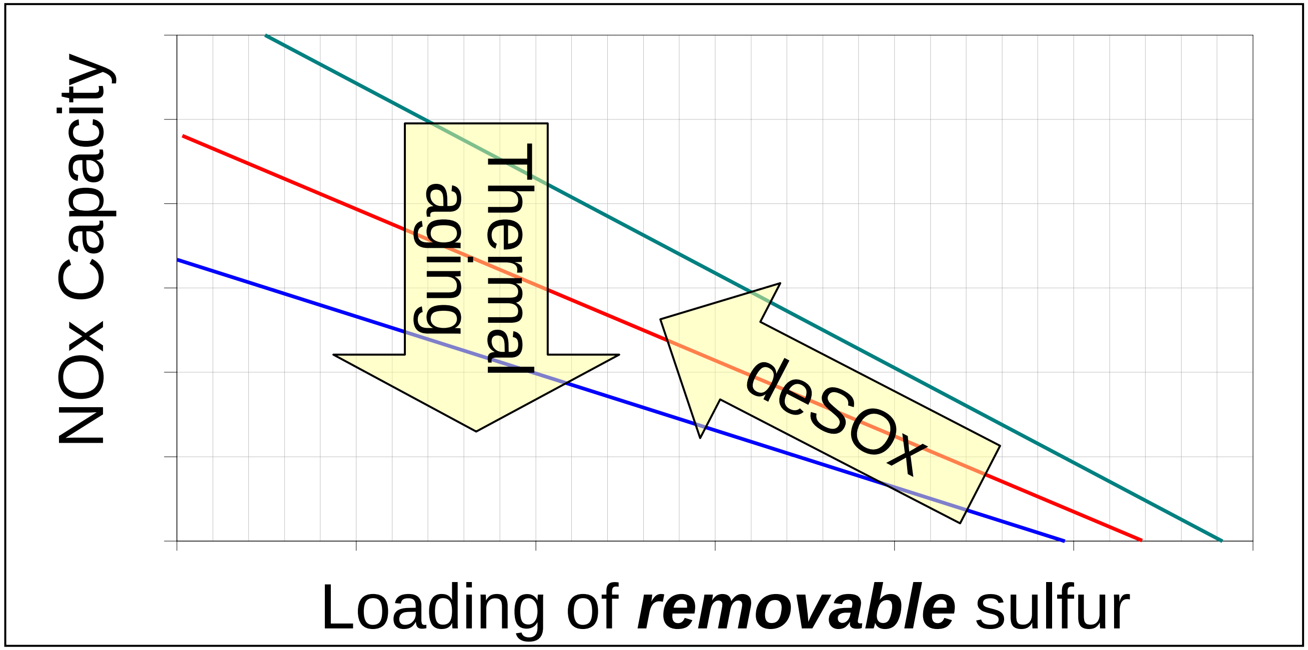
- *In-situ* H_2 generation may play a major role in deSOx (and deNOx) efficiency
  - Complex spatial profile
  - Balance in-cylinder and in-situ H_2 generation options



J.Parks, M.Swartz, S.Huff, B.West. FEERC/ORNL. DEER 2006, August 20-24, 2006, Detroit, MI

Summary: Balancing Sulfur Removal vs. Thermal Deactivation

- Minimize excessive temperature exposure
  - Accurate control of deSOx temperature
  - Minimize temperature gradients across the NAC
  - Optimize reductant quality
  - Target only relevant forms of sulfur
  - Capable laboratory diagnostic tools



Summary

- Understanding the complexity of the system components (catalysts, sensors) during the design stage allows to develop robust, apparently simple solutions:
    - In the final product, complexity is reflected in the controls and diagnostics
- Significant opportunities remain for further system optimization, e.g.:
    - Better understanding of the fundamentals of the components behavior (catalysts, sensors), including development of predictive models, would allow for tighter integration
    - Laboratory and on-board diagnostics

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