Complex Behavior In Heavy-Duty Urea SCR

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Fourth CLEERS Workshop

April 30th, 2002

Past Project: (near) Zero Regulated Emissions Powertrain (ZRE)

Targeting HD-FTP 2007+ Standards Using a Low-Emissions Diesel Powertrain with SCR/CRT Aftertreatment

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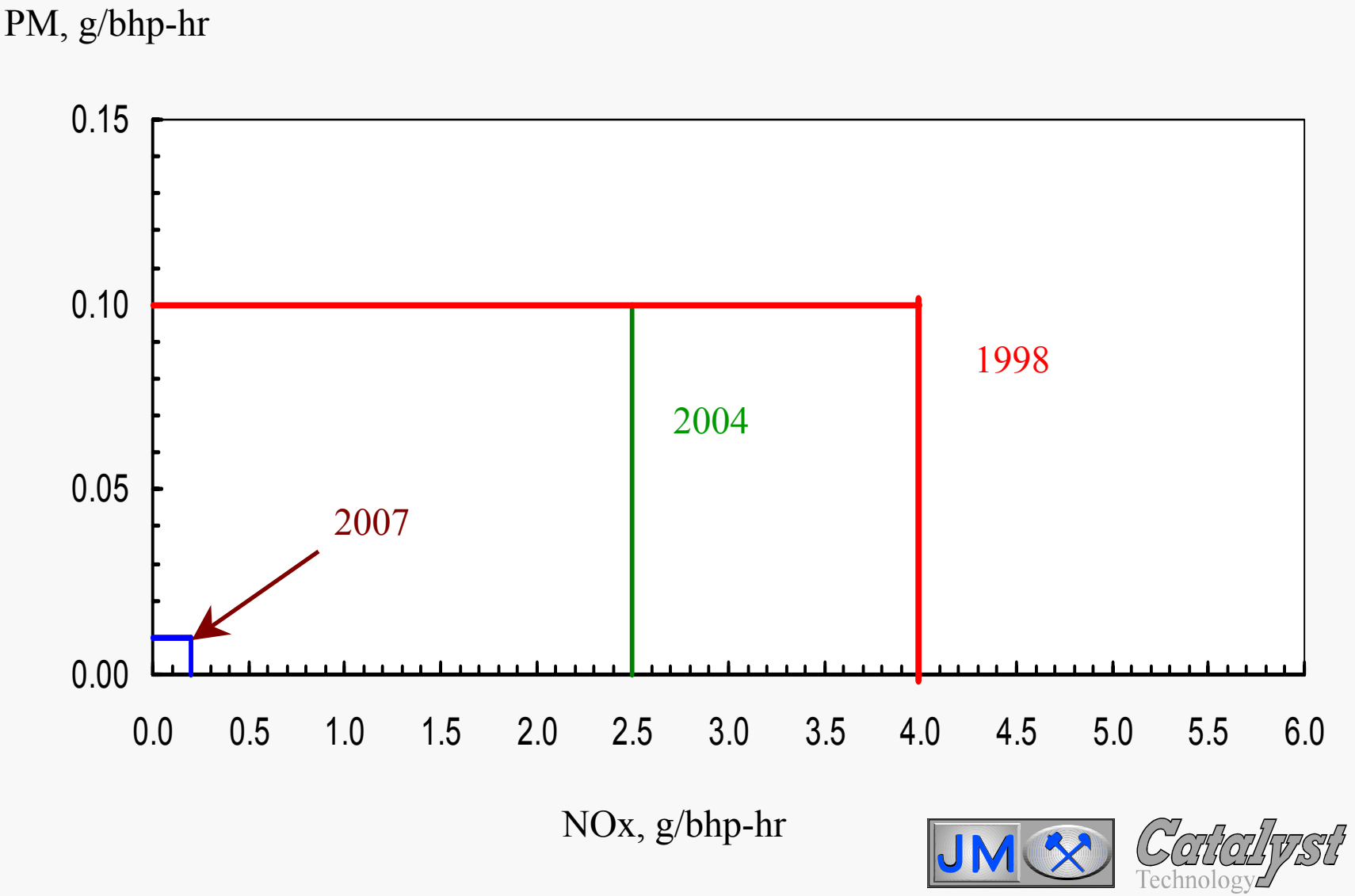
US Heavy Duty Diesel Emission Standards



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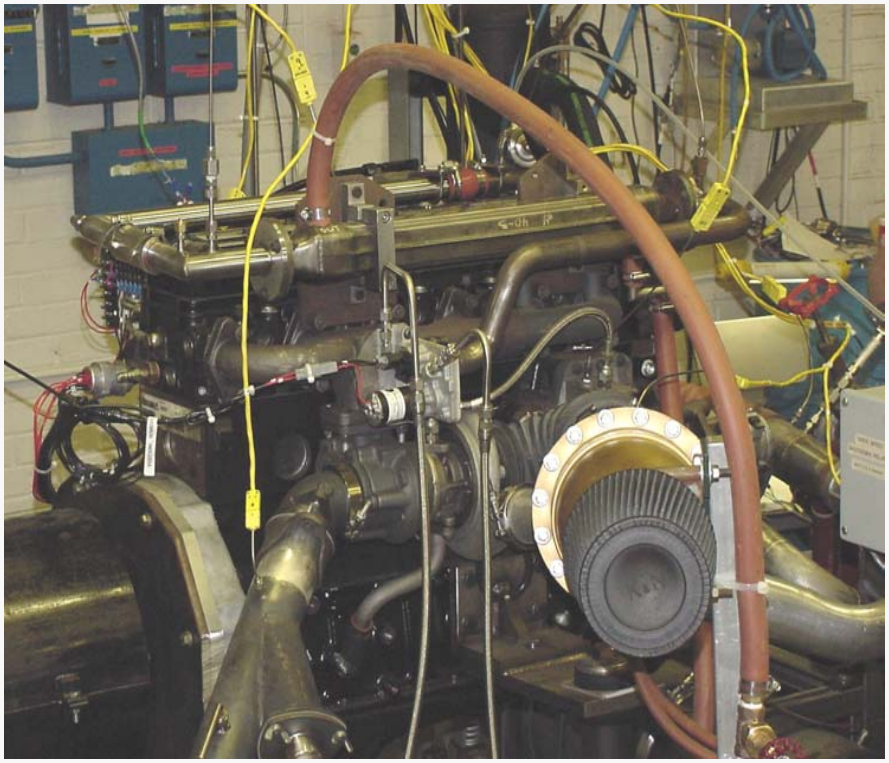
Objectives of the ZRE Project

- Evaluate, stimulate progress of “stretch” emission control technology (2007-2010)
- Show plausible pathway for low-emission HD diesel powertrain
- Provide data from an integrated system: engine technology, advanced fuel, aftertreatment. System optimization is important
- Reveal technical challenges, issues, barriers

We needed to develop a system that was: “Aggressive,” obtainable, fit schedule and budget, meshes well with other projects

The Current Experimental ZRE Powertrain



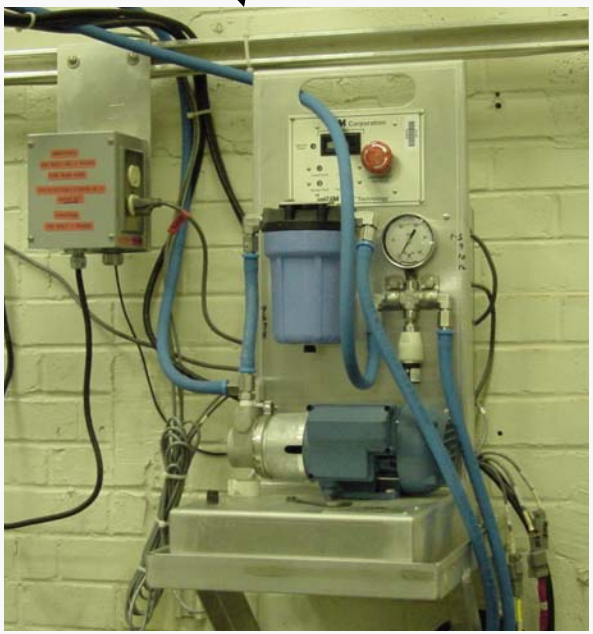
- Cummins ISB with cooled EGR, new fuel system, cooled turbo., ECU. De-rated from 215 hp to 175 hp.
- Separate EGR valve control to over-ride ECU command.
- DECSE 3 ppm sulfur diesel fuel
- Continuously Regenerated PM Trap
- Urea injection system and (~18 L) SCR catalyst
- No separate oxidation catalysts

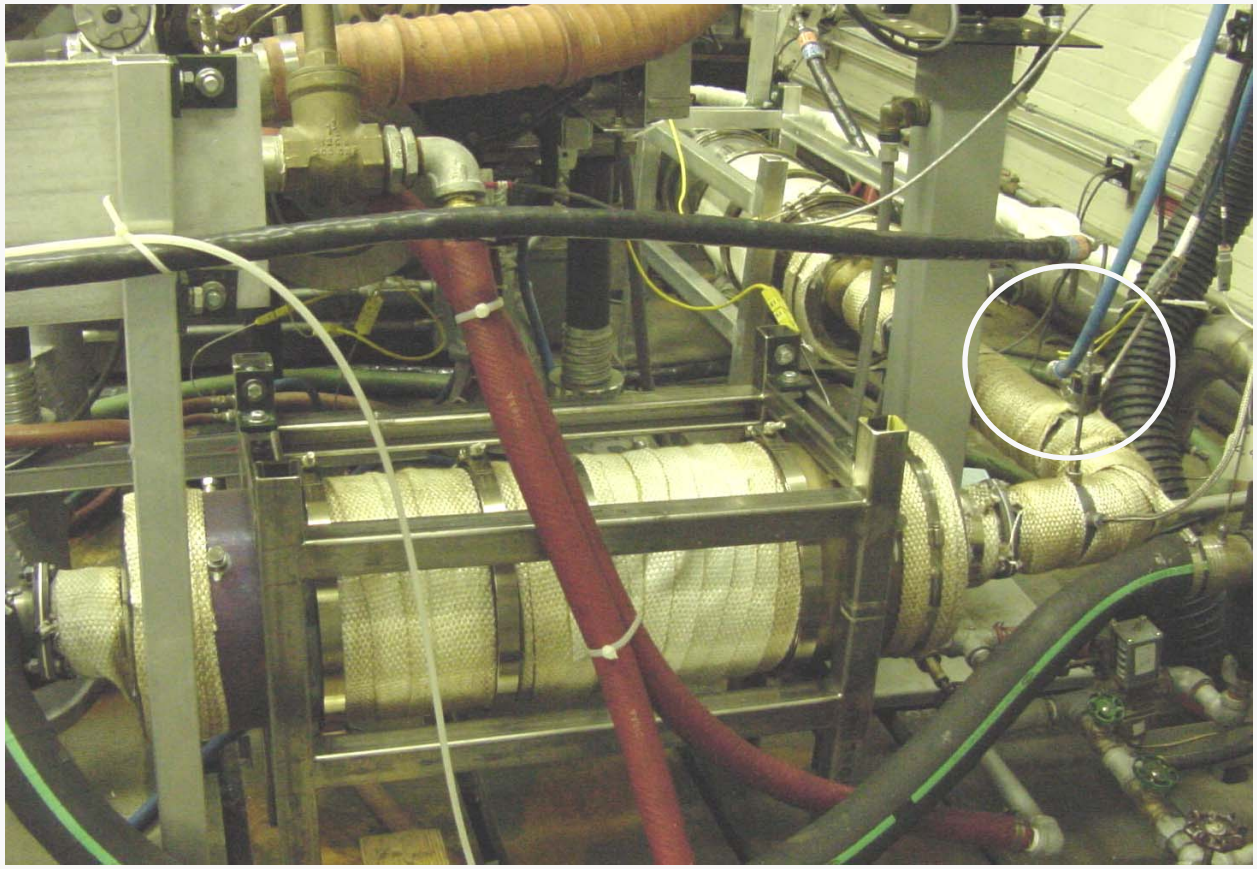
Instrumentation: HC, CO, CO_2, NOx analyzers, FTIR, PAS, UV-fast NH_3, mini-dilution tunnel

Engine and Exhaust Aftertreatment

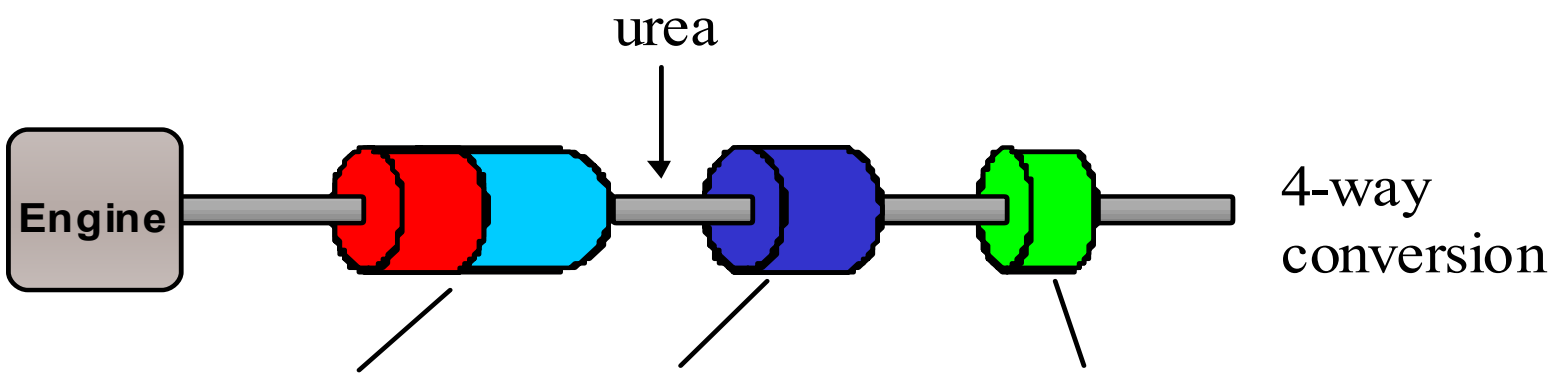
CRT & SCR catalysts

Urea injection system





SCRT™ Configuration



CRT

Removal of
HC, CO, PM

Generate NO2

SCR

Removal of
NOx

Oxidation Cat

Removal of
NH_3 slip
if required

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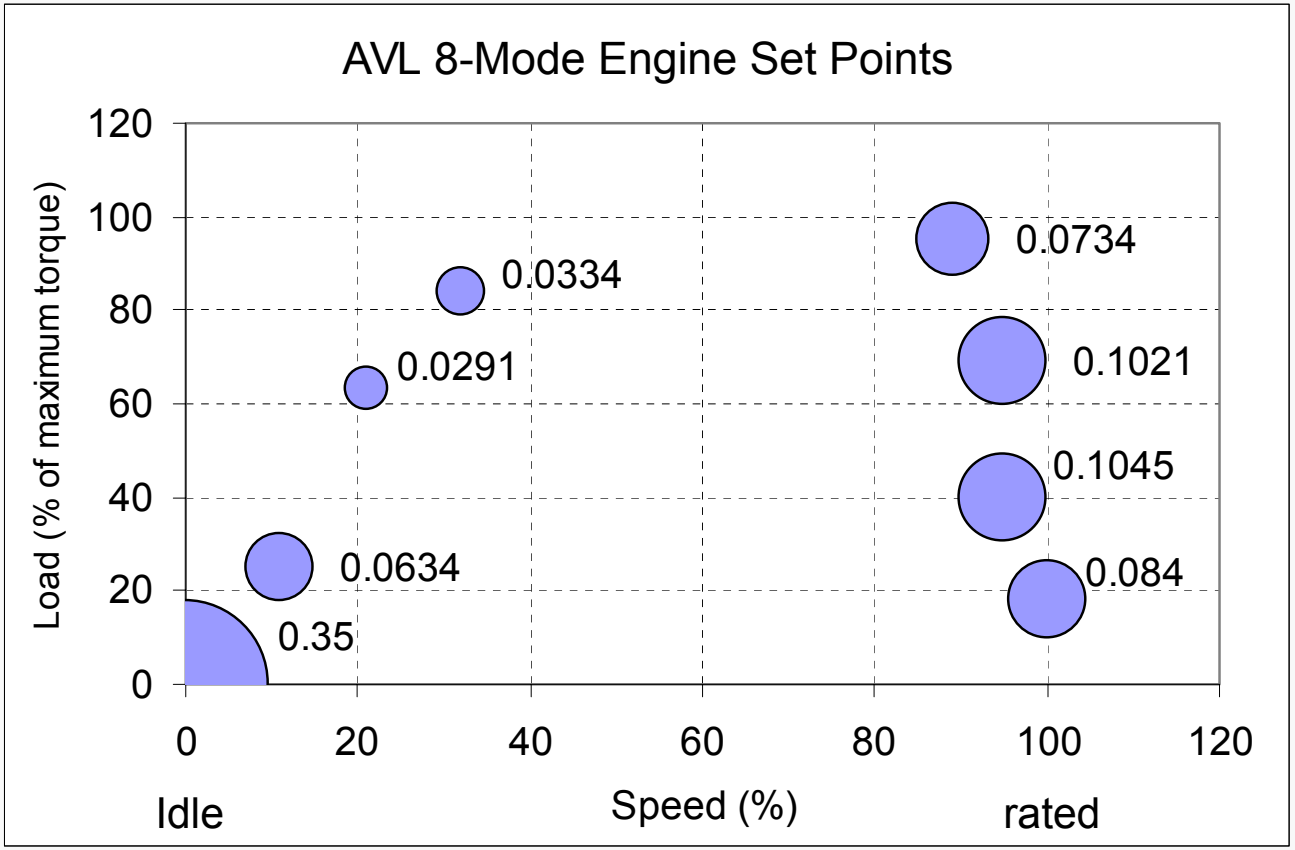
Progress in FY01

- Commercial ISB engine: AVL8-mode tests
- ISB reconfigured: cooled EGR, new fuel system, turbo, ECU. AVL 8-mode testing
- Installation of exhaust aftertreatment system. AVL 8-mode tests and special experiments
- Analysis & interpretation of results: regulated and unregulated emissions

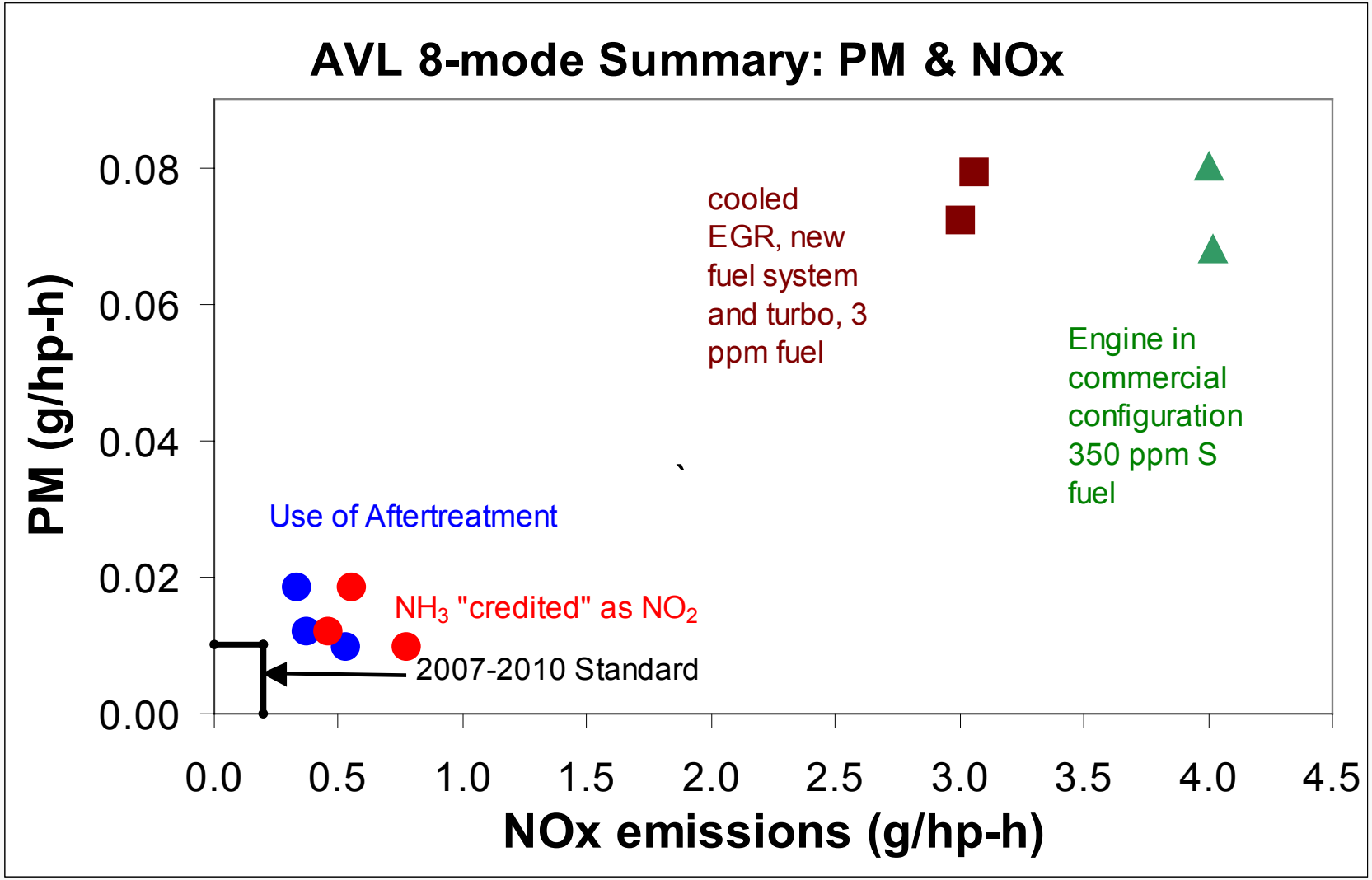
The AVL 8-Mode Test Uses 8 Steady Conditions and Weighting Factors to Estimate Results for the (transient) HD-FTP



0% speed = idle, 100% speed = rated speed

Results Indicate Significant Progress Toward The 2007 HD Target

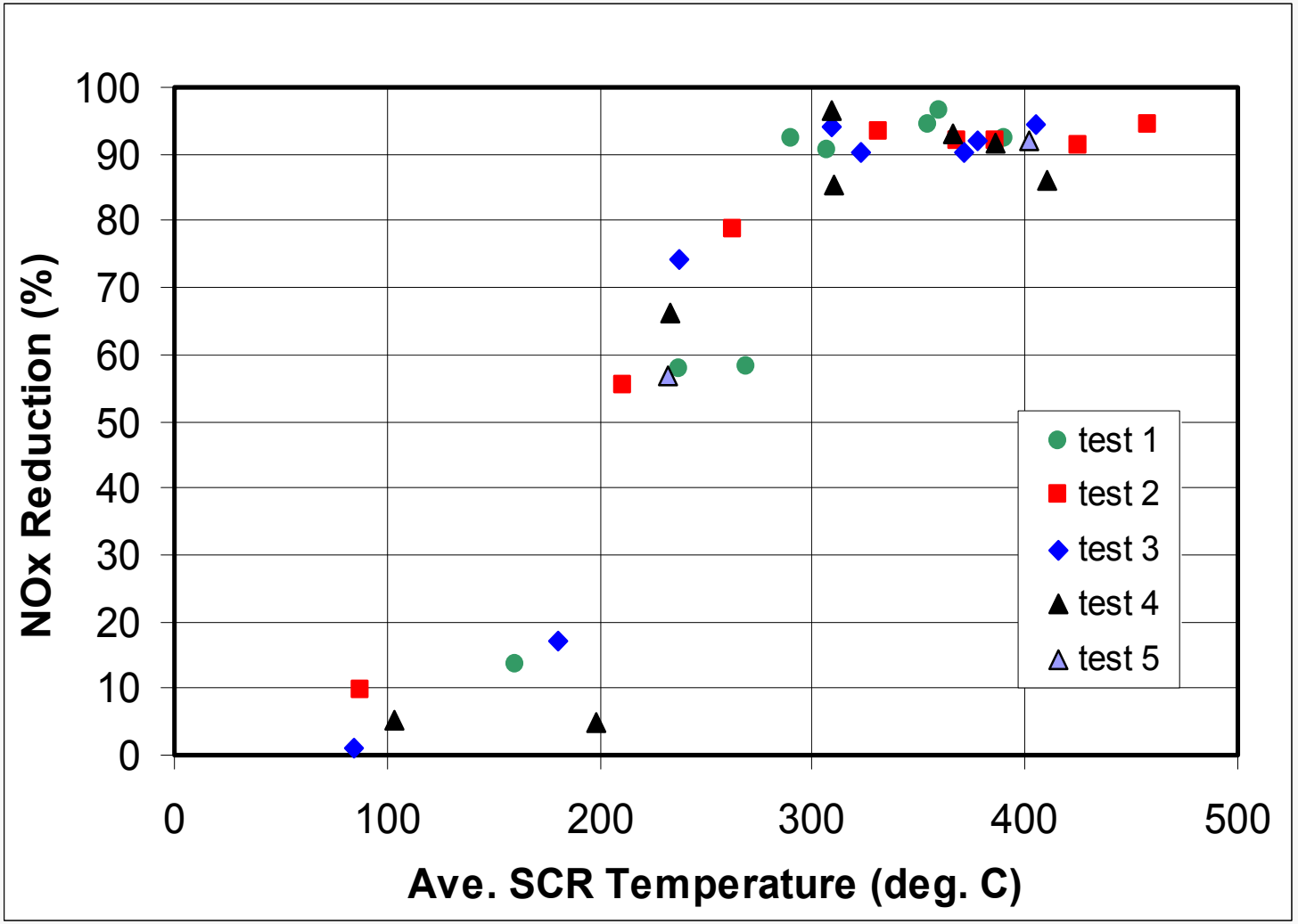
Reaching the Target is Quite Ambitious, Especially for NOx



Significant Reductions in NOx & PM Have Been Demonstrated With Exhaust Aftertreatment

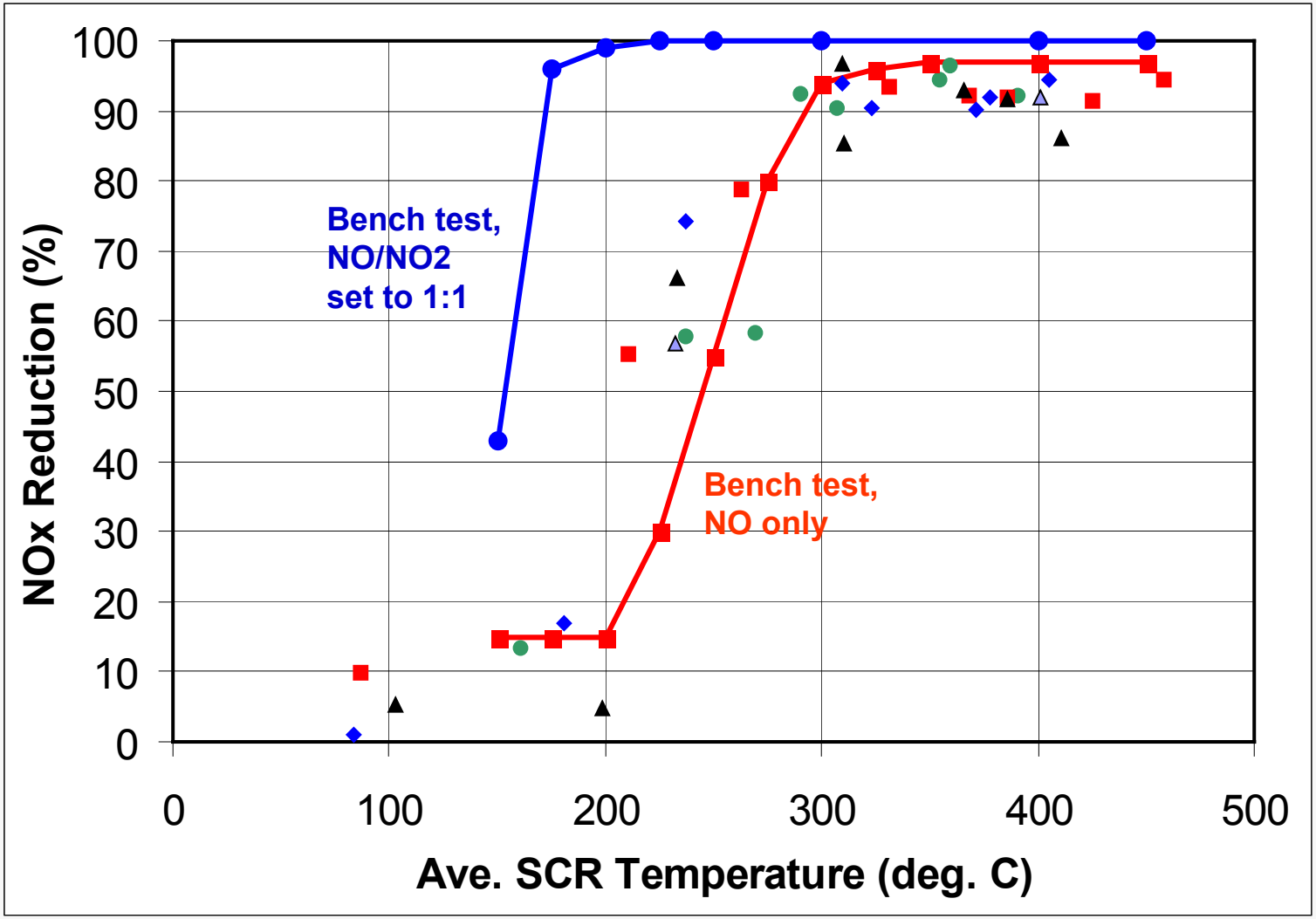
- Cummins engine, commercial configuration, 350 ppm S diesel fuel: 4 g/hp-h NOx & 0.08 g/hp-h PM
- Add cooled EGR, new fuel system, turbo., ECU, 3 ppm S DESCE fuel: 3.0 g/hp-h NOx, no increase in PM
- Add CRT, urea-injection & SCR, careful "dial in" of urea injection, add EGR on 2 modes (over-ride ECU):
  - 0.34-0.53 g/hp-h NOx, 0.01-.02 g/hp-h PM,
  - Engine out NOx ~ 2.5 g/hp-h,
  - Some PM appears to be urea-based,
  - CO < 0.9 g/hp-h, HC < .03 g/hp-h.

Results From AVL 8-Mode Tests Show the Importance of Temperature on the SCR System's Ability to Reduce NOx



NO/NO2 Ratio Is Reported to be Important to Low Temperature Activity

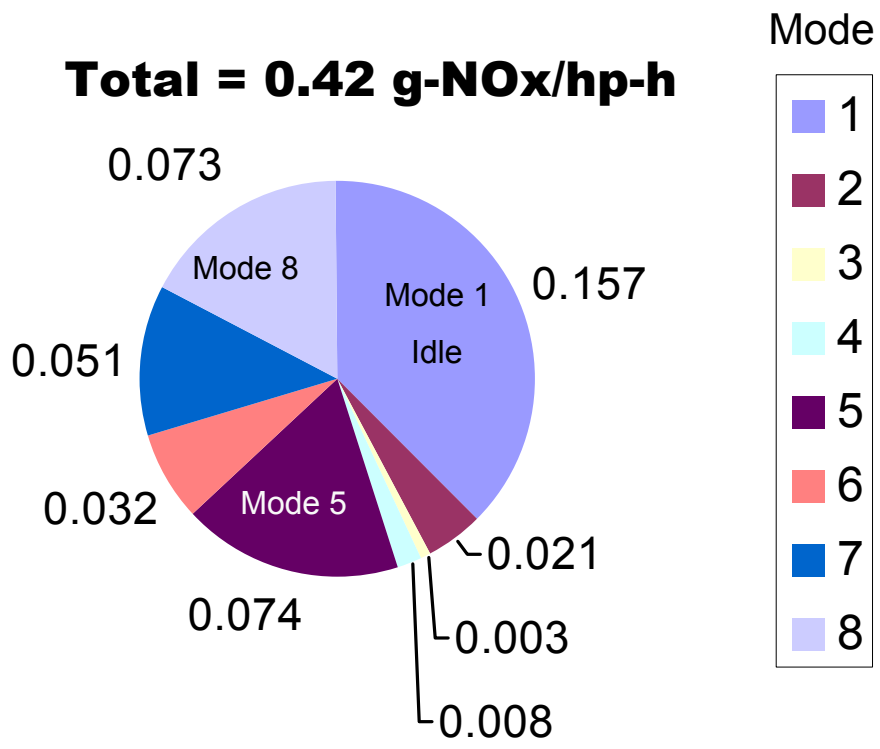
(Chandler et al, SAE 2000-01-0188)



Contribution to NOx Emissions By Mode Reveals the Importance of Idling

Average of 4 AVL 8-Mode tests

Values shown in g-NOx/hp-h

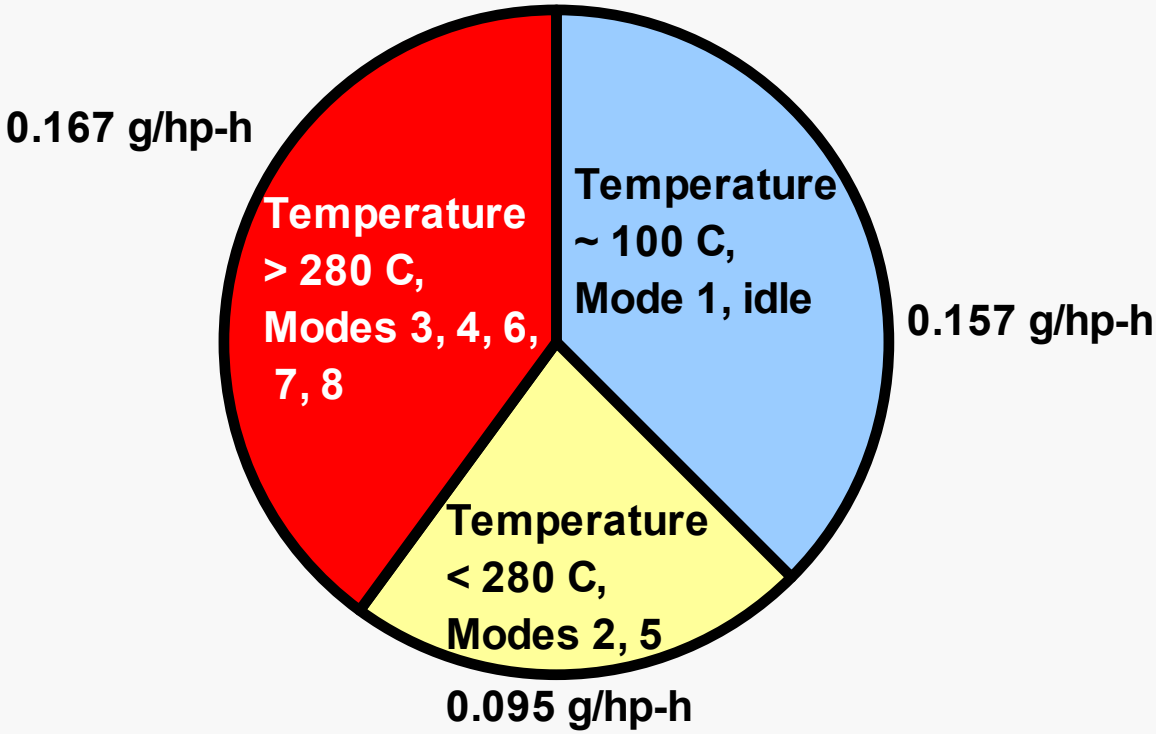


- **Idle NOx alone is > 75% of the 2007+ standard**

NOx Emission Contribution From Low-Load, Low Exhaust Temperature Conditions is Quite Large

Average of 4 AVL 8-Mode tests

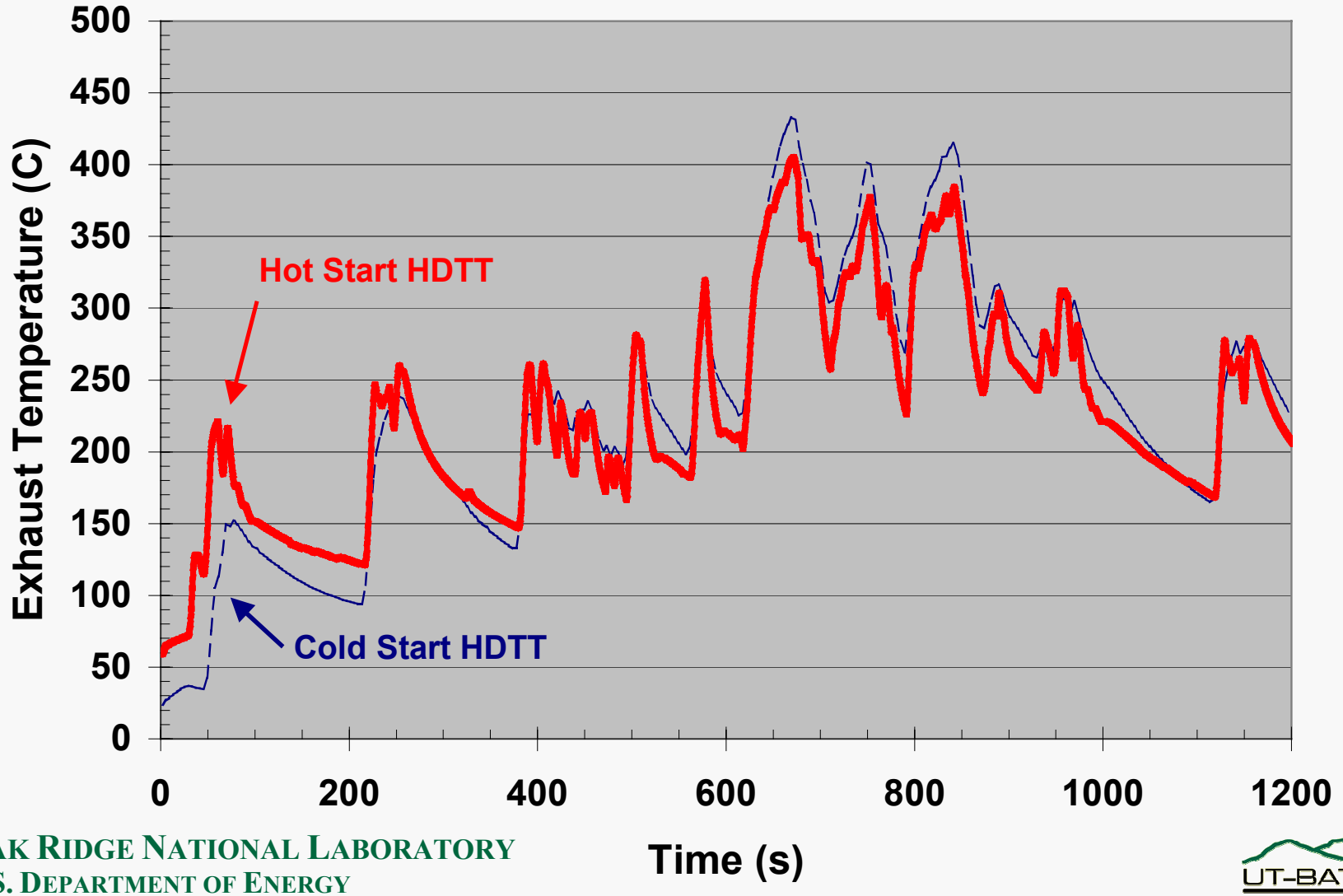
Total = 0.42 g-NOx/hp-h



Low Load NOx Reduction is Essential to Meeting the 2007+ Standard

Considerable portion of heavy-duty transient test has low exhaust temperatures

Source: Schenk et al, EPA, 2001



ZRE Project Observations & Conclusions

- The SCR system reduced NOx > 90% at ~300 C and above, efficiency begins to drop below 300 C, typical of VT cat.
- The HD standard is very challenging. NOx reduction at idle & other low-temperature conditions is critical to success
- Significant NH_3 storage was apparent. Conversion can occur for a significant length of time after injection is terminated
- Need to understand PM formation due to urea injection

Project Observations & Conclusions (cont)

- Reliable N_2O, NH_3, NO, NO_2 measurements are important. The fast UV instrument provides useful information on transients
- N_2O increased significantly during extended idle – presumably generated from the oxy-cat in the CRT
- NO/NO_2 ratio was generally far from optimum
- Advanced engine control is critical to full system integration:
    - SCR temperature control
    - reducing engine out NOx - especially idle

Areas For Progress

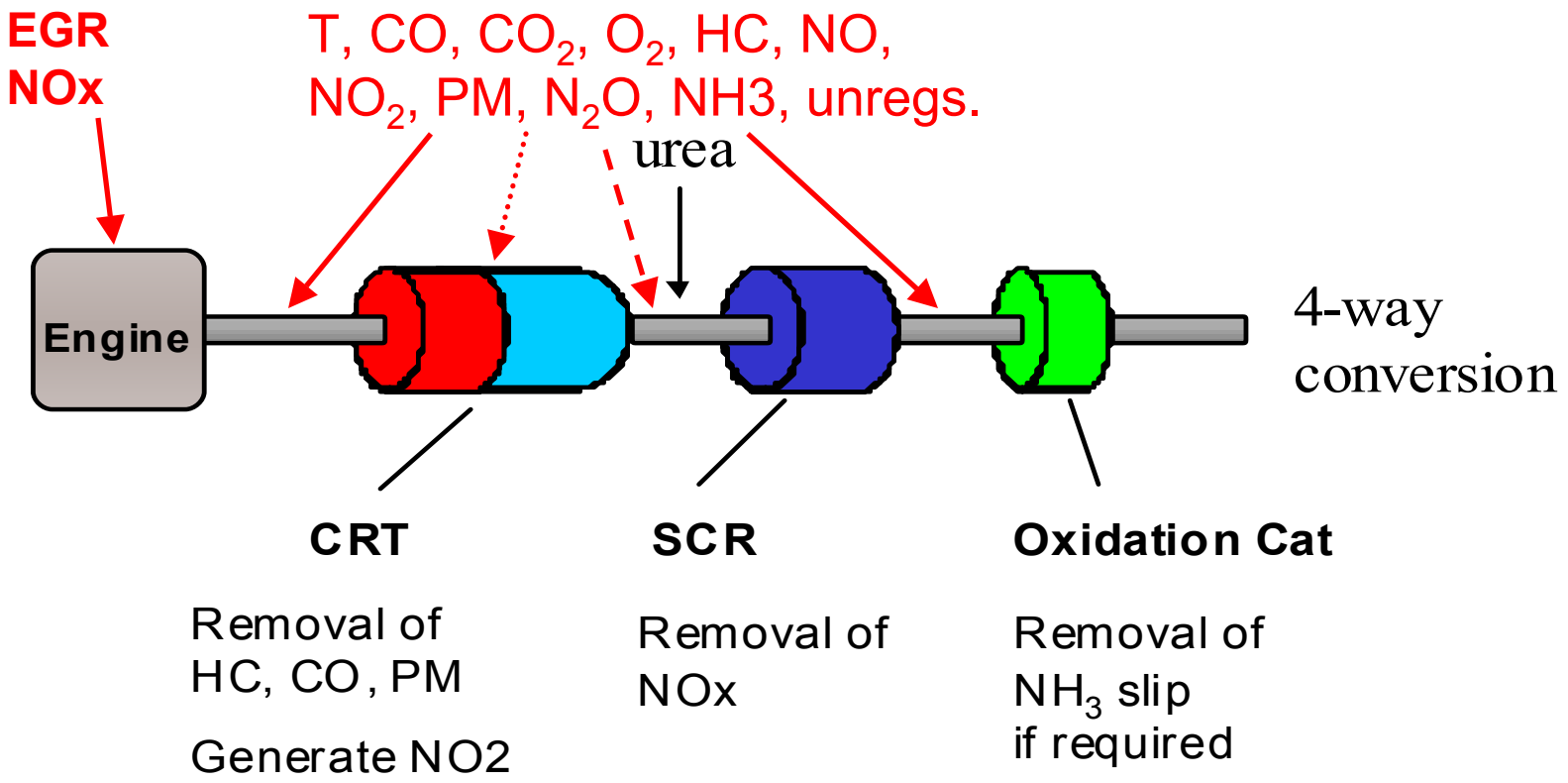
Optimize Integrated System:

- Engine calibration/control to raise temperature at low load
- Reduce Idle, low-load NOx
- NO/NO_2 ratio

- Work with catalyst suppliers for better low-temperature performance
- Investigate full transient performance
- Evaluate PM constituents and unregulated emissions in more detail

The Tested System and Experiments are Complex

SCRT™ Configuration



Typical Test: Measure ~ 20 Temps., 12+ gas analyzers, NOx and O_2 sensors, ~ 10 other sensors

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Models Could Contribute Greatly to Our Understanding

SCR Catalyst:

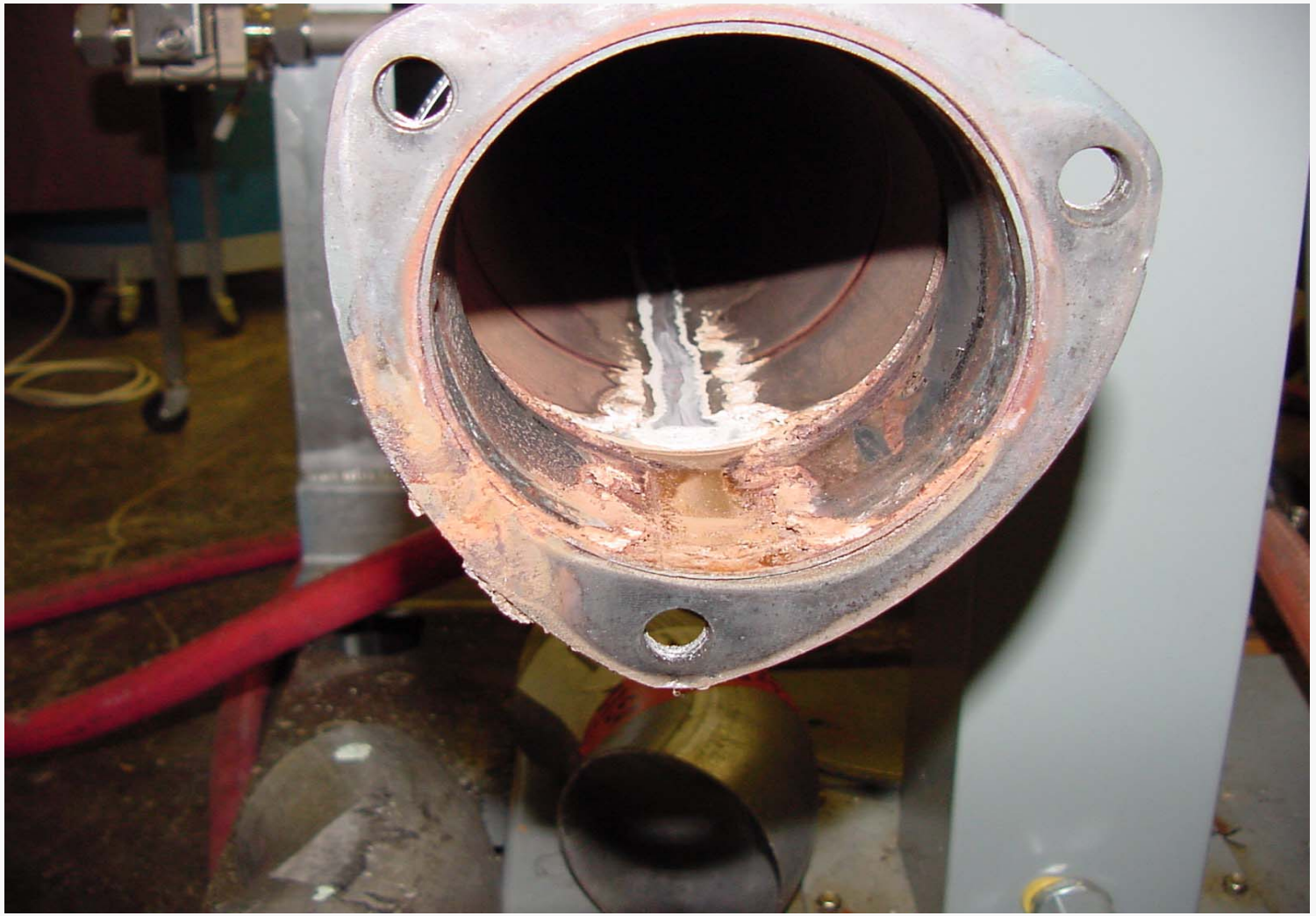
- SCR Cat. activity vs. NO/NO_2 ratio, HC, CO, other species.
- NH_3 storage, release, breakthrough, long time-scale transients
- Thermal models (thermal mass, reaction heating, heat transfer)
- N_2O formation
- Other species, any “odd” chemistry, especially that which “fools” analyzers, or difficult to detect

Models Could Contribute Greatly to Our Understanding

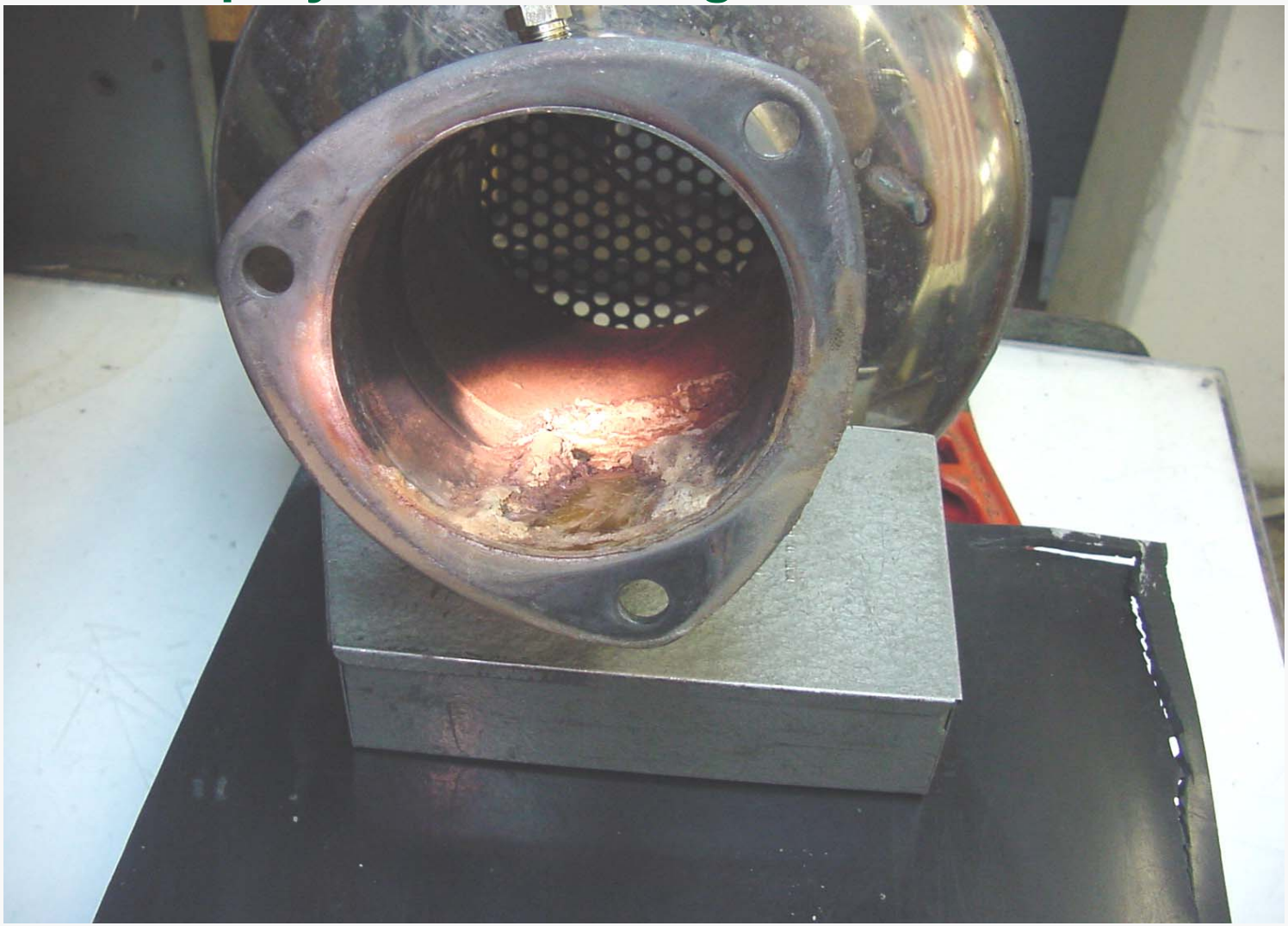
Apart from the SCR Cat.

- Oxidation catalysts – NO to NO_2 shift and other chemistry changes (catalyst type, T). When and where do they help?
- Urea spray model. Vaporization, hydrolysis, deposition, mixing, chemistry
- When would a urea hydrolysis catalyst help?
- PM trap effects on exhaust chemistry – especially if it precedes SCR cat.
- N_2O formation wherever it applies

Salt Deposit 18 Inches From Spray Nozzle Formed During Shakedown Tests



Salt Buildup Near Catalyst Due to Over-spray of Urea During Shakedown Tests



Acknowledgements

We are grateful for the support and guidance of Gurpreet Singh at DOE OTT

We thank Cummins Engine Company for donating the engine, upgrade components and engine technical support

We thank Johnson-Matthey and Jim Thoss for providing the CRT and SCR units and for very useful dialog