# Measurement and Characterization of Lean NOx Adsorber Regeneration and Desulfation and Controlling NOx from Multi-mode Lean DI engines


**Agreements: 9248 and 12249**

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**U.S. Department of Energy, FCVT**



**Project ID: ace_31_parks**

# Overview

- Timeline
  - Start
    - #9248 (LNT): FY2003
    - #12249 (Multimode): FY2007
  - Finish
    - #9248 (LNT): FY2009
    - #12249 (Multimode): FY2010
  - % Complete
    - #9248 (LNT): ~94%
    - #12249 (Multimode): ~50%
- Budget
  - FY08 Funding
    - #9248 (LNT): $300k
    - #12249 (Multimode): $200k
  - FY09 Funding
    - #9248 (LNT): $300k
    - #12249 (Multimode): $200k
  - FY10 Requests
    - Transition to lean gasoline
    - #12249 (Multimode): $250k
- Barriers
  - Emissions regulations for advanced lean engine market penetration
- Partners
  - Catalyst Suppliers
    - Manufacturers of Emissions Controls Association (MECA)
    - AirFlow Catalysts
  - CLEERS and PSAT
    - Provide database and results to enable models
  - Other ORNL Projects:
    - Advanced Combustion
    - Joule Milestone
    - Health Impacts

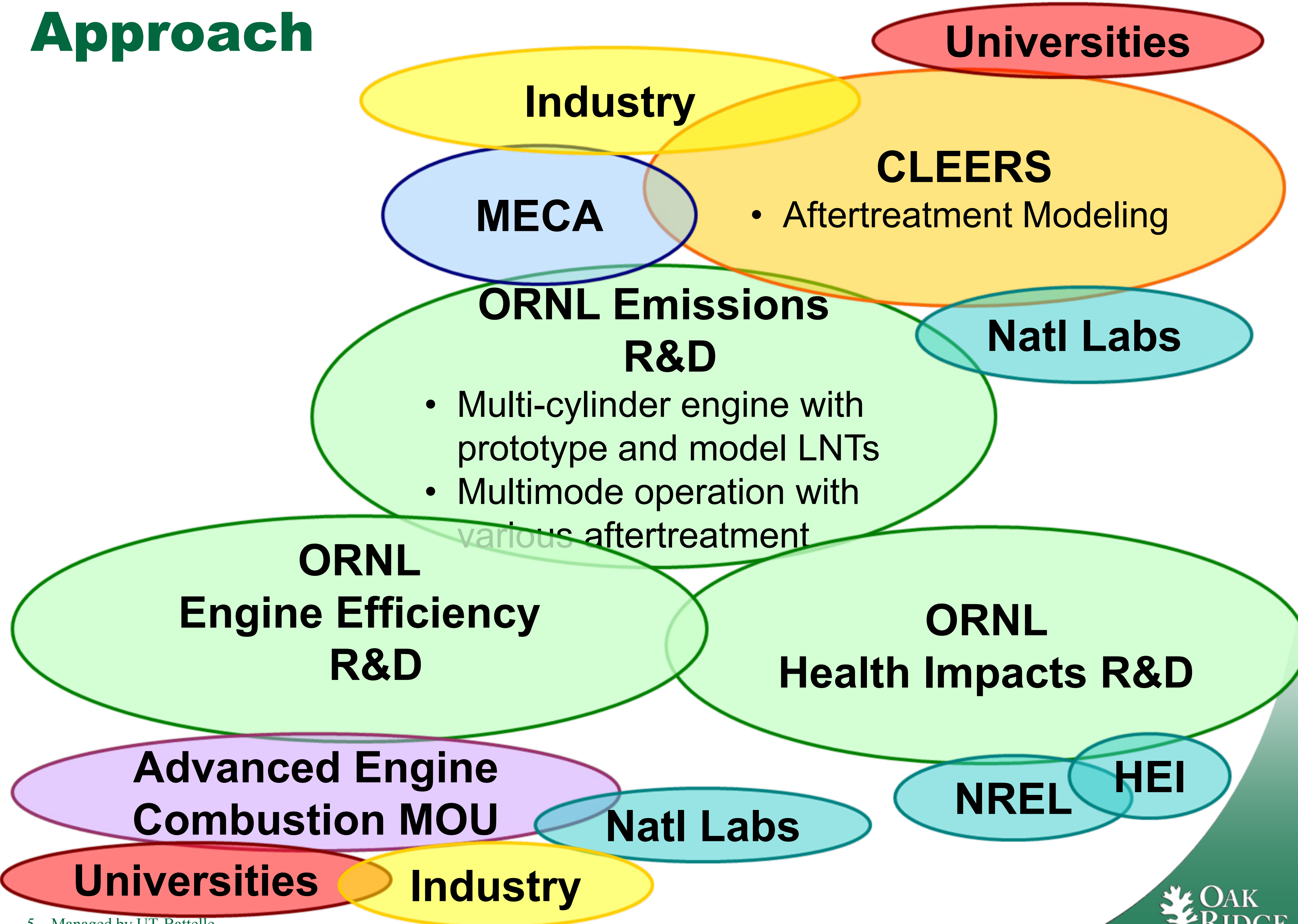
# Objectives: Enable efficient lean engine market penetration by meeting emission regulations with efficient, cost effective aftertreatment

- **Research of <u>Lean NOx Trap</u> Catalyst NOx and SOx Regeneration Chemistry and Performance (9248)**
  - Lower fuel penalty for regeneration
  - Characterize engine generated reductant utilization: $H_2$, CO, and HC's
  - Develop stronger link between bench and full-scale system evaluations
  - Provide data to CLEERS to improve models; use models to guide research
- **Research of <u>Multimode</u> Engine Operation and Potential Synergies with Aftertreatment (12249)**
  - Characterize emissions from advanced engine combustion modes and define the synergies or incompatibilities with emissions control technologies
    - LNT, Urea SCR, HC-SCR, Lean NOx Catalysis, DPF, Oxidation
  - Study effect of multimode operation on system performance

# Milestones

- **FY08 Milestones (completed):**
  - Couple advanced and conventional (multi-mode) combustion strategies with efficient emission control technologies to estimate FTP emissions from modal points (September 30, 2008)
  - Investigate feasibility of lowering platinum group metal content of lean NOx trap catalysts and determine performance impact. (September 30, 2008)
- **FY09 Milestones (planned and in progress):**
  - Exploit synergies of advanced and multi-mode combustion strategies with selective catalytic reduction emission control to estimate FTP efficiency and emissions from modal points in support of emissions part of ACEC goals. (September 30, 2009)
  - Characterize the reductant chemistry transitions through a combination lean NOx trap and selective catalytic reduction hybrid emission control system. (September 30, 2009)

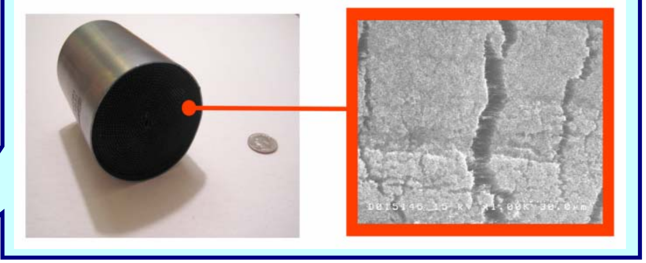
# Approach


Universities
Industry
CLEERS
• Aftertreatment Modeling
MECA
ORNL Emissions R&D
• Multi-cylinder engine with prototype and model LNTs
• Multimode operation with various aftertreatment
Natl Labs
ORNL Engine Efficiency R&D
ORNL Health Impacts R&D
Advanced Engine Combustion MOU
Natl Labs
NREL
HEI
Universities
Industry

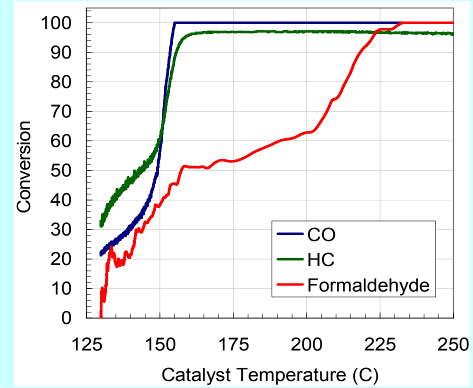
# Technical Accomplishments/Progress/Results

**Since last review (February 2008):**

- **Repeated demonstration of synergies of LNT and HECC study with DPF**
  - Tier 2 Bin 5 NOx emission levels estimated from weighted Ad Hoc load/speed points (reported at CLEERS, DEER, and Fall SAE)



- **Characterized Multiwalled Carbon Nanotube HC-SCR catalyst in slipstream setup**
  - With Mark Crocker and University of Kentucky team
- **Characterized DOC oxidation efficiency for HECC**
  - Model and AirFlow Catalyst DOCs control CO and formaldehyde/HCs except at low load points




- **Installed 4-cylinder GM diesel engine**
  - Working on Drivven controls system for GM platform

- ★ **Demonstrated potential benefit of HECC for fuel savings due to lower desoot frequency**
  - Lower soot loading from HECC results in lower frequency of desoot and reduces desoot fuel penalty from 4.2% (conventional case) to ~3.1% (mixed mode HECC +conventional)
- ★ **Characterizing (ongoing) $NH_3$ formation and utilization in LNT-SCR hybrid system**
  - Tracking fast pulse of $NH_3$ from LNT regeneration with UV spectroscopy technique

★ ***Details Presented On These Topics***

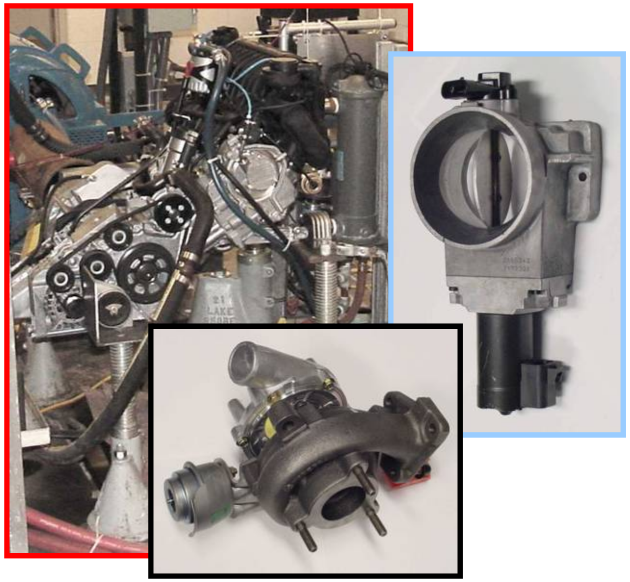
# Experiments made use of engine conditions developed by Ad Hoc working group

| Point | Speed / Load | Weight Factor | Description |
|---|---|---|---|
| 1 | 1500 rpm / 1.0 bar | 400 | Catalyst transition temperature |
| 2 | 1500 rpm / 2.6 bar | 600 | Low speed cruise |
| 3 | 2000 rpm / 2.0 bar | 200 | Low speed cruise w/ slight acceleration |
| 4 | 2300 rpm / 4.2 bar | 200 | Moderate acceleration |
| 5 | 2600 rpm / 8.8 bar | 75 | Hard acceleration |

- **Represents speed-load points for light-duty**
- **No cold-start or other transients**
- **Method for estimating drive-cycle emissions**

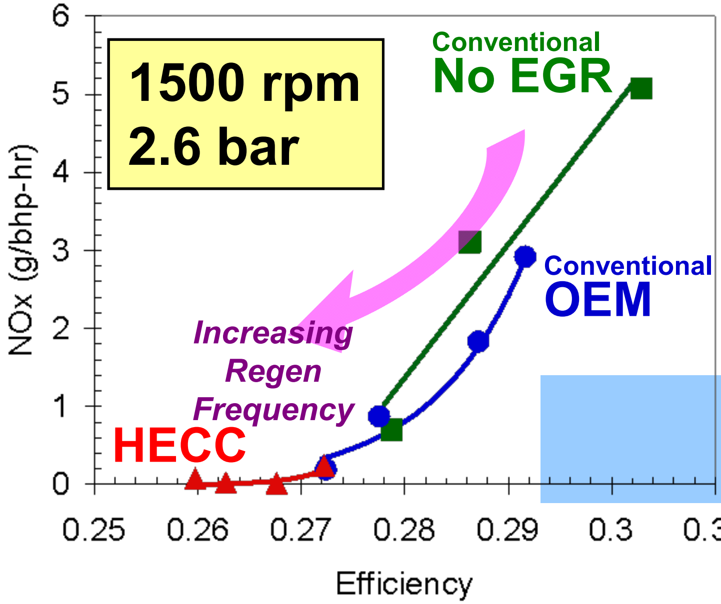
**References:** SAE 1999-01-3475 (Kenney), SAE 2001-01-0148 (Szymkowicz, French, Crellin), SAE 2001-01-0151 (Kenney *etal.*), SAE 2001-01-0650 (Hilden, Eckstrom, Wolf), SAE 2002-01-2884 (Natarajan *etal.*), SAE 2006-01-3249 (Amann), SAE 2006-01-3311 (Sluder, Wagner)

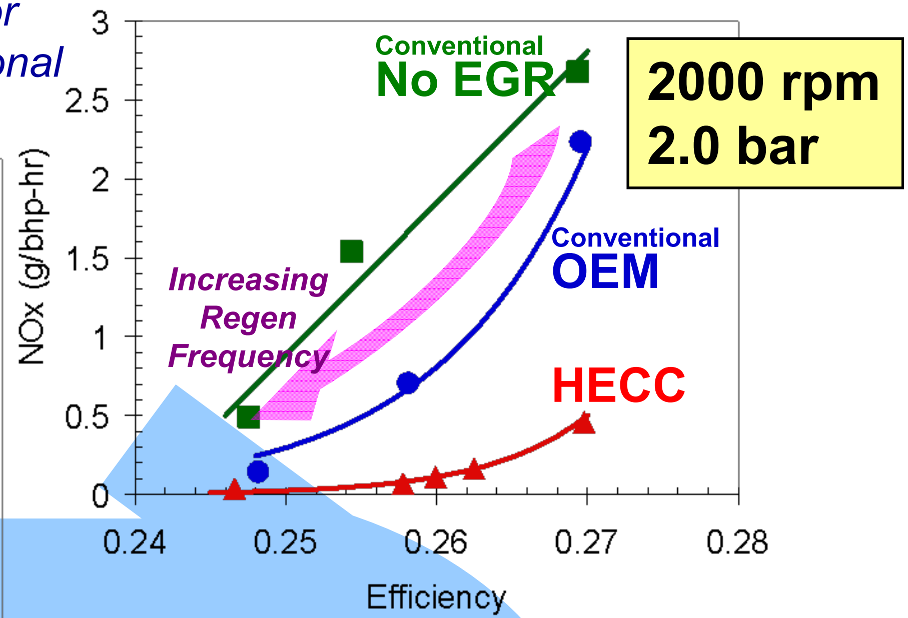
- **Modified 1.7-liter, 4-cylinder**
- **High-pressure common rail**
- **Full-pass control system (8 event)**
- **Variable geometry turbocharger**
- **Cooled EGR with low and high flow valves and electronic throttling**



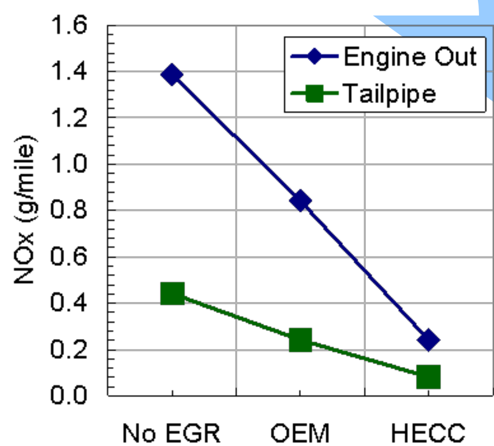
# Previous study focused on LNT regeneration

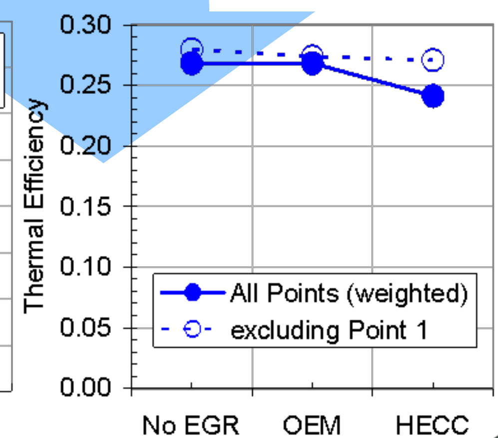
*Emissions and efficiency measured for HECC and LNT system (vs. conventional combustion) at Ad Hoc points, and…*




*…weighted performance results used to estimate FTP emissions and efficiency.*




**SAE 2008-01-2493**

# Frequent Desoot observed in new production diesel vehicles with advanced emission controls

**Dodge Cummins System (HD Pickup Truck)**

[Ken Price (Umicore), *CLEERS Telecon* (2009),*SAE LD Symposium* (2008)]

- DPF desoot at ~600ºC for 10-15 min. during ~13% of operating time (<4% fuel penalty)
- Desoot:deSulfate Ratio = 6:1

**Mercedes E320 System**

[Owen Bailey (Umicore), *CLEERS* (2008)]

- DPF desoot at ~700ºC for ~6-8 min. during ~2% of operating time
- Desoot:deSulfate Ratio = 2:1

**Volkswagen - Jetta System**

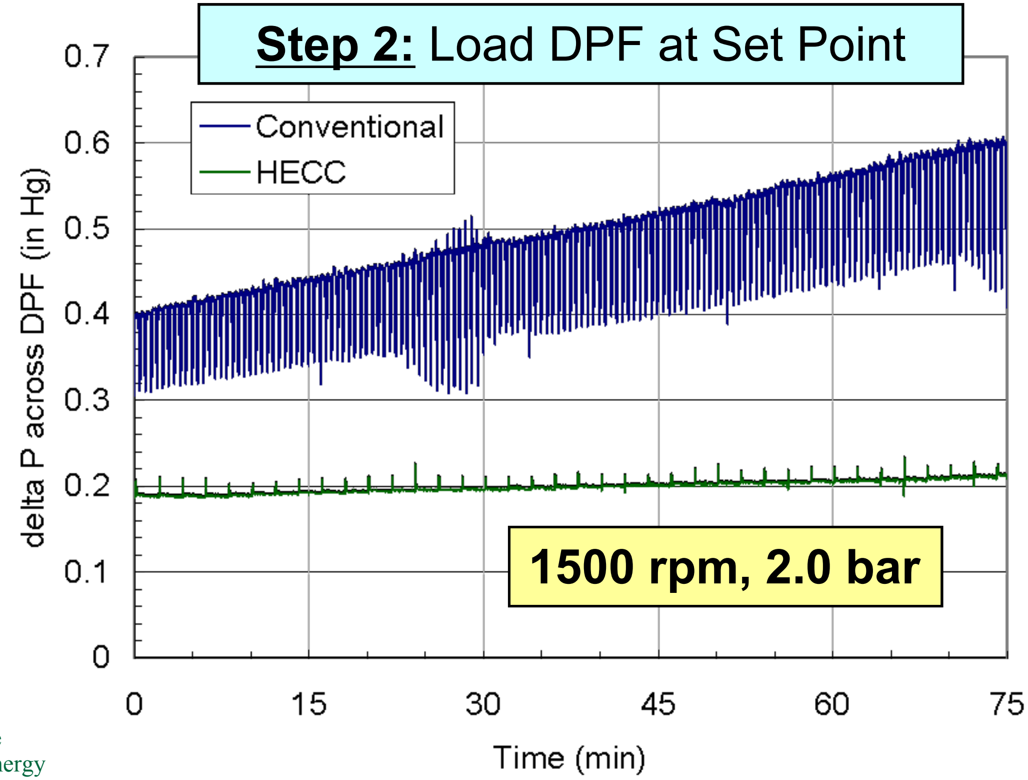
[Ing. J. Hadler etal., *Internationales Wiener Motorensymposium* (2008)]

- DPF desoot at ~650ºC for <15 min.
- Desoot:deSulfate Ratio = 4:1

# Question: Are there potential benefits of lower PM from HECC for Multimode operation?

- **Experiment designed to characterize benefit of lower PM from HECC:**
  - Measure dP rise rate for HECC as compared with conventional (OEM level EGR) combustion
  - Use standard point (1500 rpm, 5.0 bar) to compare total backpressure change consistently
    Experiments conducted with LNT regeneration frequency to achieve equal tailpipe NOx
  - DPF desoot accomplished with post injection from standard point start (~10-15 min at ~600ºC)


**Step 1:** Measure dP at standard




**Step 3:** Measure dP at standard

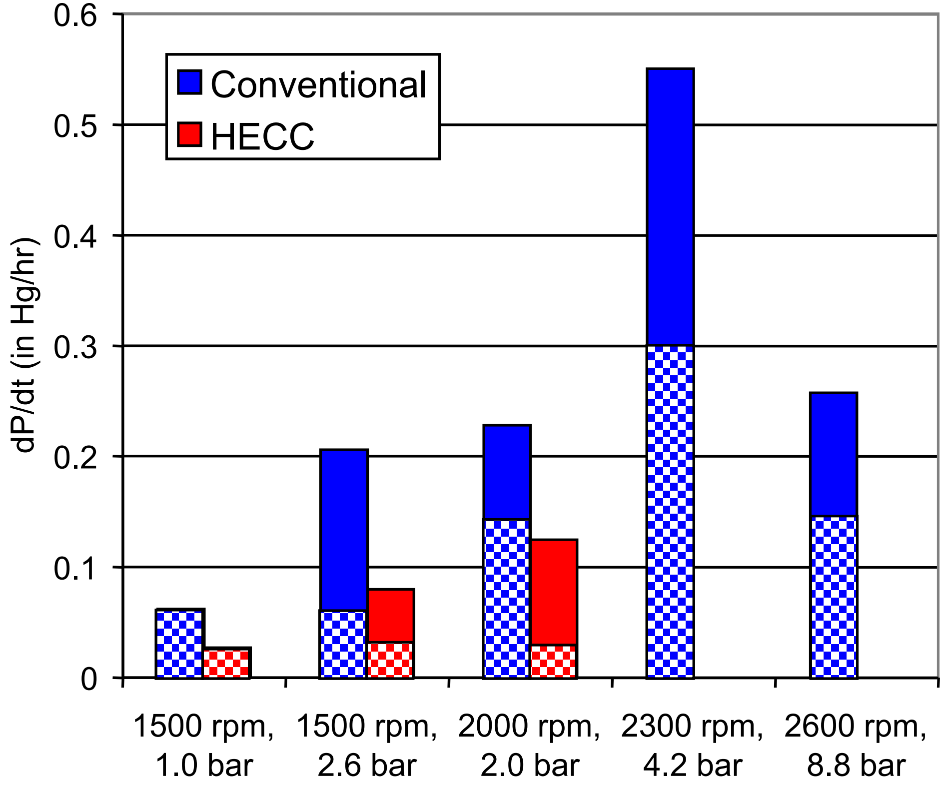
**Step 4:** desoot

# DPF backpressure rise rate lower for HECC

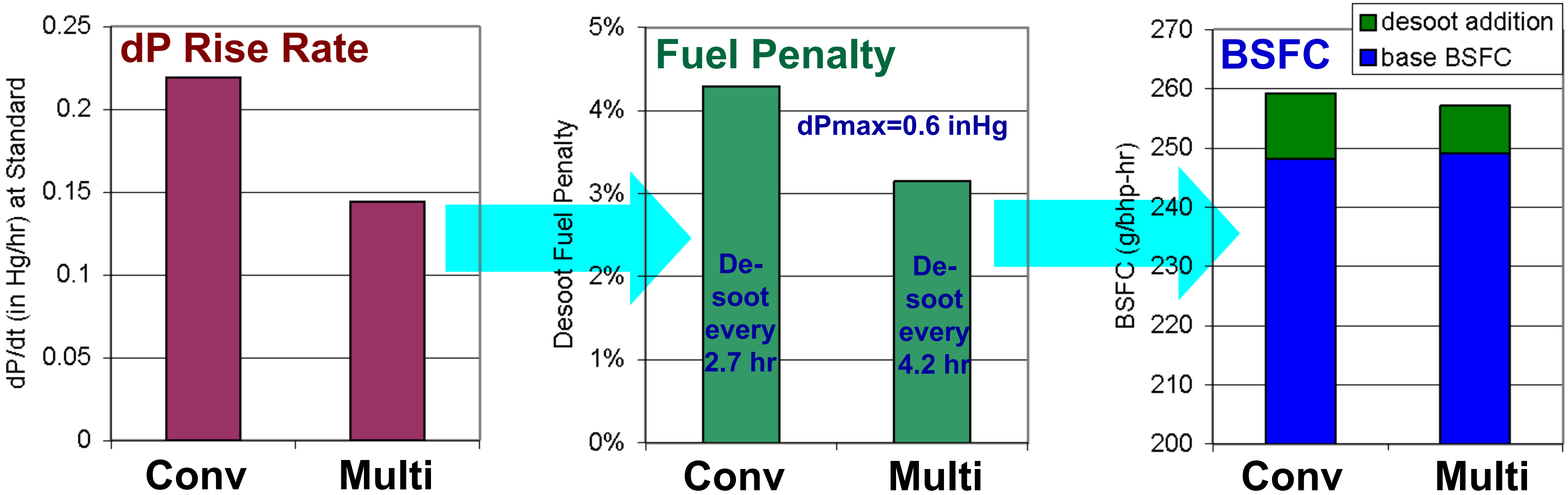
- **Rate of backpressure rise across DPF measured at various load points for Conventional (OEM EGR level) and HECC combustion**
  - **Higher PM from conventional combustion leads to higher rise rates**
  - **LNT regeneration adds to rise rates**

*All dP/dt data based on before and after measurements at standard condition*

*Note: checkered pattern indicates without LNT regeneration*



# Lower DPF loading saves fuel for multimode




- **Less PM from HECC leads to less frequent desoot & lower desoot fuel penalty**
  - **Also results in less time at high temperature for catalysts**
- **Lower desoot fuel penalty helps multimode with HECC compete with conventional combustion on BSFC basis**
- **HECC gives lower NOx, but other issues remain: EGR fouling, stability, high CO/HCs**

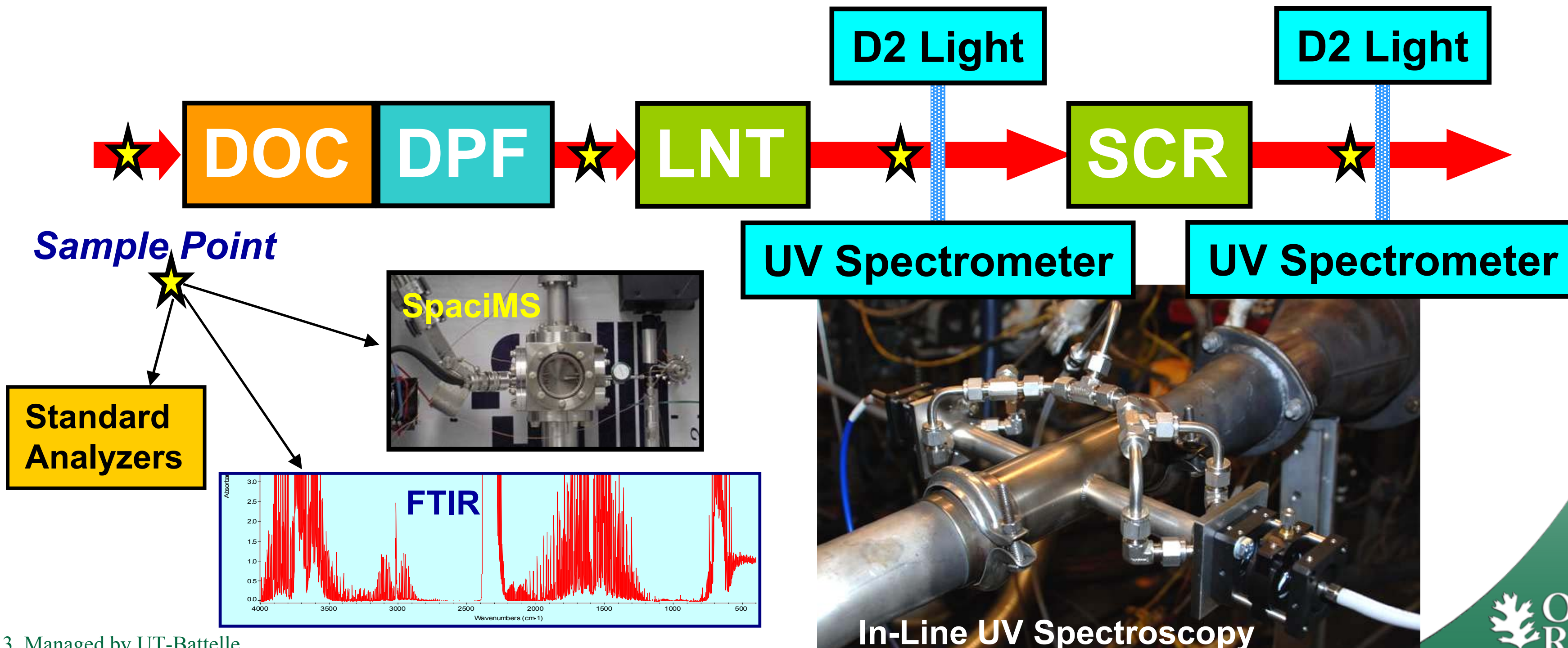
**Conv=Conventional**
**Multi=Multimode**

| Speed/Load | Conventional | Multimode |
|---|---|---|
| 1500 rpm/1.0 bar | OEM* | HECC* |
| 1500 rpm/2.6 bar | OEM | HECC |
| 2000 rpm/2.0 bar | OEM | HECC |
| 2300 rpm/4.2 bar | OEM | OEM |
| 2600 rpm/8.8 bar | OEM | OEM |

***no regeneration of LNT (low temp)***

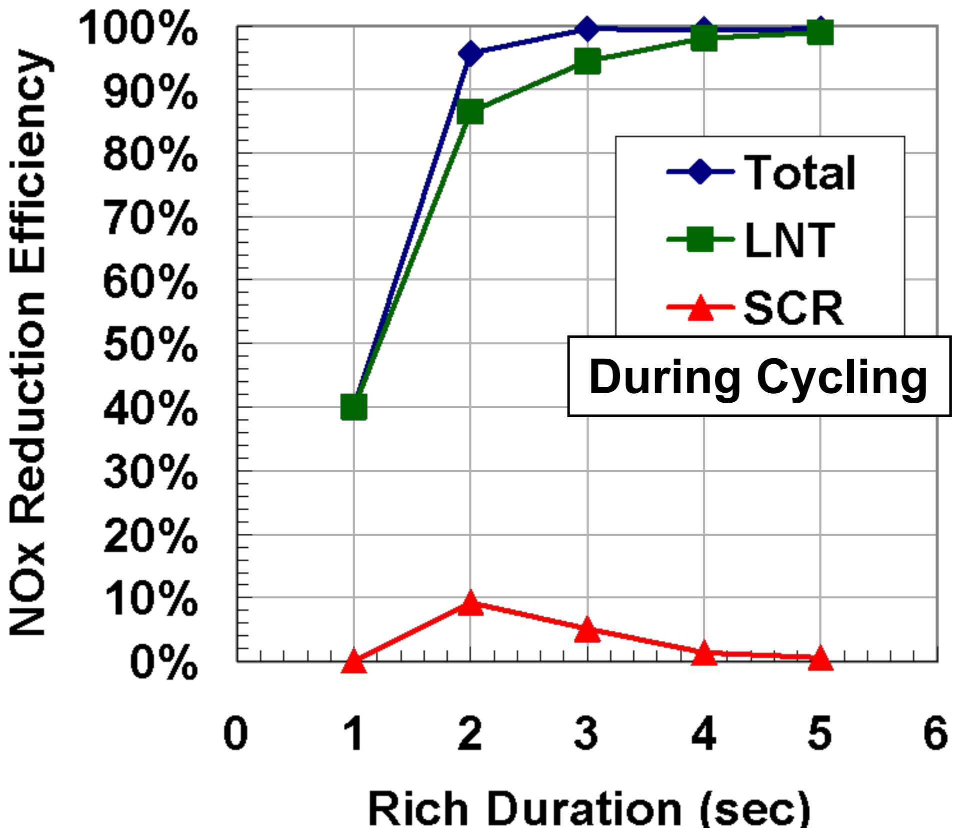
# Study of $NH_3$ formation and utilization in hybrid LNT-SCR system

- **Focus on characterization of utilization reductants (from engine to LNT to SCR):**
  - DOC and DPF (SiC) in same can upstream of LNT-SCR
  - LNT and SCR catalysts provided by MECA; model LNT also studied (results shown here)
  - Current LNT and SCR SV=25-40k/hr; plan to reduce SV for further study
- **Measurement of reductants with variety of techniques:**
  - Standard analyzers for CO (NDIR) and HC (FID) reductants (and CLD for NOx)
  - Magnetic sector SpaciMS for $H_2$
  - FTIR for $NH_3$, $N_2O$, NOx, HCs, and other species
  - UV spectroscopy for fast in-line measurement of $NH_3$, NOx, and HCs

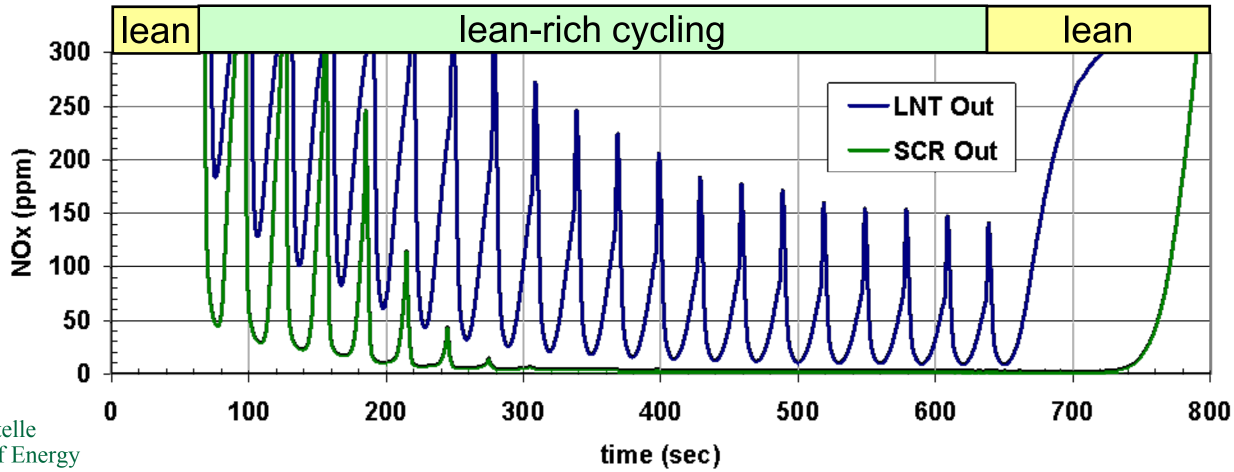


# SCR reduces NOx that breaks through LNT

- 1500 rpm, 50 ft-lbs, Lean=30sec, Rich=1-5sec
- Constant cycling with start and stop to observe $NH_3$ storage effects
- SCR benefits overall NOx reduction when LNT NOx reduction not complete
- Excess $NH_3$ stored by SCR enables more NOx reduction after cycling ends

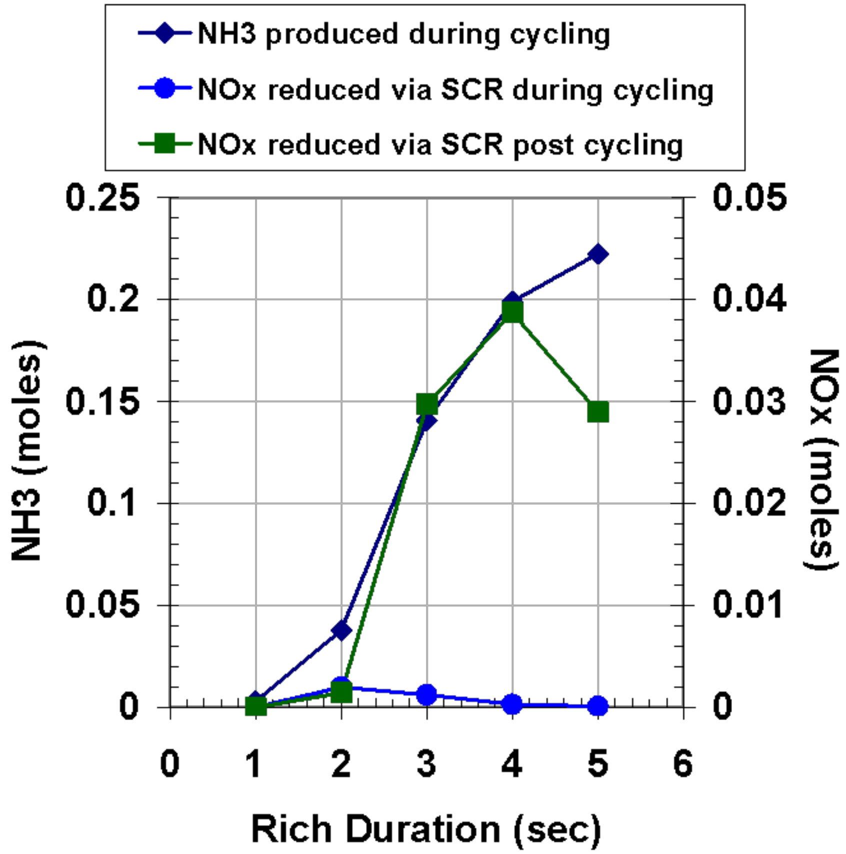


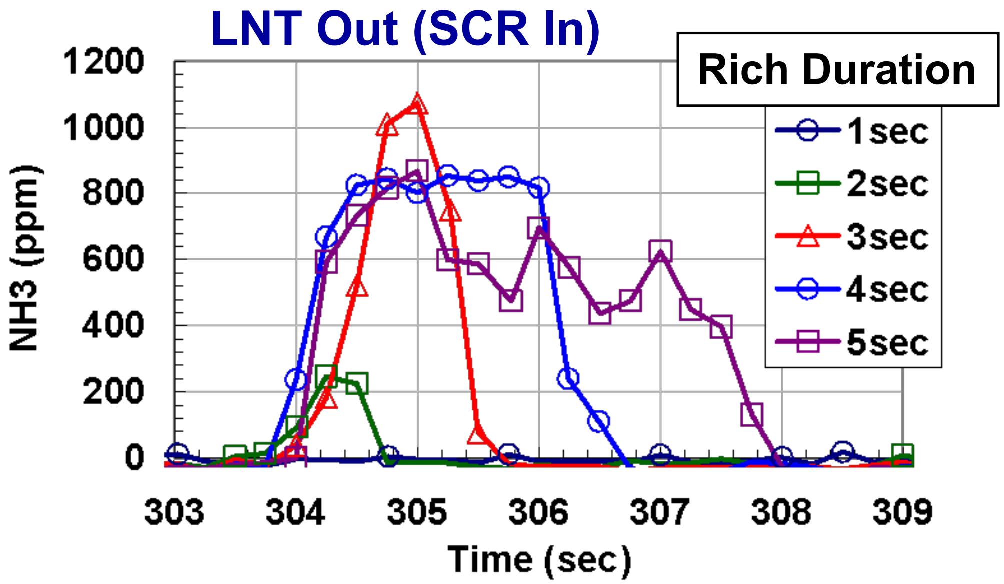

***Example Raw Data***



# SCR stores excess $NH_3$ generated

- $NH_3$ generation occurs when excess reductant supplied to LNT
- Extending rich duration increases $NH_3$ production
  - Timing consistent with bench studies

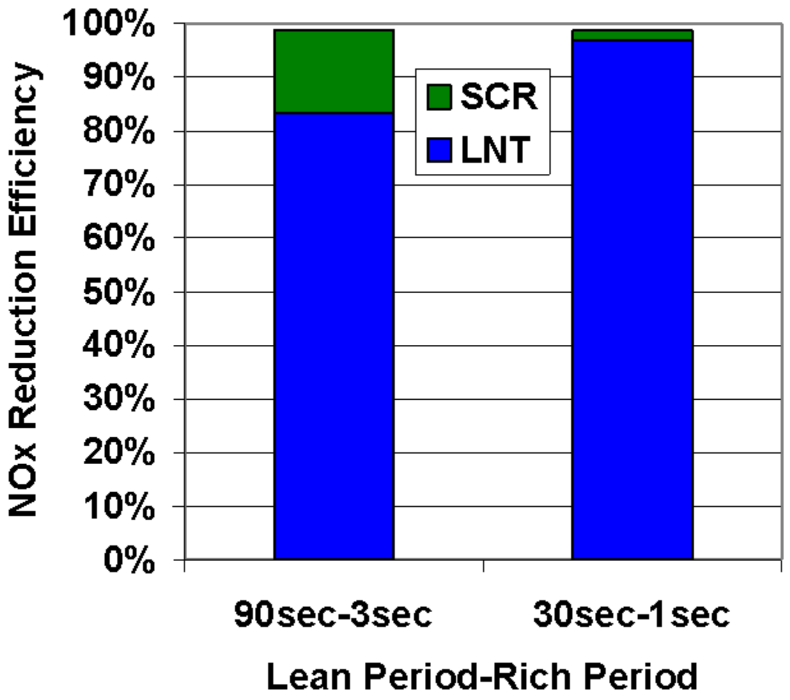


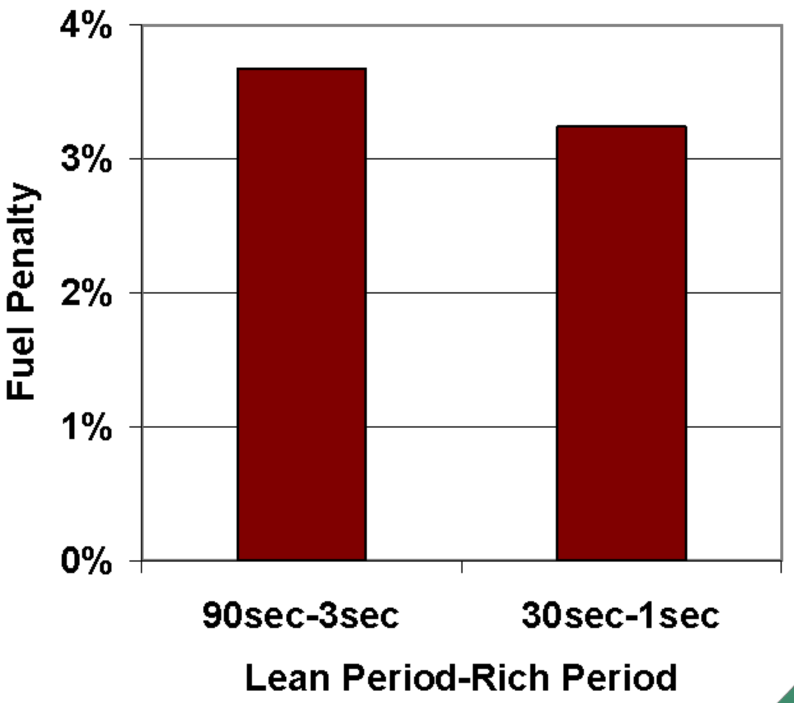




- For specific cycle, low amount of $NH_3$ used by SCR for NOx reduction
- $NH_3$ not utilized during cycle is stored
- Stored $NH_3$ beneficial for future NOx reduction in transient scenario

# Similar fuel penalty for equivalent NOx reduction

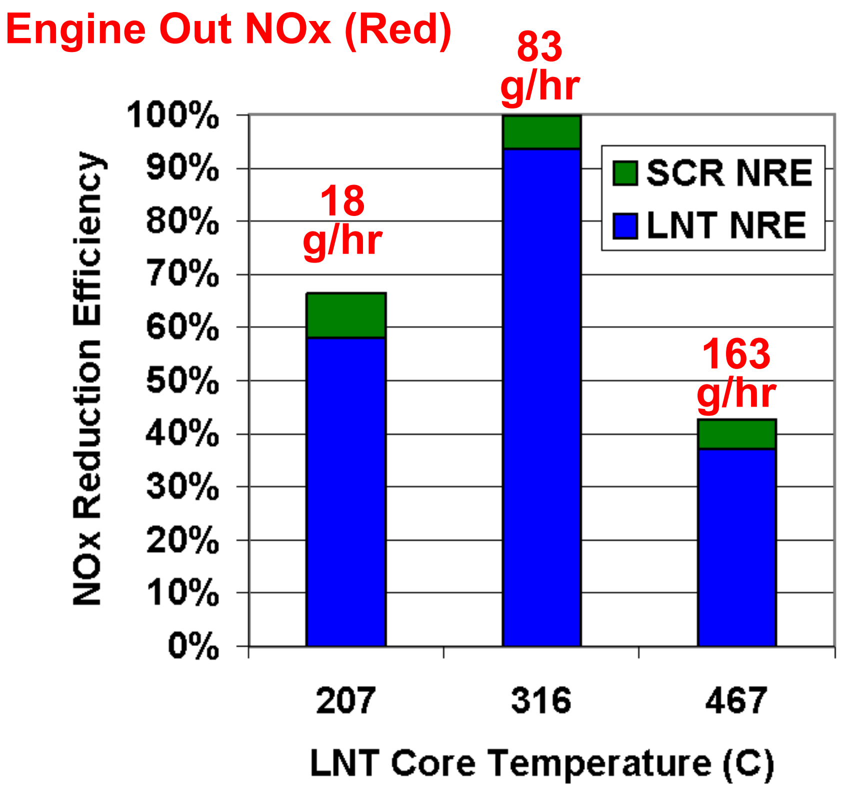
- 1500 rpm, 50 ft-lbs, EGR=24%
- Lean Period – Rich Period: 90sec-3sec vs. 30sec-1sec
- For cases where LNT is effective, no fuel penalty benefit is gained by LNT-SCR system (on cycle basis)
- Trade-off between frequency and duration of regeneration

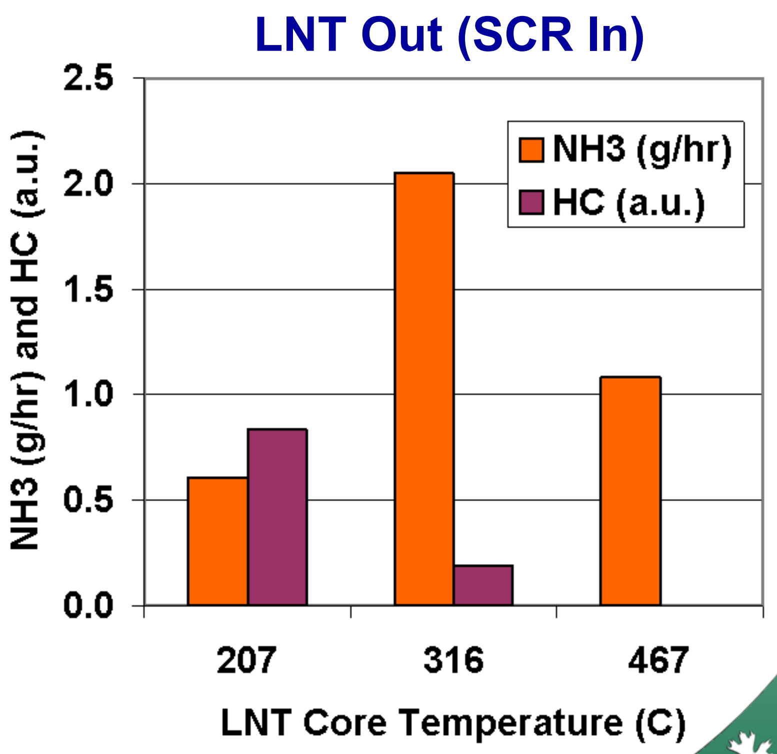


# $NH_3$ production limits SCR NOx reduction

- LNT temperature varied by selecting 3 engine conditions (engine out NOx not equivalent)
- When LNT NOx capacity is lower, less $NH_3$ is produced
- At low temperature (207ºC), more hydrocarbons slip past LNT



# Future Work

- **Remainder of FY2009**
  - Continue $NH_3$ Utilization Study
  - Develop controls for GM engine
  - Study urea SCR synergies with multimode operation
  - Transition to lean gasoline (project #9428)
  - Present Results at CLEERS, NAM, DEER, Fall SAE
- **FY2010**
  - Integrate emissions database into Joule milestone efforts (efficiency +emissions goals)
  - Install lean gasoline engine and characterize exhaust conditions and LNT performance

# Summary

- **Engine-based studies of emission control technologies focus on:**
  - **Synergies with advanced combustion**
  - **Reductant utilization and fuel efficiency**
- **Engine out reductions of both NOx and PM emissions lead to fuel efficiency benefits for HECC and multimode operation**
  - **Lower PM emissions lead to less frequent desoot operation, and thereby, fuel savings (vs. conventional)**
- **$NH_3$ produced by LNT during regeneration can be utilized by SCR in hybrid system to enable higher NOx reduction efficiency**

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