Reductant Utilization in a LNT + SCR System

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Investigation of the potential synergies of LNT and SCR for treating NO_x emissions from a diesel engine

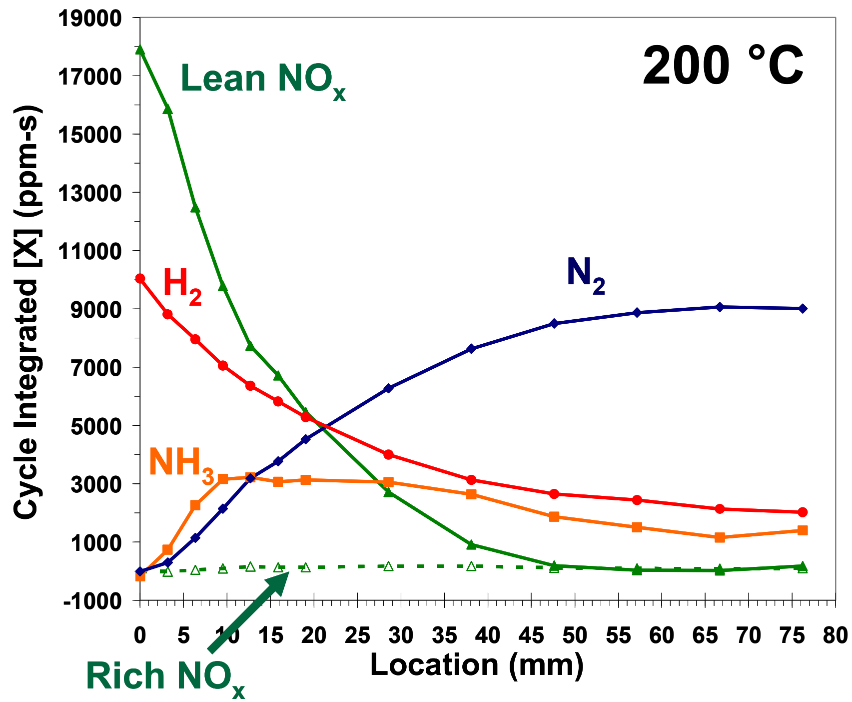
- **Selective Catalytic Reduction (SCR)**
  - Treats NO_x under lean conditions using ammonia (NH_3) as a reductant requiring onboard storage of urea/ammonia and urea/ammonia distribution networks
- **Lean NO_x Trap (LNT)**
  - Stores NO_x during normal lean exhaust conditions and then reduces the stored NO_x during periodic short rich excursions with diesel fuel
- **LNT+SCR**
  - Ammonia produced during LNT regeneration is stored on SCR for further NO_x reduction eliminating the need for onboard ammonia storage
  - Reduces burden of LNT in NO_x reduction
  - Prevents NH_3 slip

References for LNT+SCR R&D in the literature:

SAE2006-01-3552; SAE2006-01-0210; SAE2006-01-3551; SAE2007-01-1244; SAE2008-01-2642

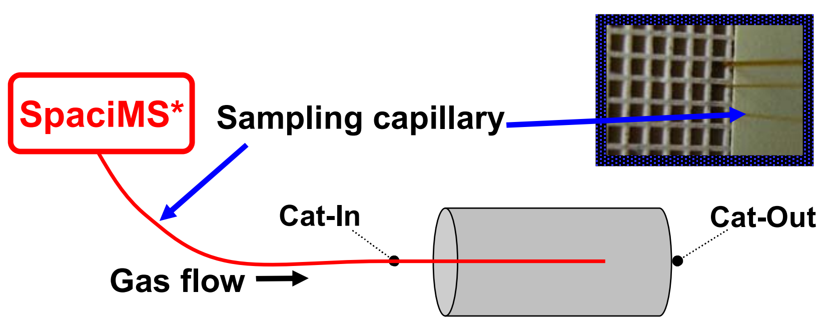
NH_3 formation in LNT originates from stored NOx during regeneration process

- Bench flow reactor data with Argon carrier (for N_2 detection)
- H_2 reductant
- Gas species measured along catalyst flow axis with SpaciMS
- NH_3 formation consistent with NOx storage locations



In Situ

Intra-Channel Speciation



**Spatially Resolved Capillary Inlet Mass Spectrometer*

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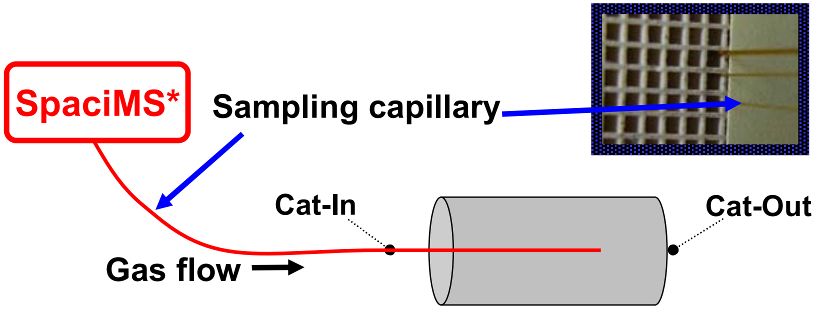
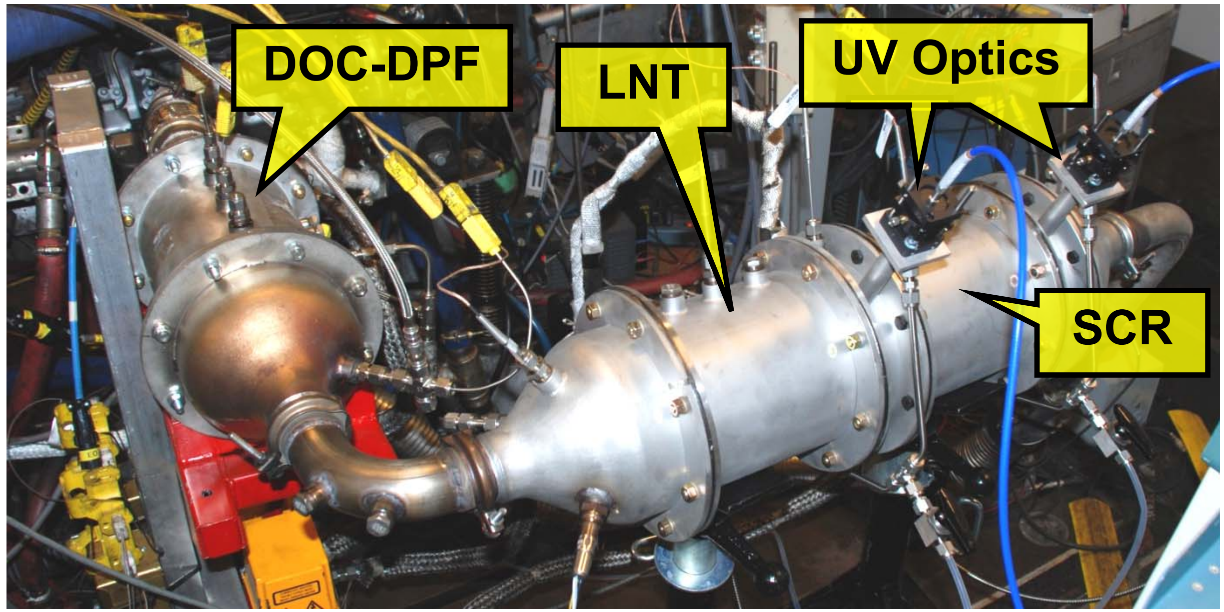


**Spatially Resolved Capillary Inlet Mass Spectrometer*

Approach: operate multi-cylinder diesel engine with in-cylinder LNT regeneration strategy and study chemistry along LNT + SCR

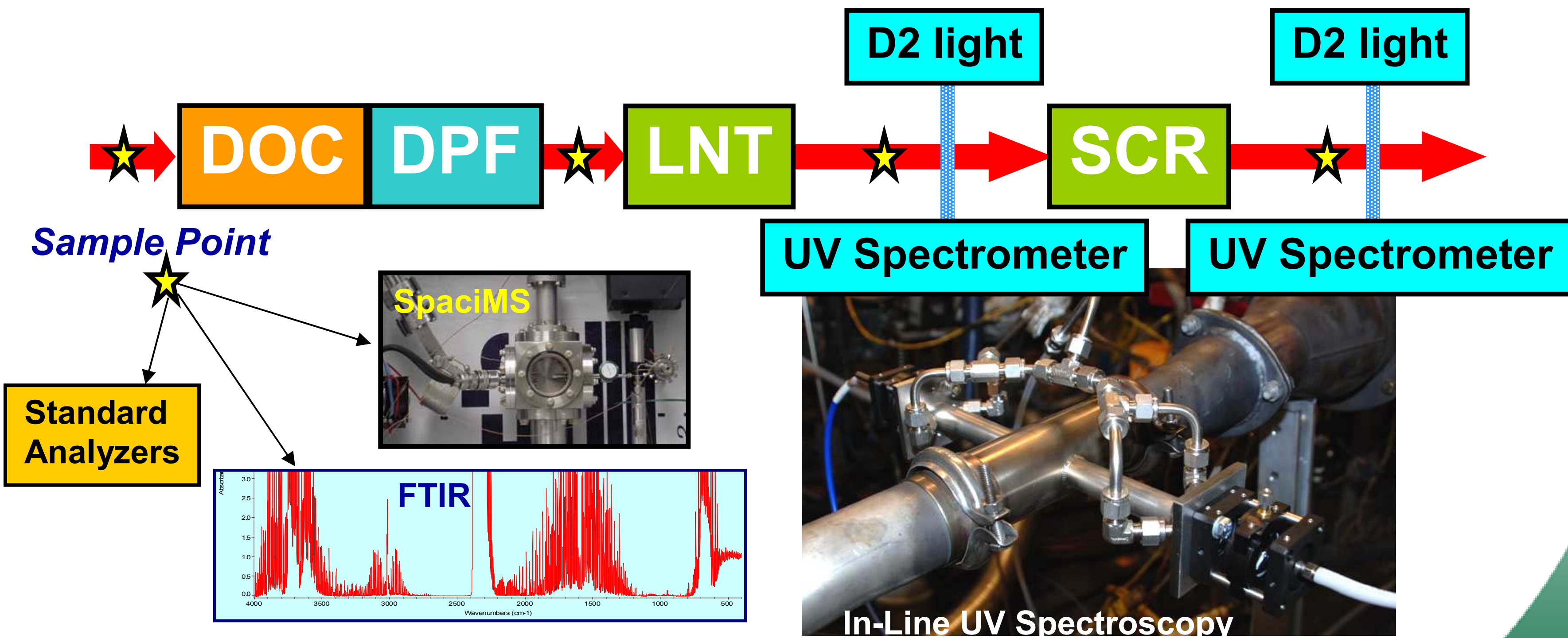
- **Engine**
  - Modified 1.7-liter, 4-cylinder
  - High-pressure common rail
  - Full-pass control system
  - Variable geometry turbocharger
  - Cooled EGR with low and high flow valves
  - Electronic throttling



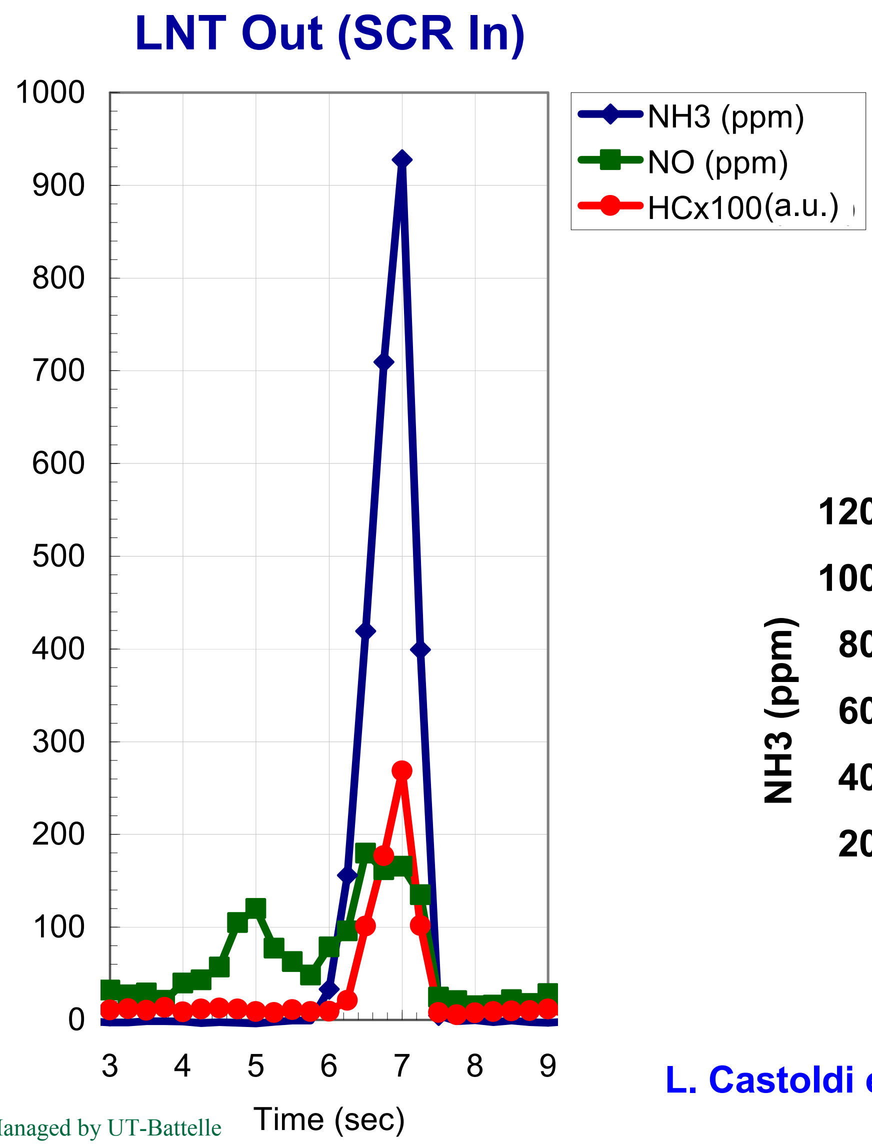
- **Catalyst System**
  - DOC and DPF (SiC) were installed upstream of LNT-SCR
  - Model Ba-based LNT and Fe-zeolite SCR [SCR provided by member of Manufacturers of Emissions Control Association (MECA)]
    - 5.66-inch x 6-inch bricks (volume = 2.47 liters)

Experiment Notes: Analytical Tools

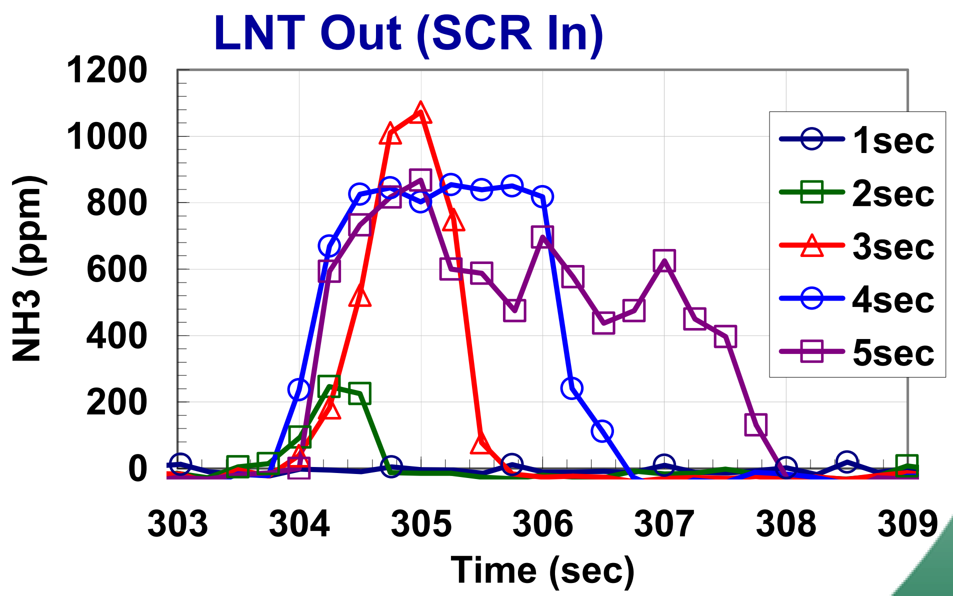
- Standard analyzers for CO (NDIR), HC (FID) and NO_x (CLD)
- Magnetic sector SpaciMS for H_2
- FTIR for NH_3, N_2O, NO_x, HCs, and other species
- UV spectroscopy for fast in-line measurement of NH_3, NO_x, and HCs



Temporal profile of NH_3 production in engine study consistent with bench reactor studies



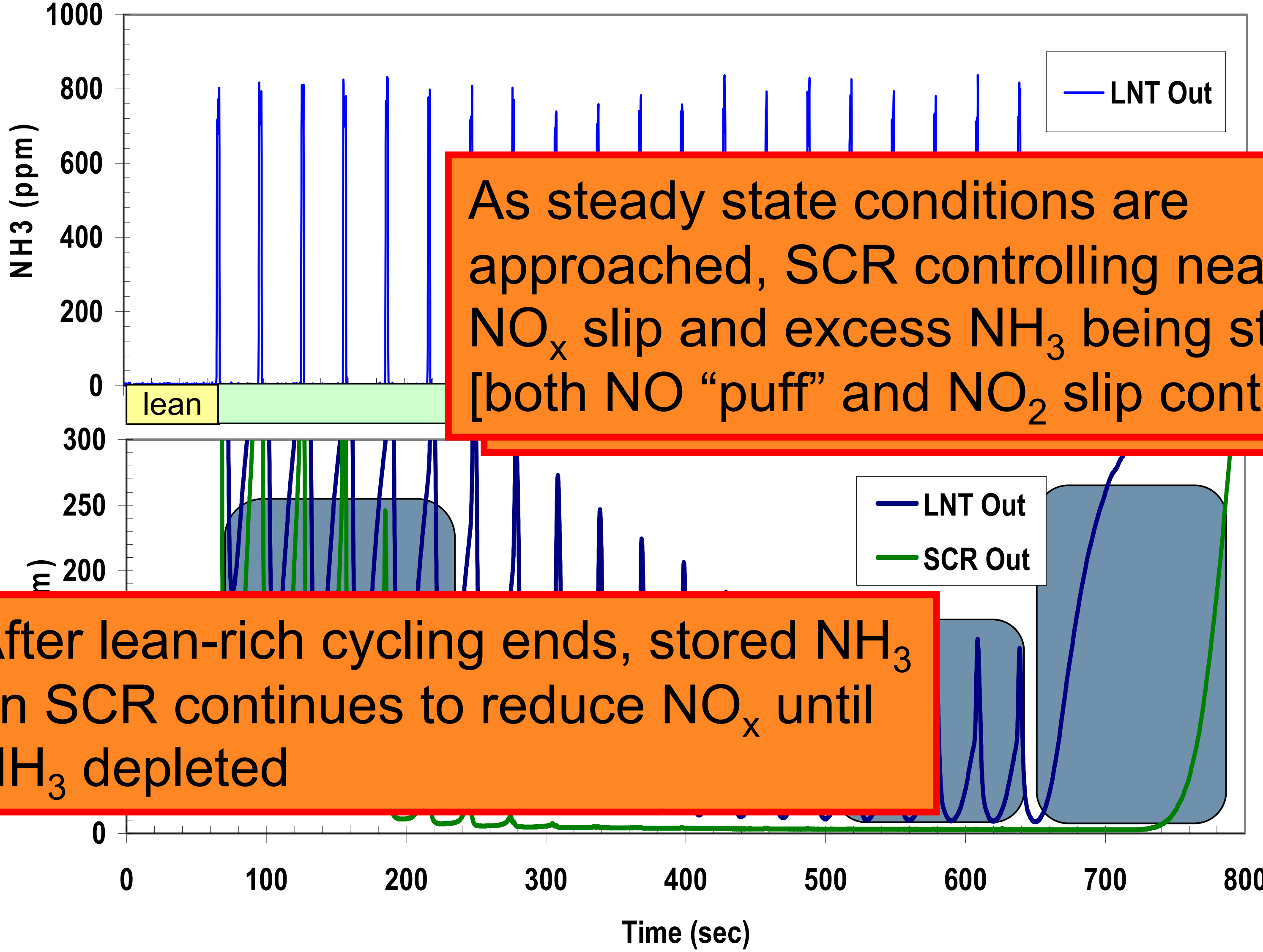
- NH_3 emission generally follows initial NOx puff
- NH_3 and HC breakthrough occur simultaneously
- Increasing rich period prolongs NH_3 emission with slow tailing off of concentration



L. Castoldi et al, *Catalysis Today* 96 (2004) 43–52

Typical set of LNT and SCR out NO_x emission data

- **1500 rpm, 50ft-lbs, 27s/3s lean/rich cycling (EO NO_x = 500ppm)**



As steady state conditions are approached, SCR controlling nearly all NO_x slip and excess NH_3 being stored [both NO “puff” and NO_2 slip controlled]

After lean-rich cycling ends, stored NH_3 on SCR continues to reduce NO_x until NH_3 depleted

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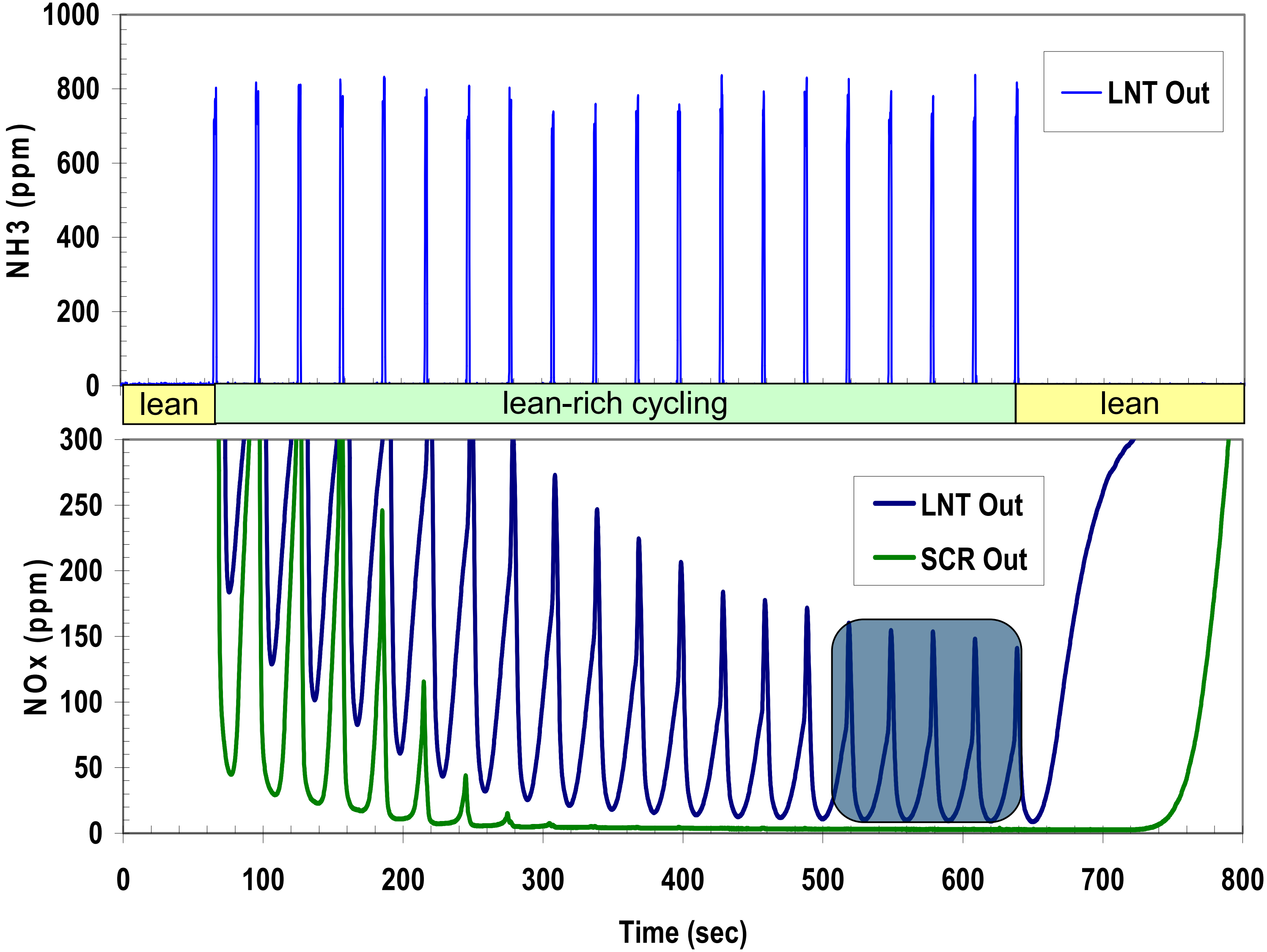
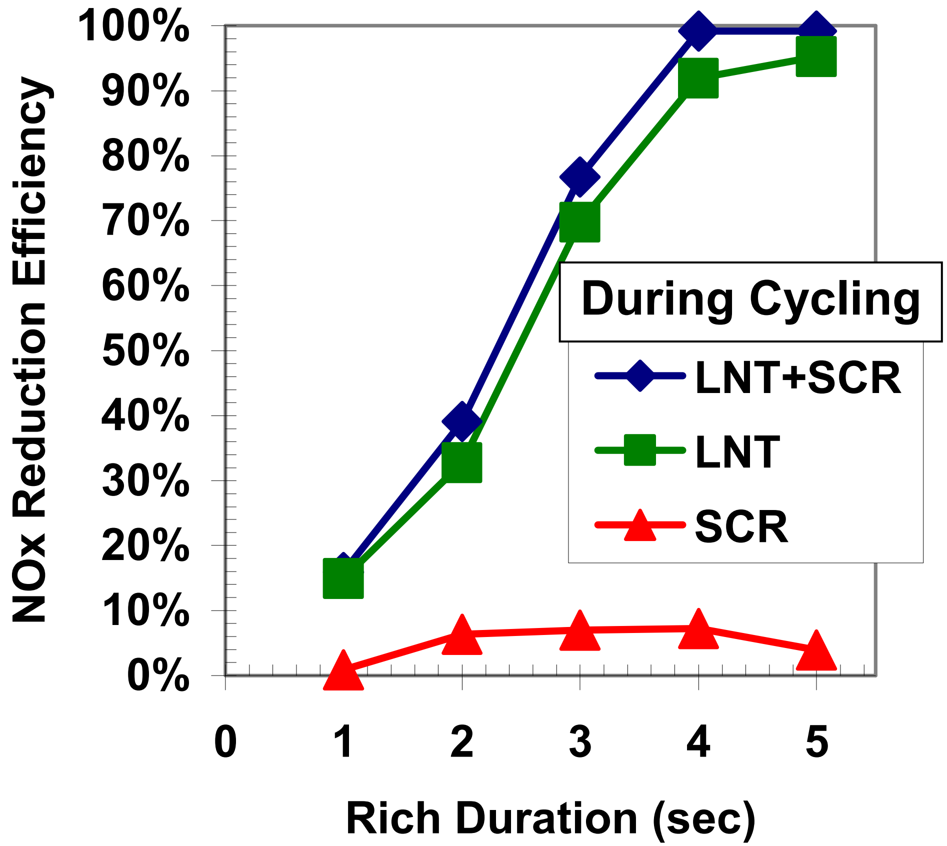
Following results during lean-rich cycling…



Following results are presented toward the end of cycle run when no cycle-to-cycle variation was observed

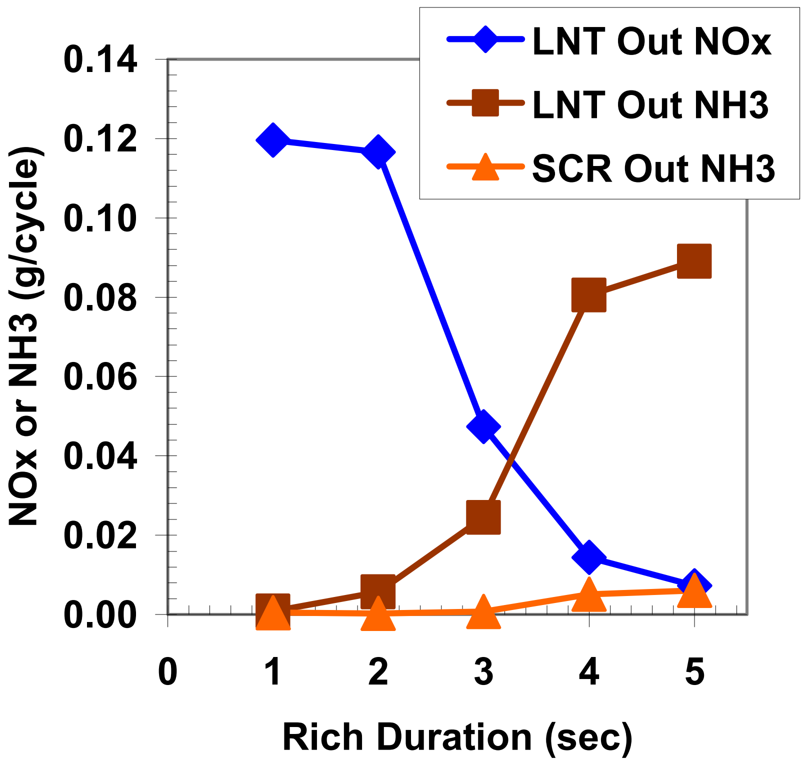
SCR reduces NOx that breaks through LNT

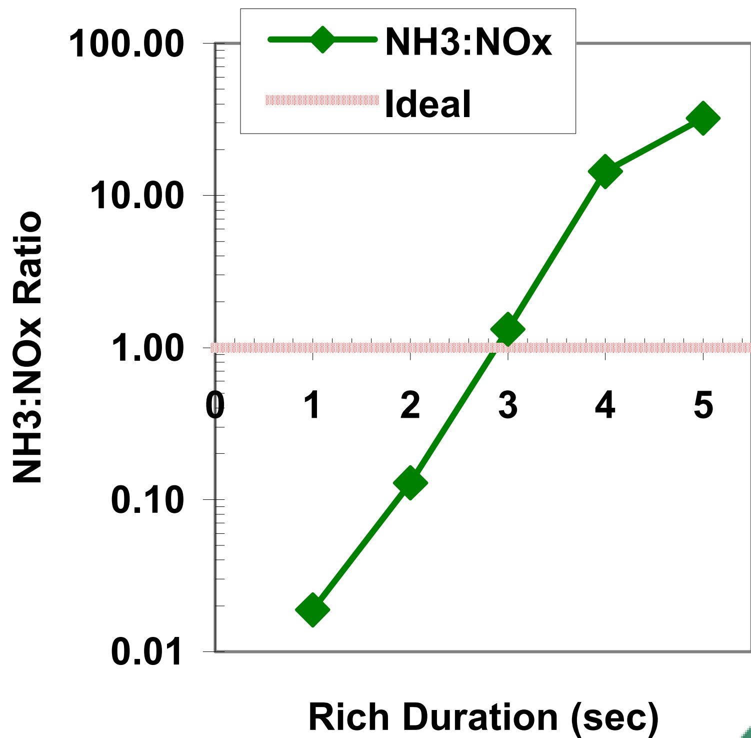
- 1500 rpm, 50 ft-lbs, Lean=30sec, Rich=1-5sec (minAFR=13.5)
- Constant cycling with start and stop to observe NH_3 storage effects
- SCR benefits overall NOx reduction when LNT NOx reduction not complete
- Excess NH_3 stored by SCR enables more NOx reduction after cycling ends



SCR contribution limited by LNT Out NH_3 and LNT Out NOx

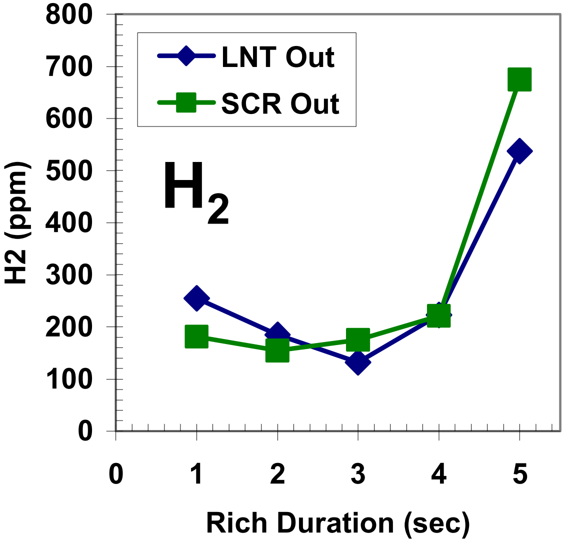
- When LNT is under-regenerated…SCR contribution limited by NH_3 (NH_3:NOx < 1)
- When LNT is over-regenerated…SCR contribution limited by inlet NOx (NH_3:NOx >>1)

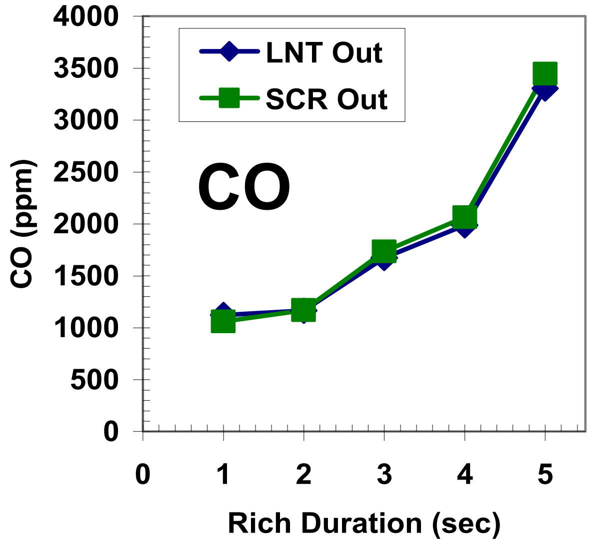


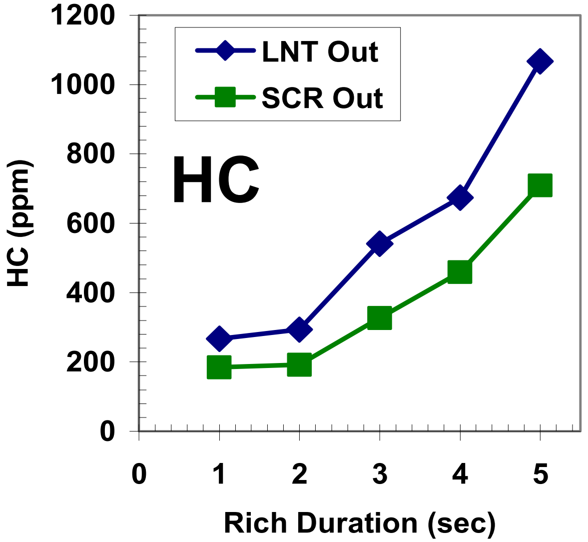


H_2 and CO do not appear to aid NOx reduction over SCR; HCs may be trapped by SCR

- H_2 and CO levels similar upstream and downstream of SCR indicating NH_3 is primary reductant for SCR NOx reduction
- HCs may be trapped by SCR

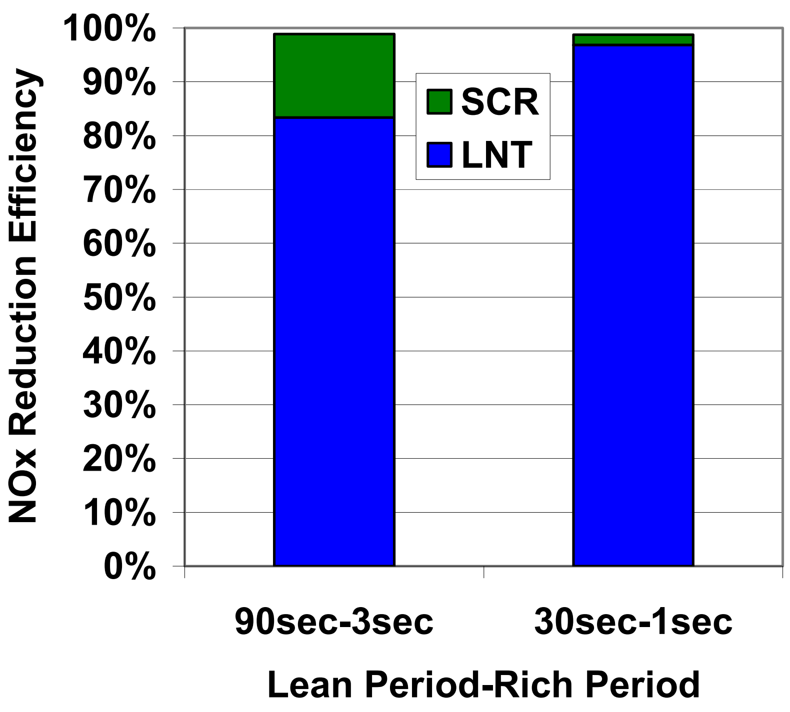


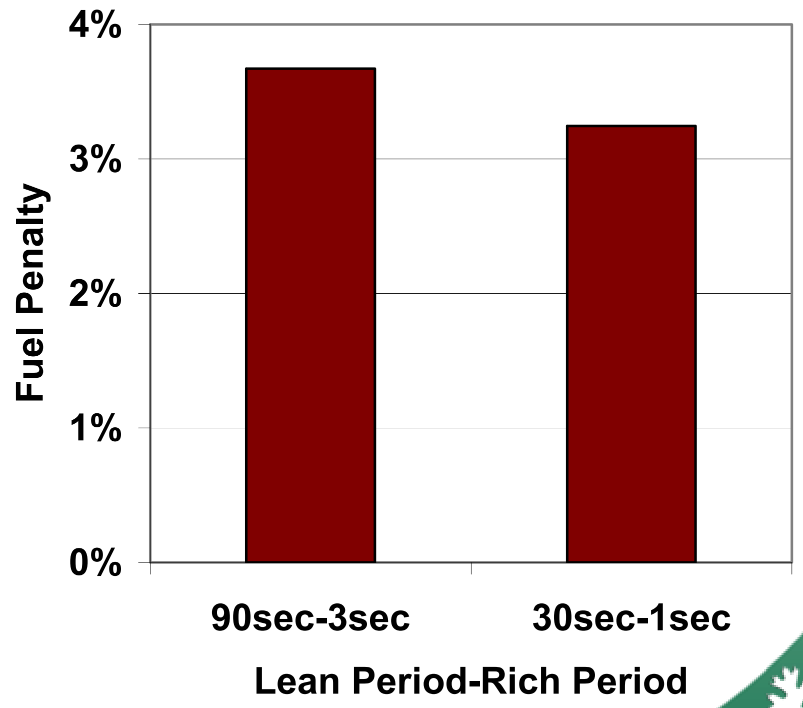




Similar fuel penalty for equivalent NOx reduction

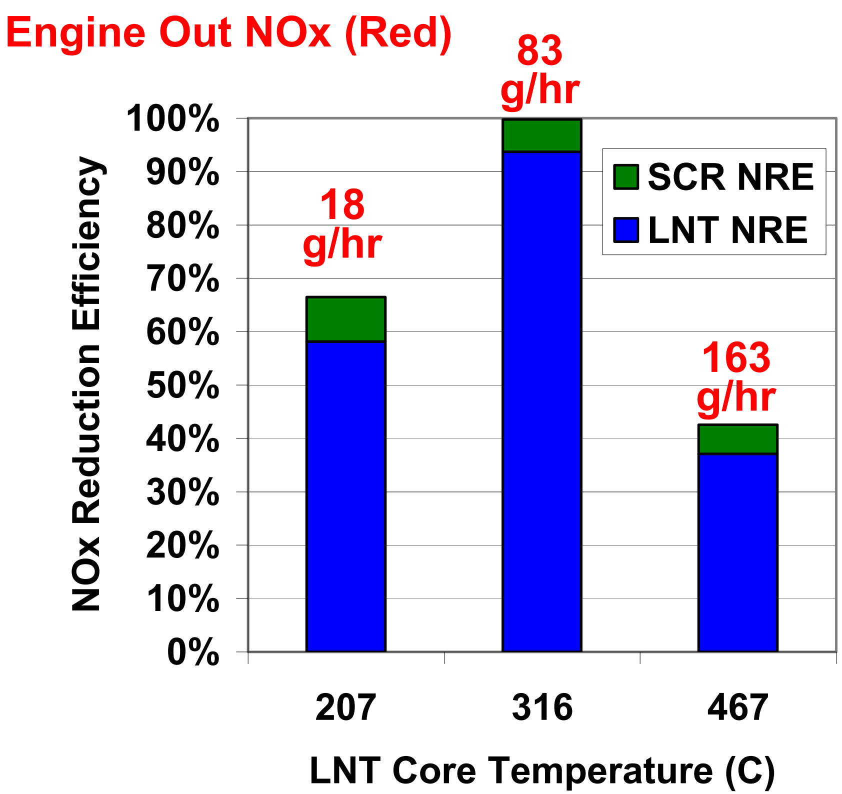
- 1500 rpm, 50 ft-lbs, EGR=24%
- Lean Period – Rich Period: 90sec-3sec vs. 30sec-1sec
- For cases where LNT is effective, no fuel penalty benefit is gained by LNT-SCR system (during constant lean-rich cycling)
- Trade-off between frequency and duration of regeneration

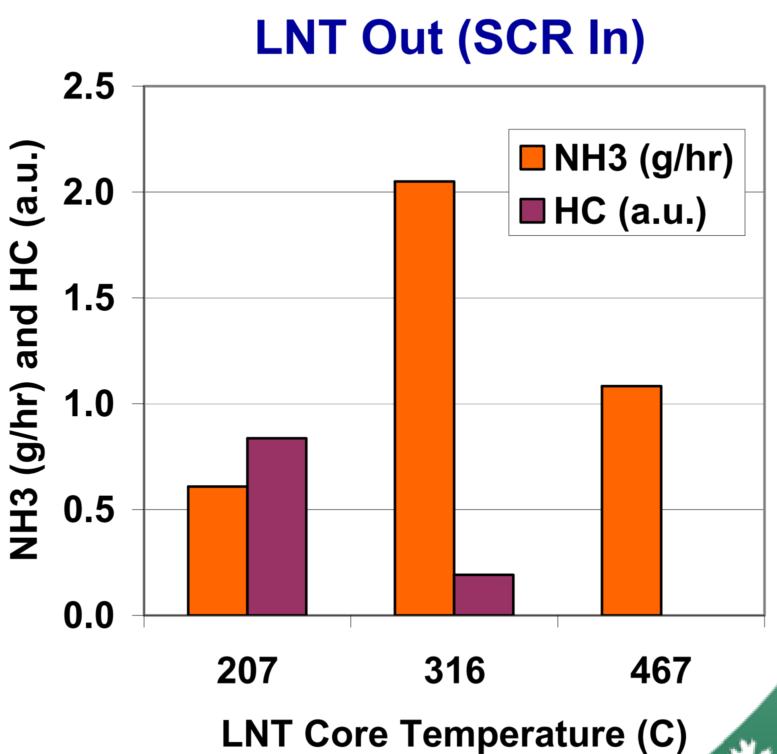




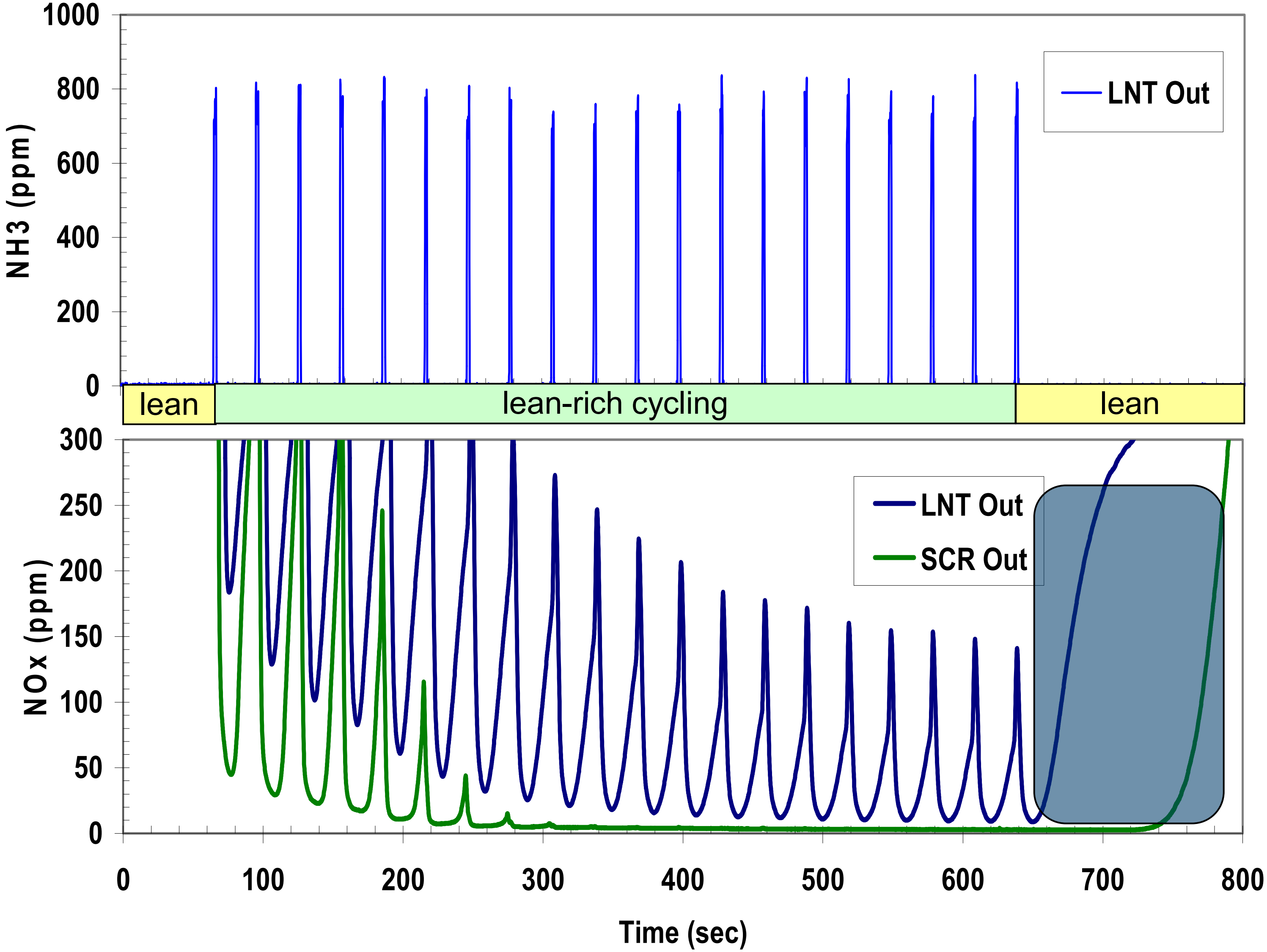
NH_3 production limits SCR NOx reduction

- 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





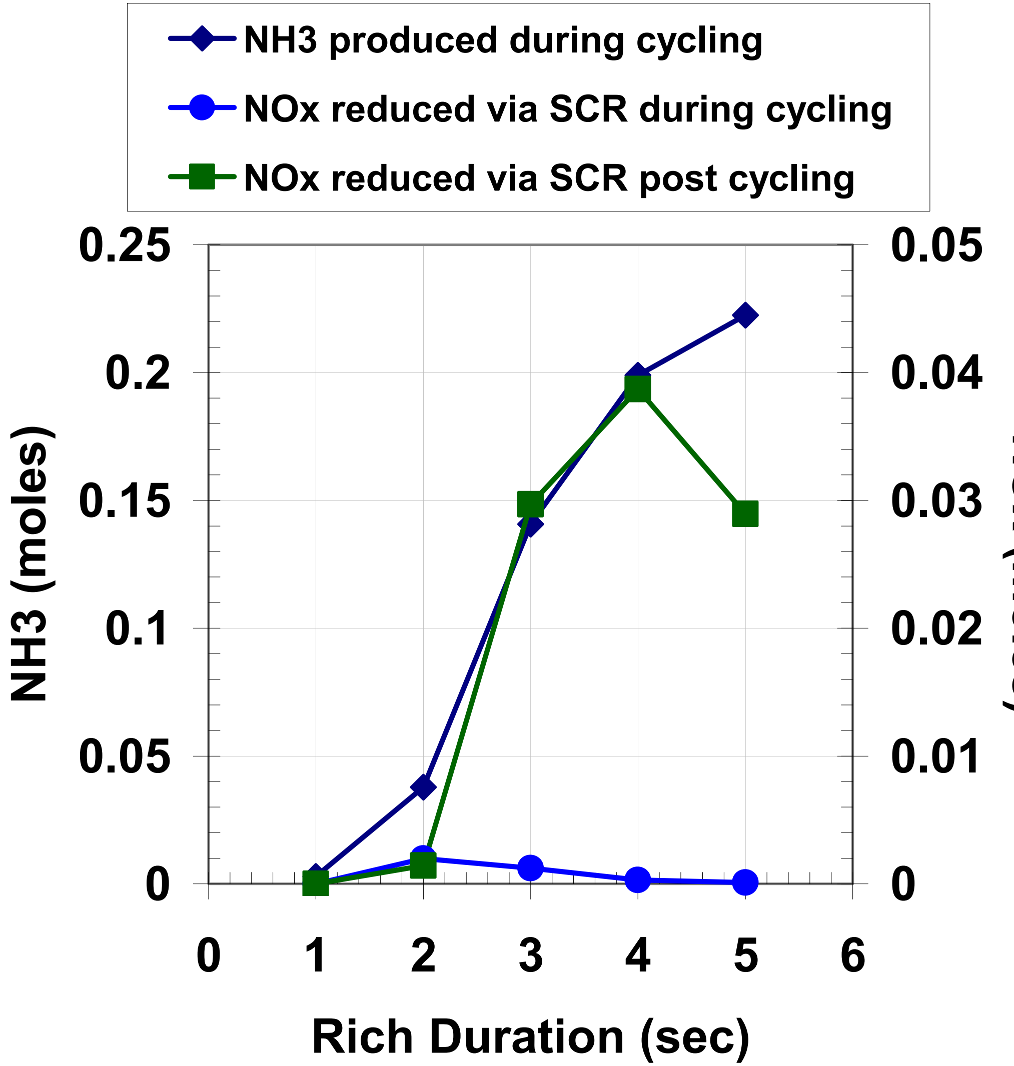
Following results after lean-rich cycling stopped…



Following results are presented for lean period after 10 minutes of lean-rich cycling

Stored NH_3 vs. rich period consistent with NOx reduction after lean-rich cycling, but magnitudes differ

- **Engine Conditions: 1500 rpm and 5.0 bar**
- **Most NH_3 ends up being stored**
- **NH_3:NOx molar ratio ~5 for stored NH_3 vs. NOx reduction after lean-rich cycling**
- **Oxidation of NH_3 on SCR may be occurring during cycling**



Summary

- **Combining LNT with SCR in a LNT+SCR system enables excellent NOx reduction in diesel applications**
  - **The performance is highly dependent on lean-rich parameters**
  - For shorter rich durations, the SCR contribution to overall NOx reduction is limited by NH_3 production
  - For longer rich duration, the SCR contribution is limited by less LNT NO_x slip
- **Details of NH_3 formation observed in engine experiments during LNT regeneration were consistent with previous bench flow reactor studies**
- **Greatest benefit of the LNT+SCR system may be in low load periods of transient operation where stored NH_3 can be utilized for NOx reduction instead of more regeneration, but…oxidation of NH_3 may limit overall NH_3 efficiency**