Effect of Regeneration Strategy on LNT-SCR Hybrid System Performance

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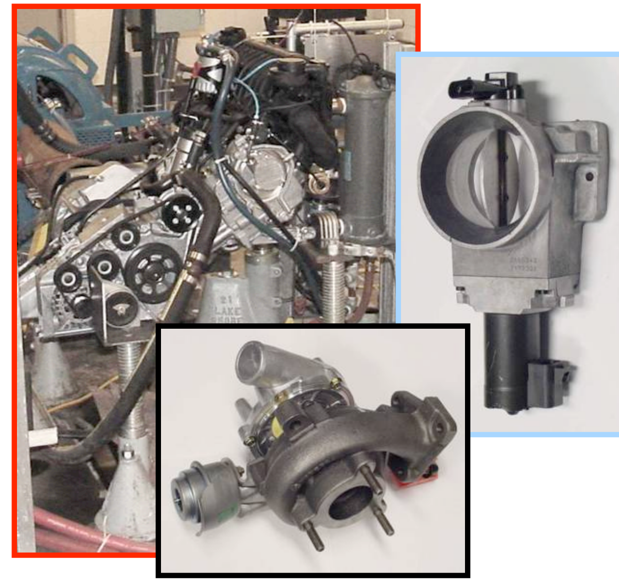
This work is undertaken to investigate the potential synergies of LNT and SCR for treating NO_x emissions from a diesel engine

- **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
    - **Characterizing NH_3 formation during LNT regeneration**
  - Reduces burden of LNT in NO_x reduction
    - **What is SCR's contribution to NO_x reduction in LNT-SCR system?**
  - Prevents NH_3 slip
    - **How is NH_3 utilized in LNT-SCR system?**

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

Approach: operate multi-cylinder diesel engine with in-cylinder LNT regeneration strategy and study synergies of LNT with SCR



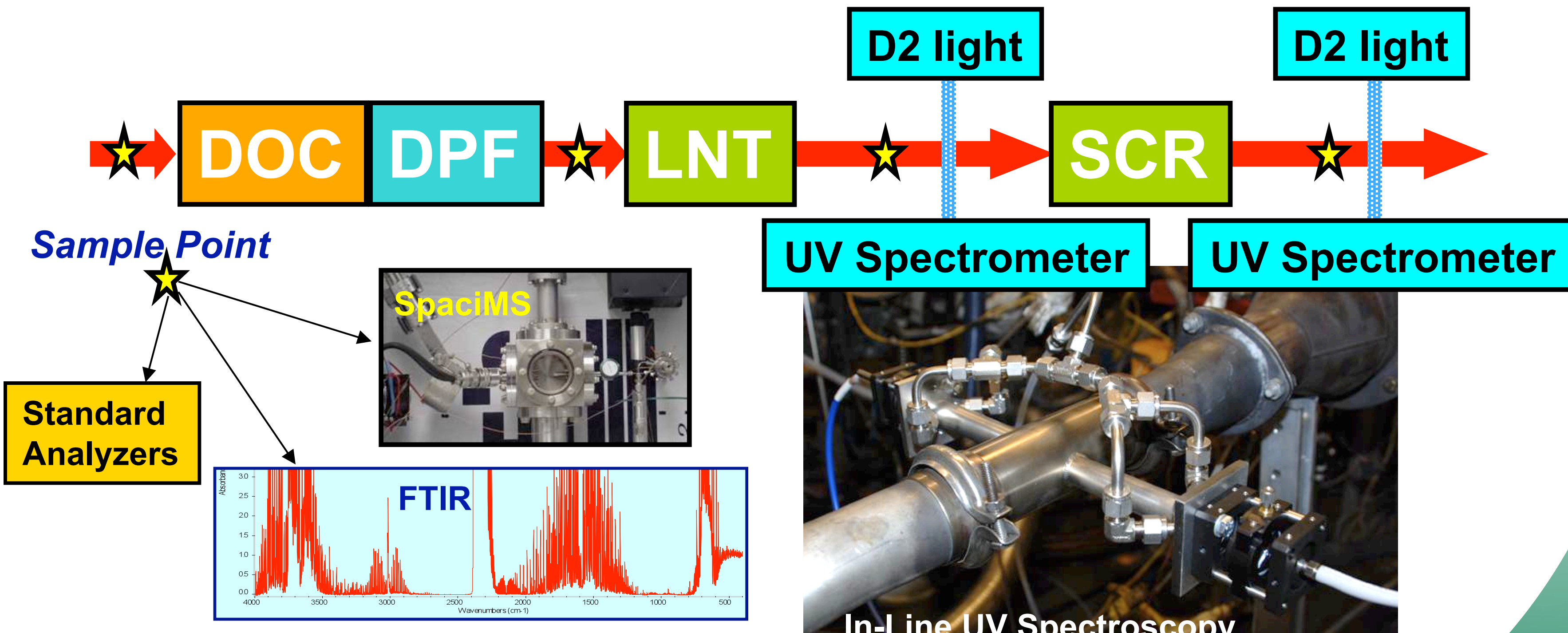
- **Engine**
  - Modified 1.7-liter, 4-cylinder
  - High-pressure common rail
  - Full-pass control system (8 event)
  - Variable geometry turbocharger
  - Cooled EGR with low and high flow valves and electronic throttling
- **Catalyst System**
  - DOC and DPF (SiC) were installed upstream of LNT-SCR
  - 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: Engine Conditions

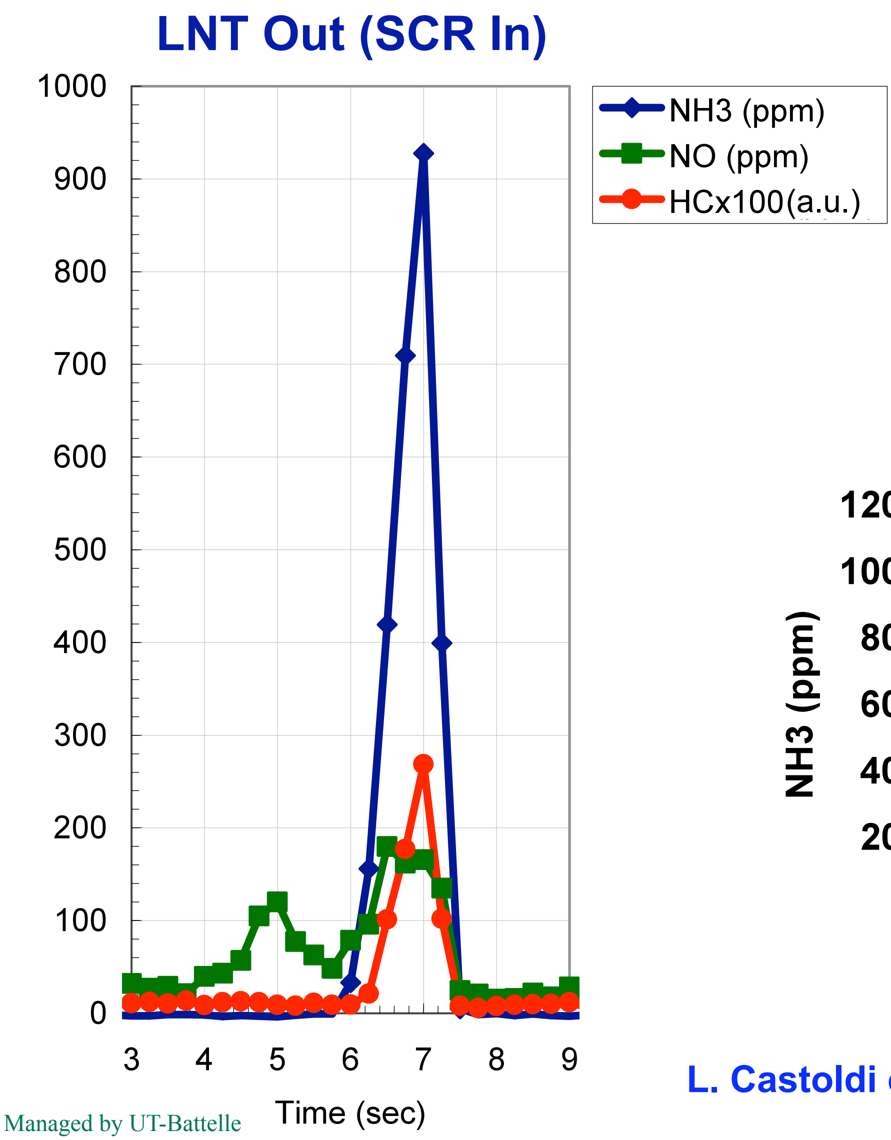
- **Evaluate catalyst system at different engine speed/load points**
- **Operate engine with/without EGR at each speed/load point**
  - No EGR: low PM and CO/HCs, high NO_x
  - OEM EGR: moderate PM, NOx, and CO/HCs
- **Vary LNT regeneration duration from 1 to 5s for a 30s cycle while maintaining minimum AFR of 13.5**
  - O_2 reduction using throttle
  - Fuel enrichment by delaying and extending main (DEM) injection pulse

Experiment Notes: Analytical Tools

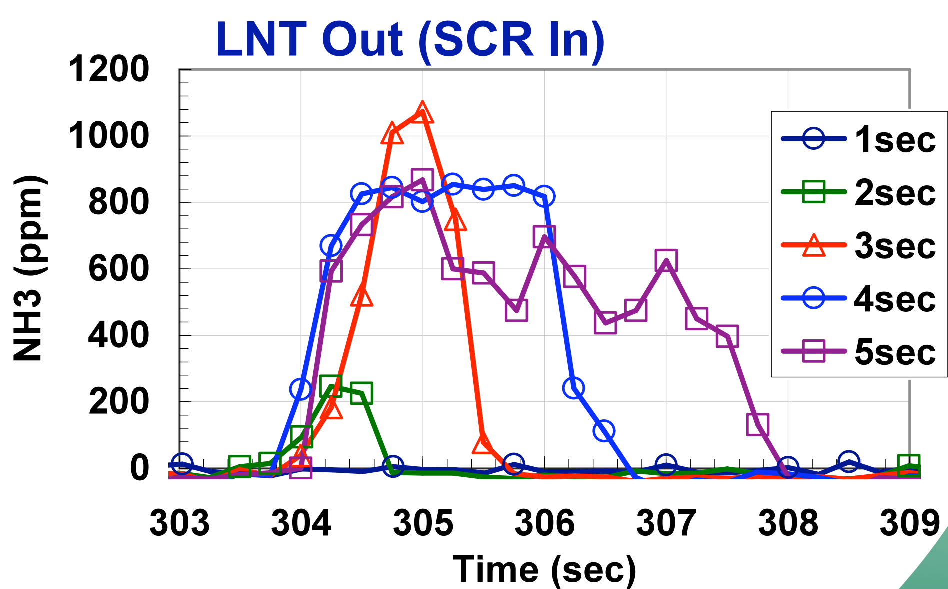
- Standard analyzers for CO (NDIR), HC (FID) and NO_x (CLD)
- Magnetic sector SpaciMS for H_2
- FTIR for NH_3, N_2O, NO_x, HCs, and other species
- UV spectroscopy for fast in-line measurement of NH_3, NO_x, and HCs



Temporal profile of NH_3 production consistent with bench 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

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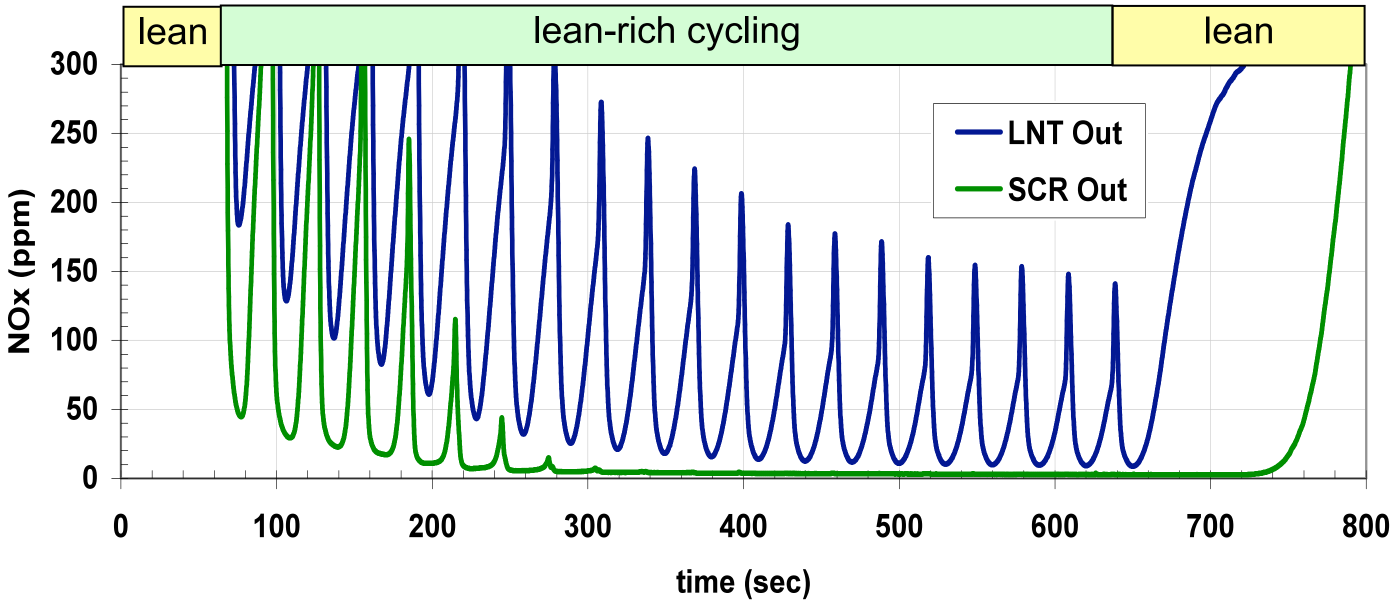
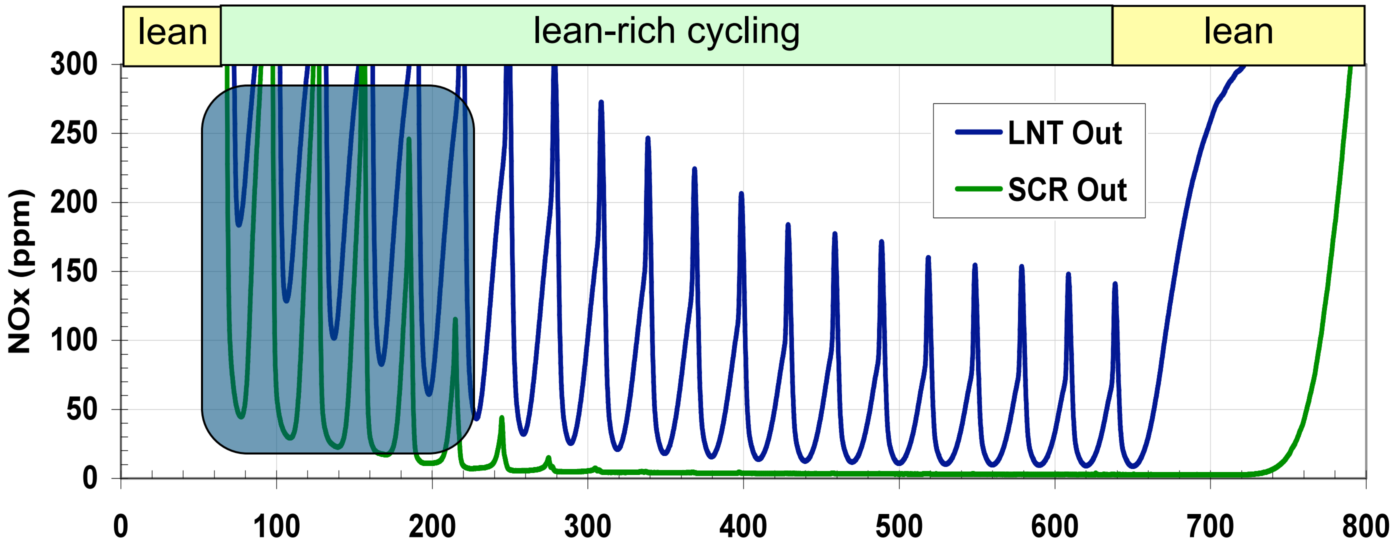
Typical set of LNT and SCR out NO_x emission data



- **1500 rpm, 50ft-lbs, 27s/3s lean/rich cycling (EO NO_x = 500ppm)**
- **SCR benefits overall NO_x reduction when LNT NO_x reduction not complete**
- **Both NO dominated NOx puff and NO_2 dominated NOx slip can be reduced by SCR**
- **Excess NH_3 stored by SCR enables more NO_x reduction after cycling ends**

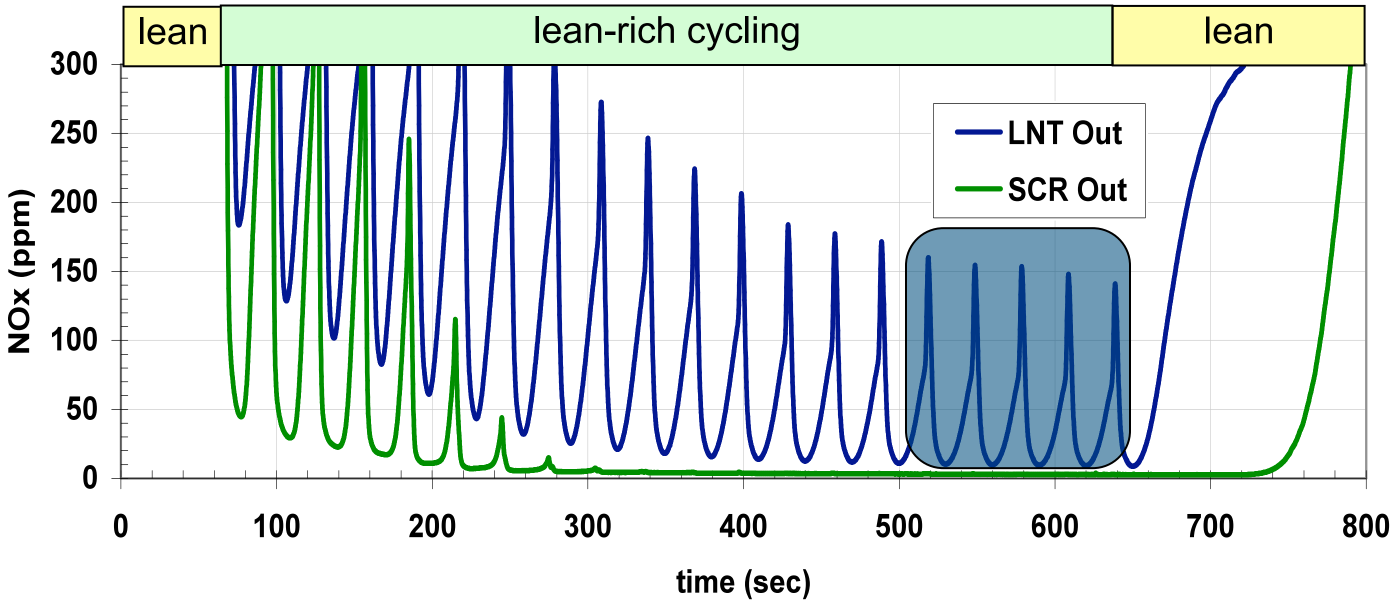
Typical set of LNT and SCR out NO_x emission data



As lean-rich cycling begins, NH_3 is produced and used rapidly to control NO_x slip

- = 500ppm)
- eduction not complete
- x slip can be reduced by SCR
- Excess NH_3 stored by SCR enables more NO_x reduction after cycling ends

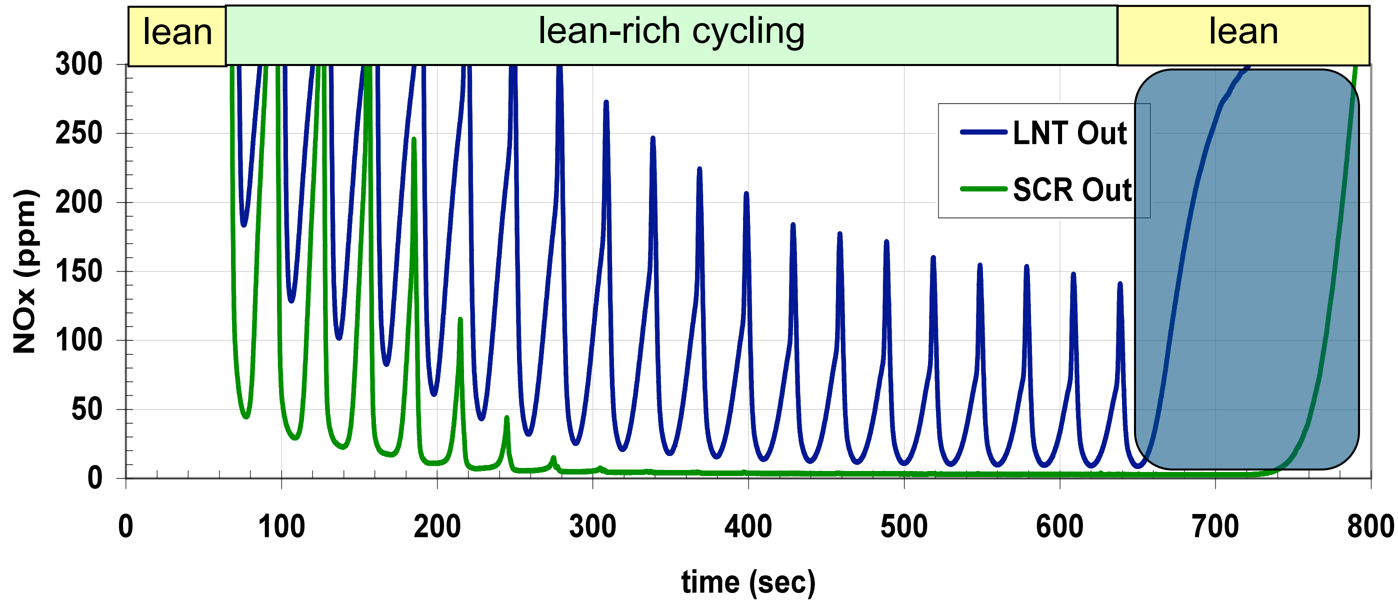
Typical set of LNT and SCR out NO_x emission data



- **1500 rpm, 50ft-lbs, 27s/3s lean/rich cycling (EO NO_x = 500ppm)**
- **SCR be complete**
- **Both N reduced by SCR**
- **Excess ing ends**

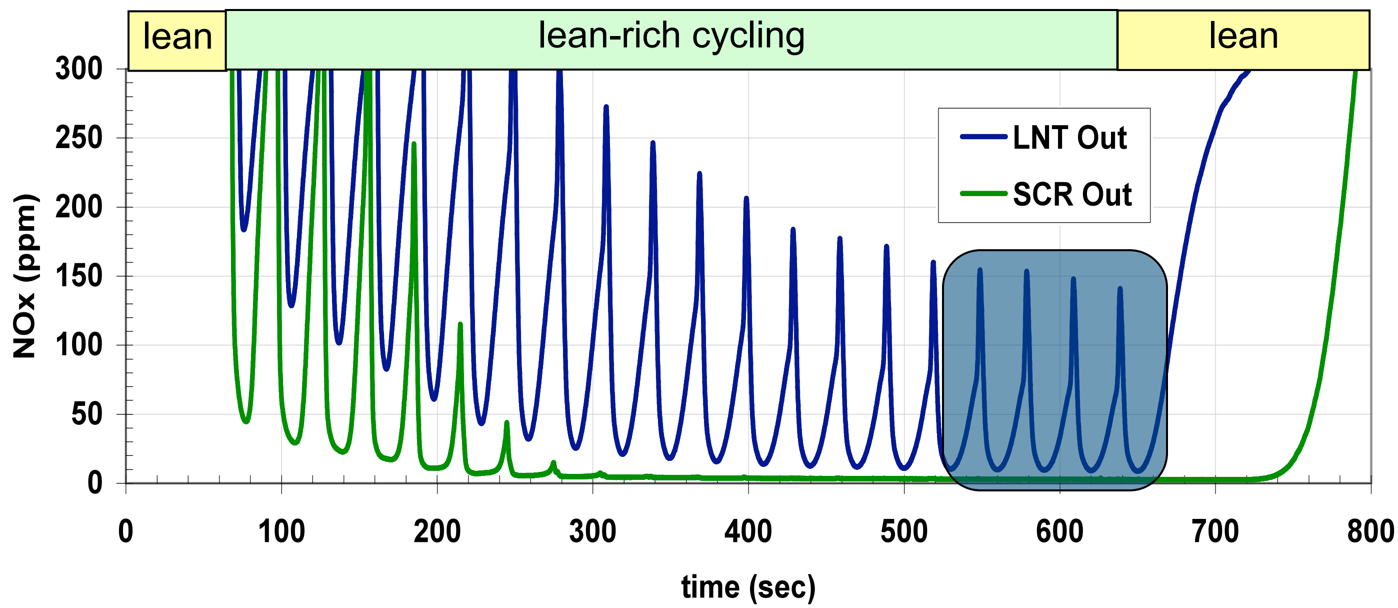
As steady state conditions are approached, SCR controlling nearly all NO_x slip and excess NH_3 being stored

Typical set of LNT and SCR out NO_x emission data



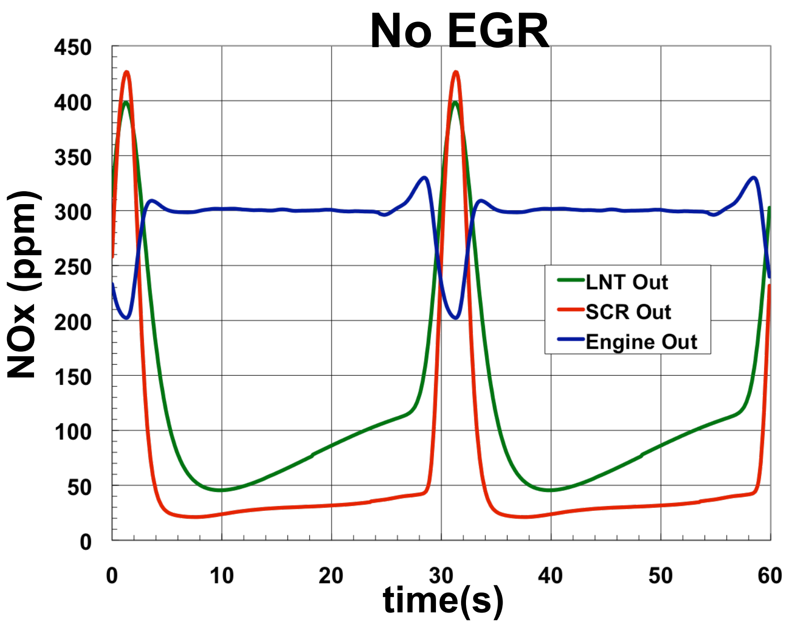
- 1500 rpm, 50ft-lbs, 27s/3s lean/rich cycling (EO NO_x = 500ppm)
- SCR benefits overall NO_x reduction when LNT NO_x reduction not complete
- Both NO dominated NOx puff and NO_2 dominated NOx slip can be reduced by SCR
- Excess NH_3 stored b

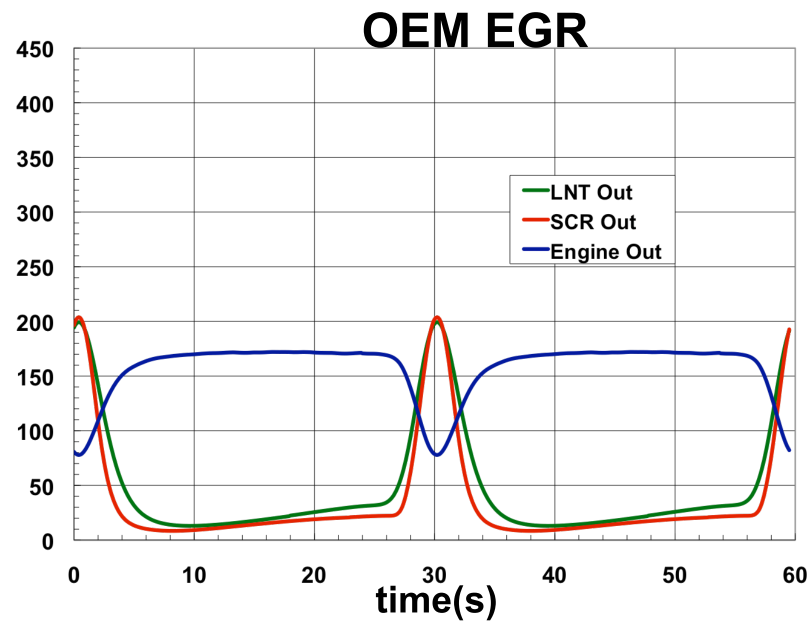
After lean-rich cycling ends, stored NH_3 on SCR continues to reduce NO_x until NH_3 depleted



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

Example of raw data for 1500 rpm / 2.6 bar with and without EGR



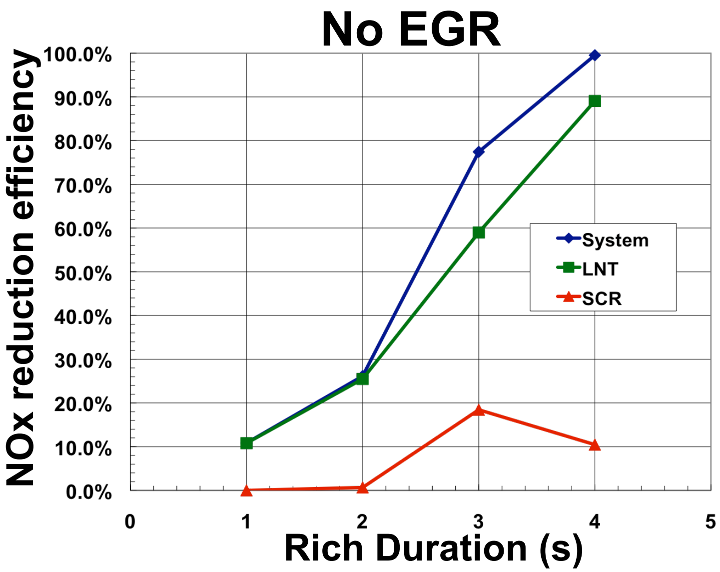


- **EO $BSNO_x$ = 3.5 g/bhp-hr**
- LNT/SCR SV = 24000 1/hr
- LNT T in varied from 225C to 310C as regeneration time increased

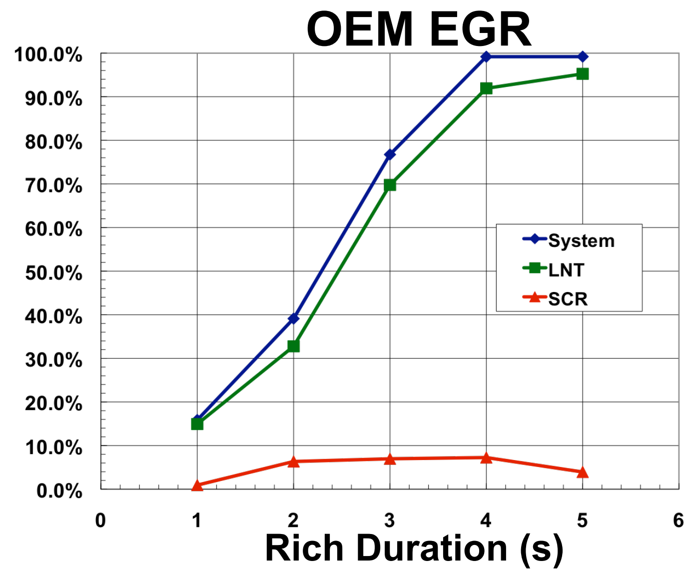
- **EO $BSNO_x$ = 2.1 g/bhp-hr**
- LNT/SCR SV = 23000 1/hr
- LNT T in varied from 242C to 325C as regeneration time increased

SCR benefits overall NO_x reduction when LNT NO_x reduction not complete

Engine Out NOx=3.5 g/bhp-hr

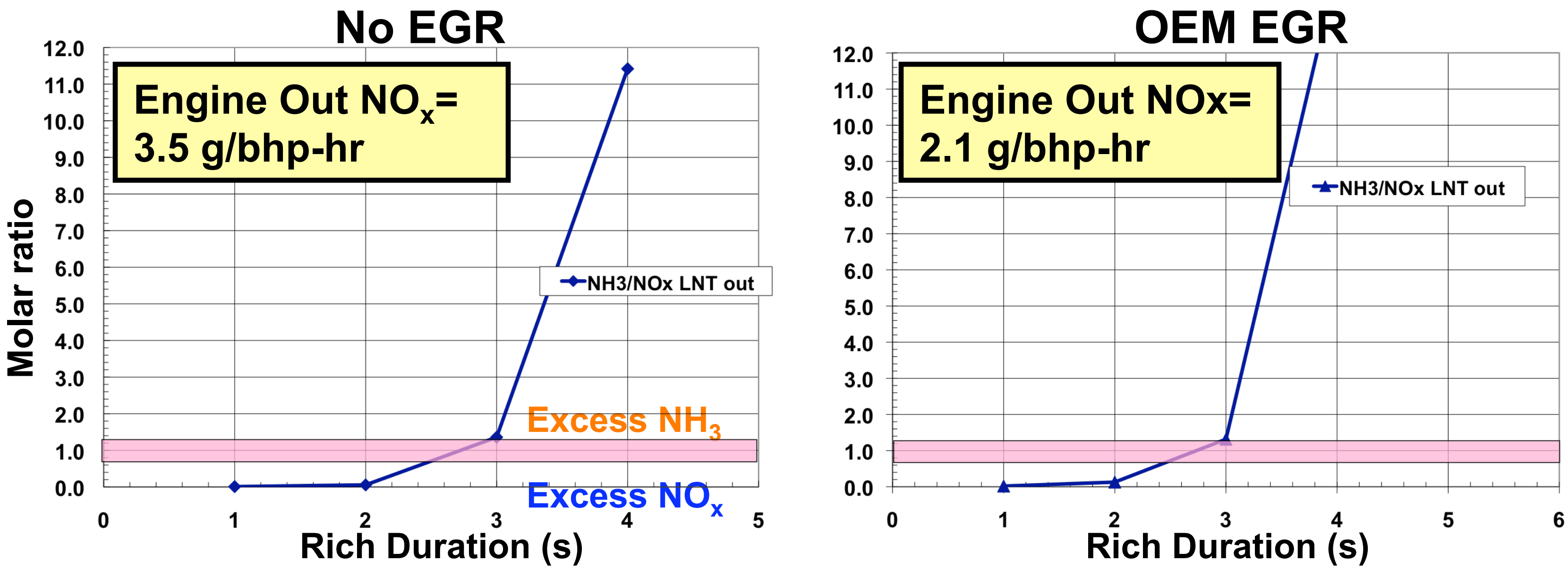


Engine Out NOx=2.1 g/bhp-hr



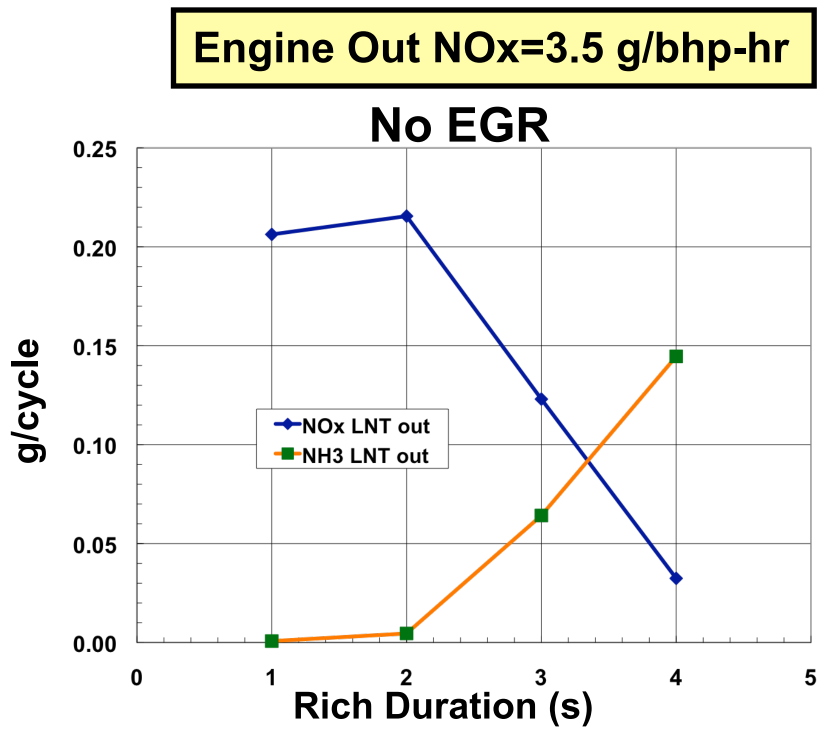
- **SCR contribution to overall NO_x reduction initially increases with increasing regen duration, then levels off and finally decreases**
- **Pick SCR contribution is higher for no EGR case (higher NOx loading)**

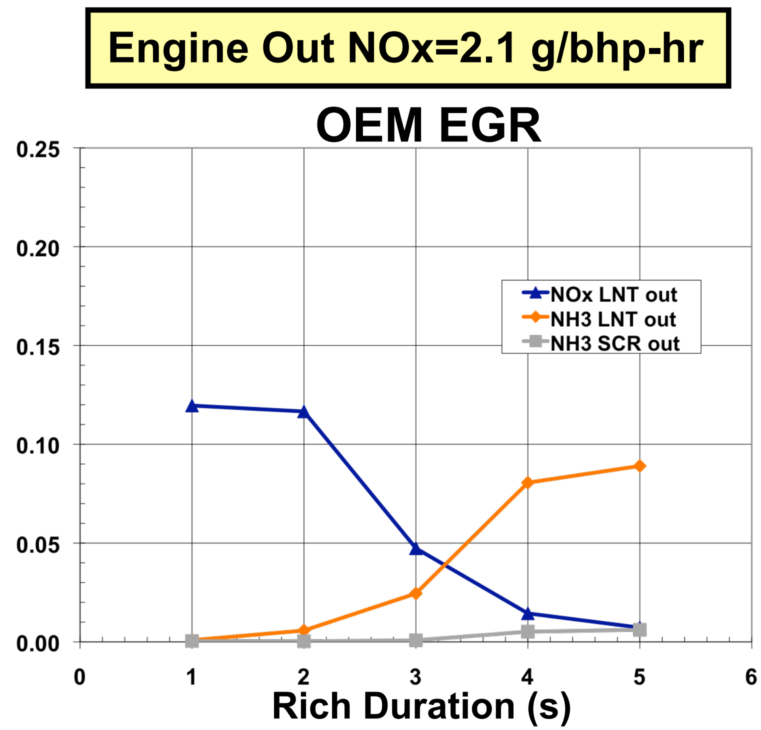
LNT out NH_3/NO_x=1 molar ratio is needed for optimal operation of LNT-SCR system



- **NH_3/NO_x ratio increases with increasing rich duration**
  - System's NO_x conversion increases with increasing rich duration while SCR contribution eventually decreases
  - high NH_3/NO_x ratios (>>1) at longer regen durations suggest that most of the excess NH_3 either goes unreacted through SCR or being stored by SCR
- **Near stoichiometric NH_3/NO_x molar ratio at 3s rich duration which is a point of highest SCR contribution to NO_x reduction: 18% for no EGR and 7% for OEM EGR cases**
- **NH_3/NO_x >> 1 for EGR case at 4 and 5s regen (14 and 32)**

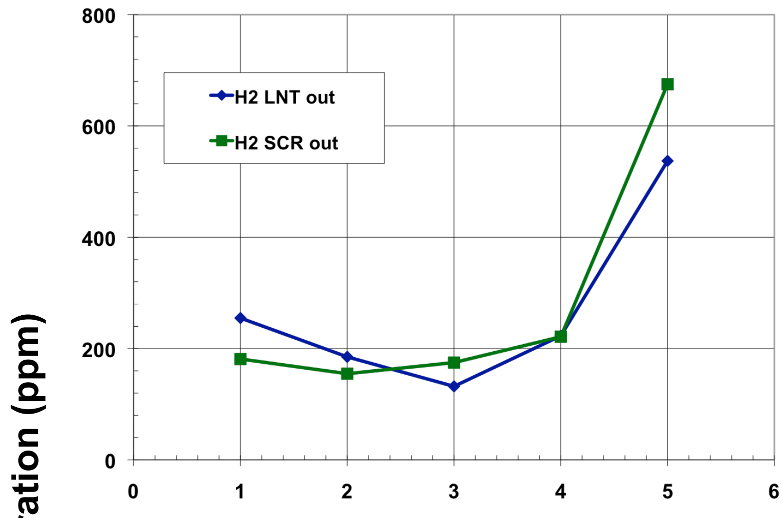
SCR contribution to overall NO_x reduction initially increases with increasing regen duration, then levels off and finally decreases

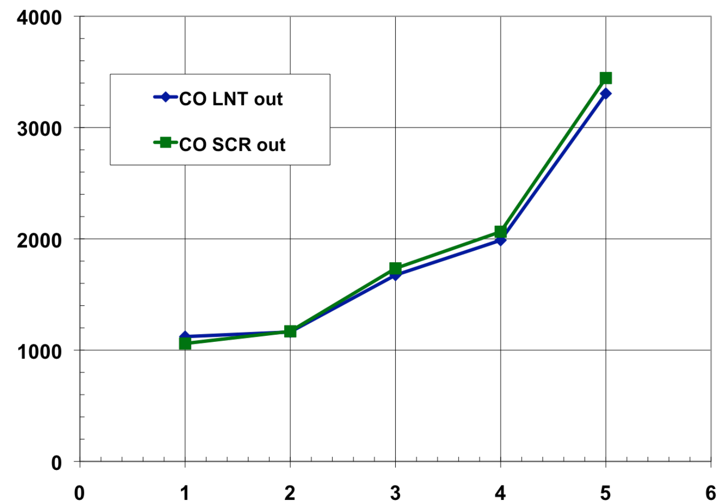


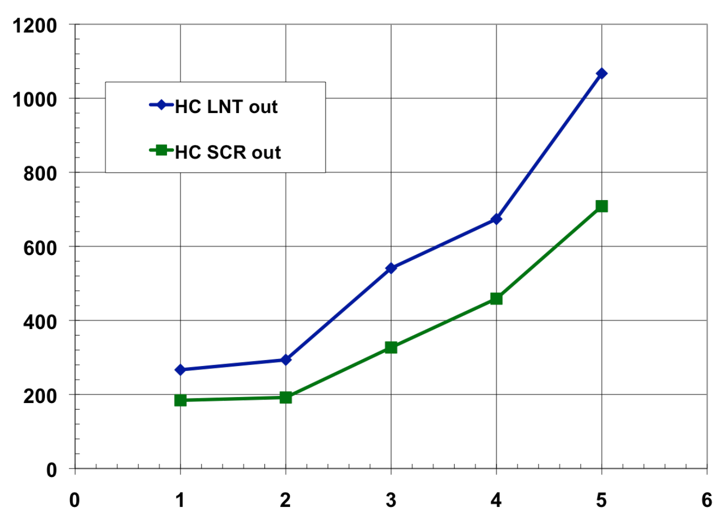


- **Extending rich duration increases NH_3 production**
  - **At shorter regen times SCR contribution is limited by NH_3 generation due to limited reductant availability**
- **Extending rich duration decreases LNT NO_x slip**
  - **At longer regen times SCR contribution is limited by LNT NO_x slip**

Reductants at OEM EGR case







- **Reductant concentrations generally increase with increasing rich duration**
- **HC apparently being stored on SCR**

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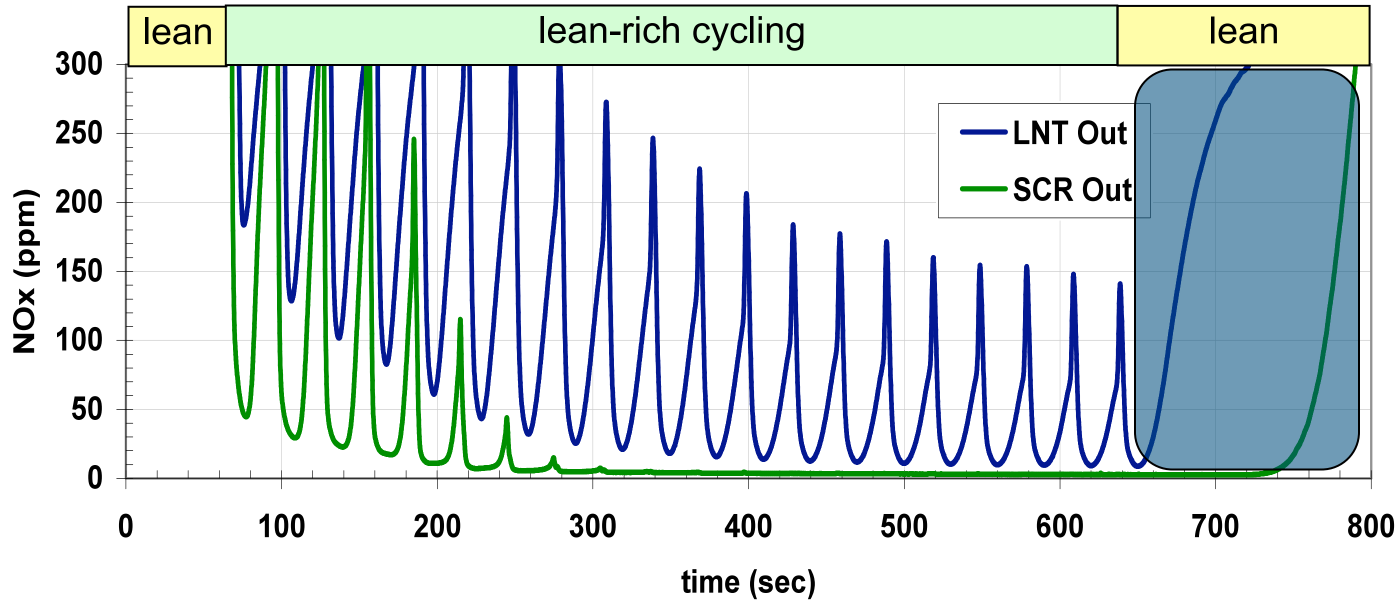
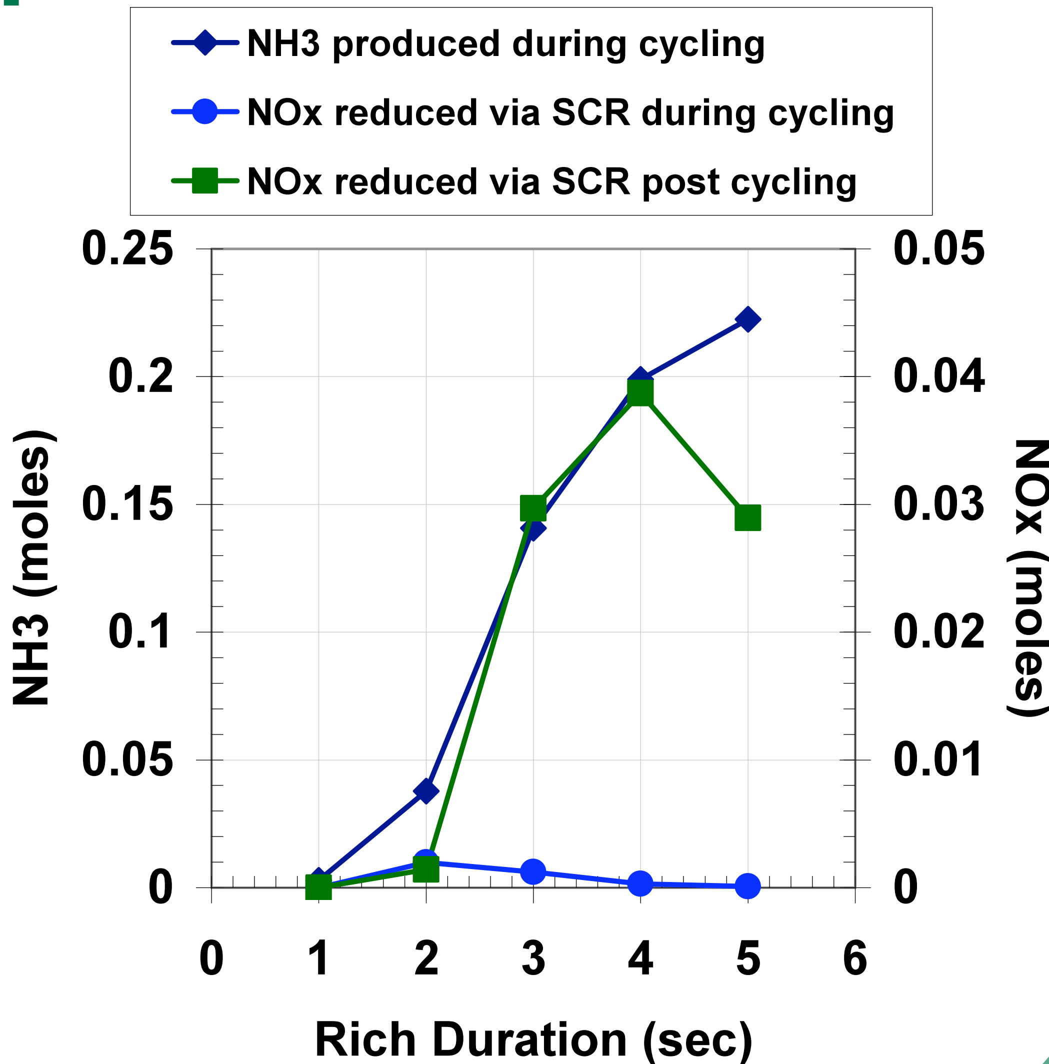


Following results are presented for lean period after 10 minutes of lean-rich cycling

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



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Summary

- Extending regen time increases NH_3 production and decreases LNT NO_x slip
  - At shorter durations SCR contribution is limited by NH_3 production
  - At longer duration SCR contribution is limited by LNT NO_x slip
- SCR contribution to system NOx reduction peaks when NH_3/NOx=1
- Greatest benefit of hybrid 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