Passive TWC+SCR Systems for Satisfying Tier 2, Bin 2 Emission Standards on Lean-Burn Gasoline Vehicles

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Passive TWC+SCR Systems for Satisfying Tier 2, Bin 2 Emission Standards on Lean-Burn Gasoline Engines

Fuel economy (FE) a major consideration for customers when purchasing vehicles, even with low fuel prices

Popular fuel economy actions on gasoline engines today include

- Engine down-sizing + turbocharging + direct injection
- DFSO during decels, Start-stop during idles
- Valve timing actions (iVCT)
- Cooled EGR
- Vehicle weight reductions (down-sizing, material changes)
- Cylinder deactivation
- Improved vehicle aerodynamics

Lean operation can improve FE vs stoichiometric operation

- Reduced pumping losses, thermodynamics of combustion
- 5 to 15% improvement, depending on reference and combustion strategy

In 2011 Ford began 4.5-year DOE program to improve the fuel economy of its Taurus by 25% while meeting Tier 2, Bin 2 emission standards (later Tier 3, Bin 30)

- 3.5 L PFI to 2.3 L GTDI engine
- Lean cruises considered as an optional FE action
- 2 Passive approaches (i.e., no customer action) → TWC+LNT/SCR, <u>TWC+SCR</u>
- Both require periodic rich operation to purge LNT and/or make NH_3 for the SCR

TWC+SCR Systems Major Challenges

High NO_x conversion during lean/rich cycling

<u>Without a LNT, no NOx is stored during lean operation</u>

- All NH_3 comes from FG NO during purges
  → need low FG NO lean, high FG NO rich

Rich periods reduce fuel economy benefit from lean operation

<u>Limited opportunities for lean operation on the FTP</u>

<u>HC and CO slip during rich periods</u>

Stratified-charge operation can generate high PM and NOx levels
→ Homogenous lean-burn, limits fuel economy improvement

Cost of aftertreatment

N_2O emissions

Sulfur poisoning

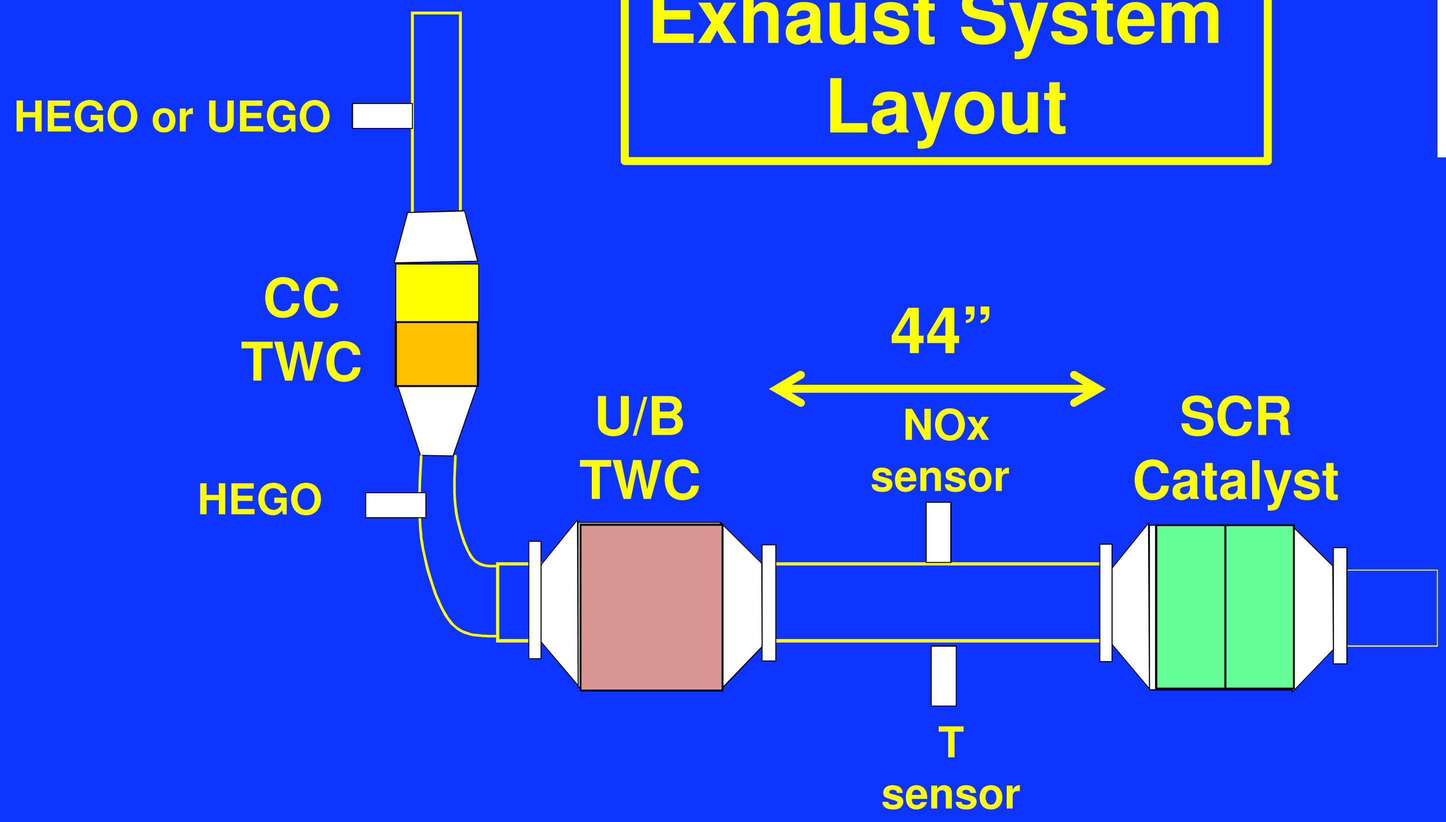
Emission Budgeting

Tier 2, Bin 2 Standards	NMHC	NOx	CO
Emission Requirement	10 mg/mile	20 mg/mile	2.1 g/mile
Engineering tolerances	1.7	5	0.5
Cold-start emissions	~7	7	0.3
Stoichiometric emissions (Post-lightoff)	~0	3	~0
Lean/rich cycling	1.0 mg/mile	5.0 mg/mile	1.3 g/mile

Assumed engine-out PM would satisfy Tier 2, Bin 2 standard of 10 mg/mile

- No GPF

Exhaust System Layout



Assumptions

Close-coupled TWC + U/B TWC to satisfy FTP & US06 standards

Third SCR converter downstream for lean NO_x control

- **44" from outlet of U/B TWC to achieve 300-350°C during FTP**

Catalysts

CC TWC	Medium OSC	40 or 200 gpcf Pd/Rh
	No OSC	200 or 116 gpcf Pd only

Most CC TWC samples aged on 4-mode schedule (960 C max)
Exception: No OSC with 116 gpcf Pd degreened 2 hrs 800 C lean

U/B TWC 26 gpcf Pt on Ce/Zr Model catalyst
26 gpcf Pd on Ce/Zr Model catalyst

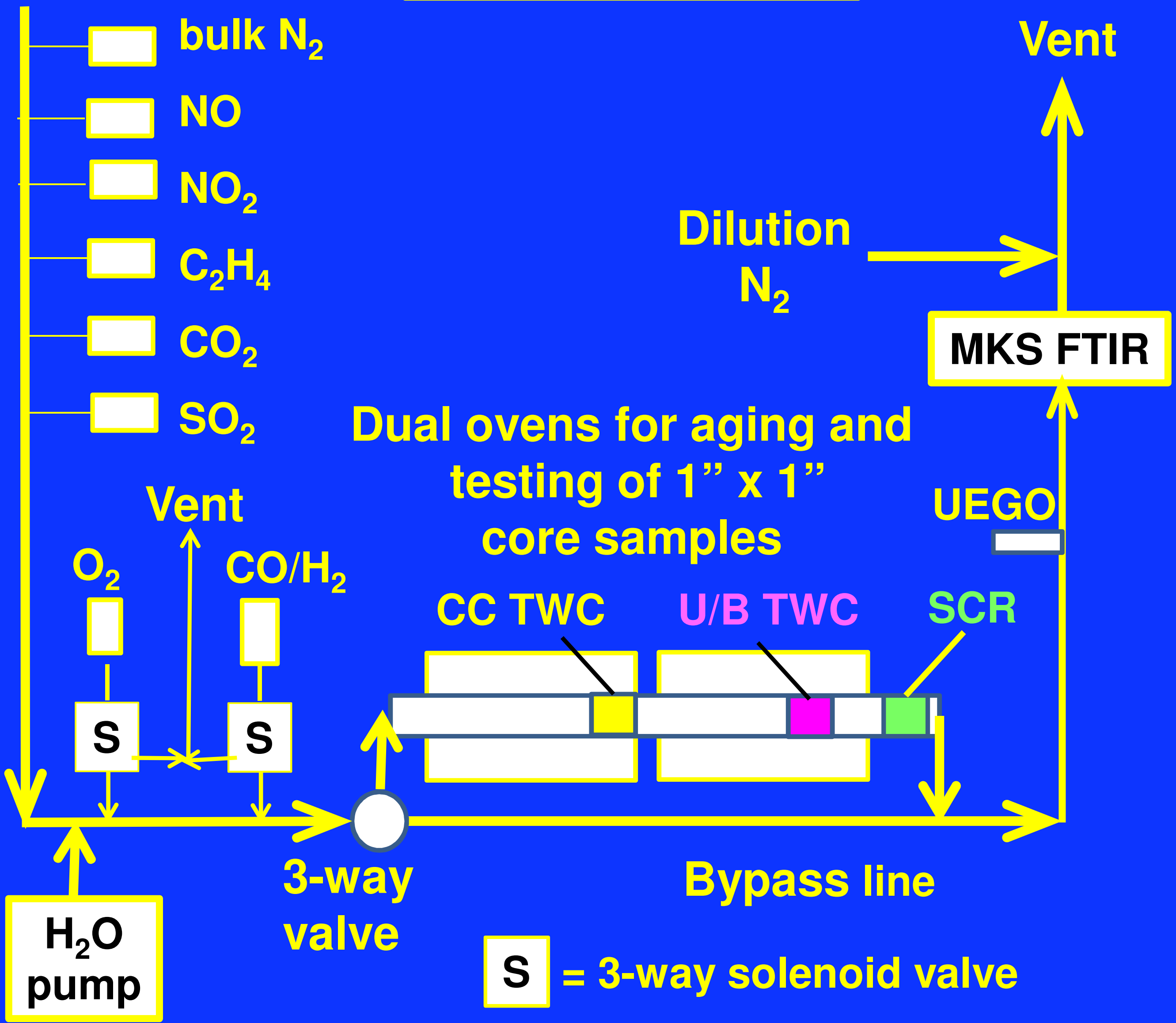
U/B TWC samples aged 175 hours at 800 C in an oven

SCR - copper/chabazite formulation in production on Ford diesel trucks

Initial SCR samples aged on rig 20-25 hrs at 800 C lean or hydrothermally aged 80 hrs at 800 C lean

Later TWC+SCR systems were aged on 4-mode cycle

Flow Reactor



Some tests performed with CC TWC + SCR (i.e., no U/B TWC)

Some tests performed with CC TWC + U/B TWC + SCR

Flow Reactor Conditions

	Lean	Rich	Rich C2H4	Rich λ
O2 %	10 (2.0 λ)	None		
CO/H2 %	None	4.0/1.3 2.5/0.8 1.5/1.0 0.5/0.2 0.5/0.2	2,500 2,500 2,500 2,500 800	0.81 0.86 0.91 0.95 0.99
C_2H_4 ppm	2,500 800			
NO ppm	200	500 1,000 1,500 2,000		
H_2O %	5	5		
CO_2 %	5	5		

6.4 L/min flow
→ 30k hr^{-1} for 1" length

NH_3 yield =
(Ave NH_3)/(Ave FG NO)*100%

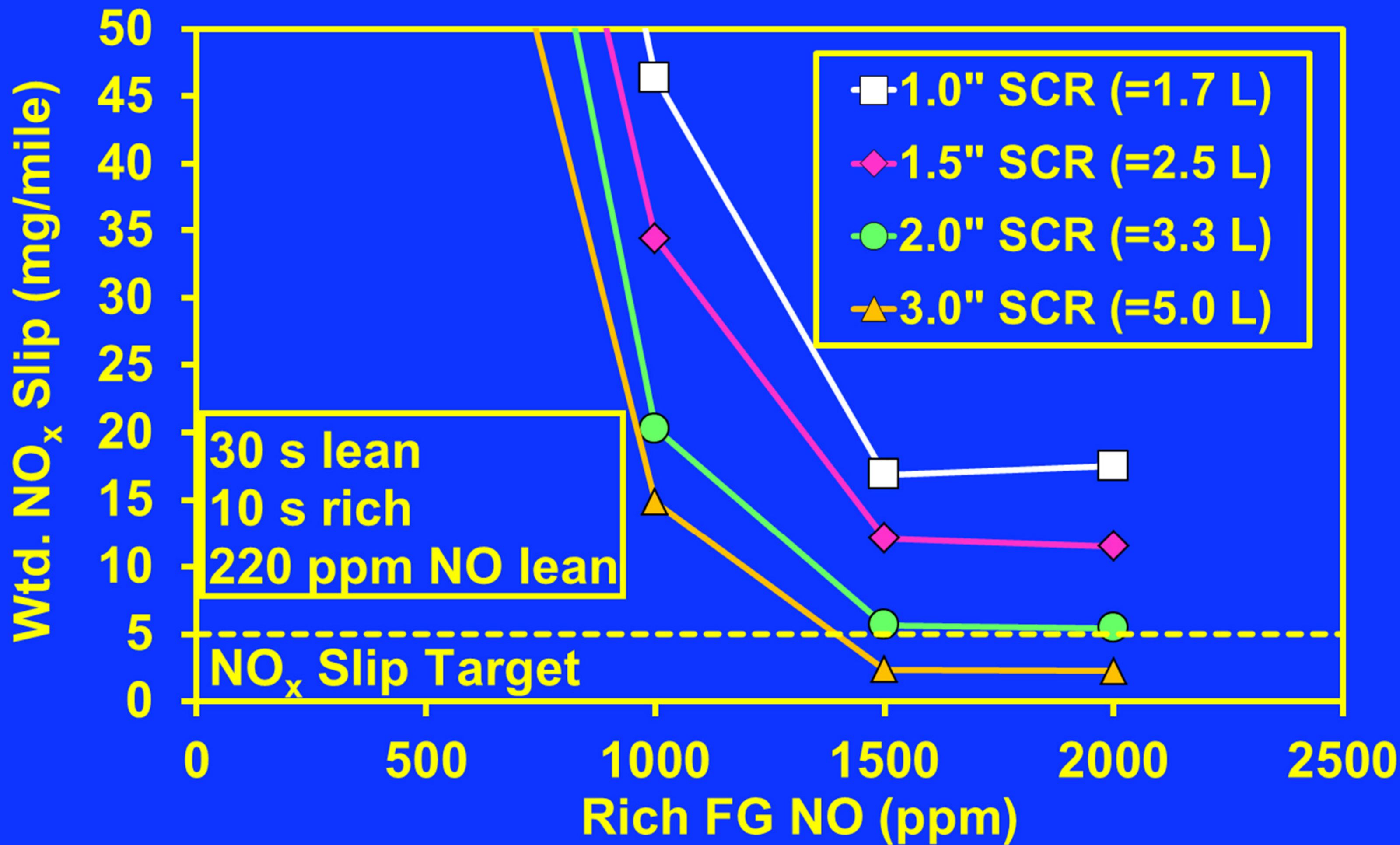
N_2O yield =
2*(Ave N_2O)/(Ave FG NO)*100%

"Purge test"
- **Lean duration constant**
- **Rich purge time varied**

Total lean weighted flow on vehicle during FTP used to convert ppm measurements from reactor into weighted emissions on vehicle during L/R cycling
- Compare with targets

Effect of SCR Volume & FG NO Level

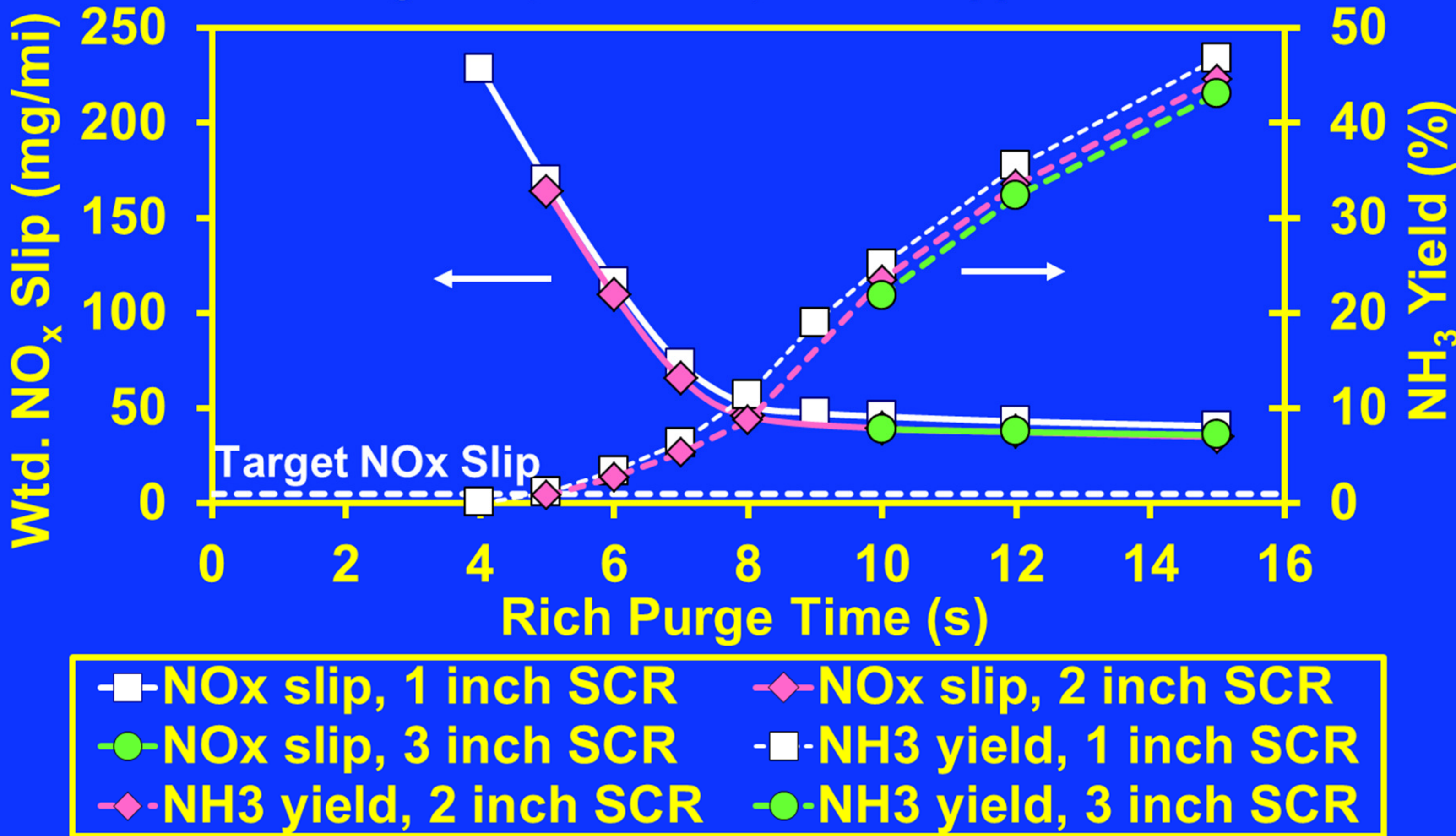
1" Reduced OSC TWC (116/40 gpcf), aged 960°C max, Eval 550°C
1.0, 1.5, 2.0, or 3.0" of SCR Catalyst, aged 800°C lean, Eval 330°C



With 220 ppm FG NO lean, data suggest that a 5 L SCR catalyst and 1500 ppm FG NO rich are needed to achieve NO_x slip target.

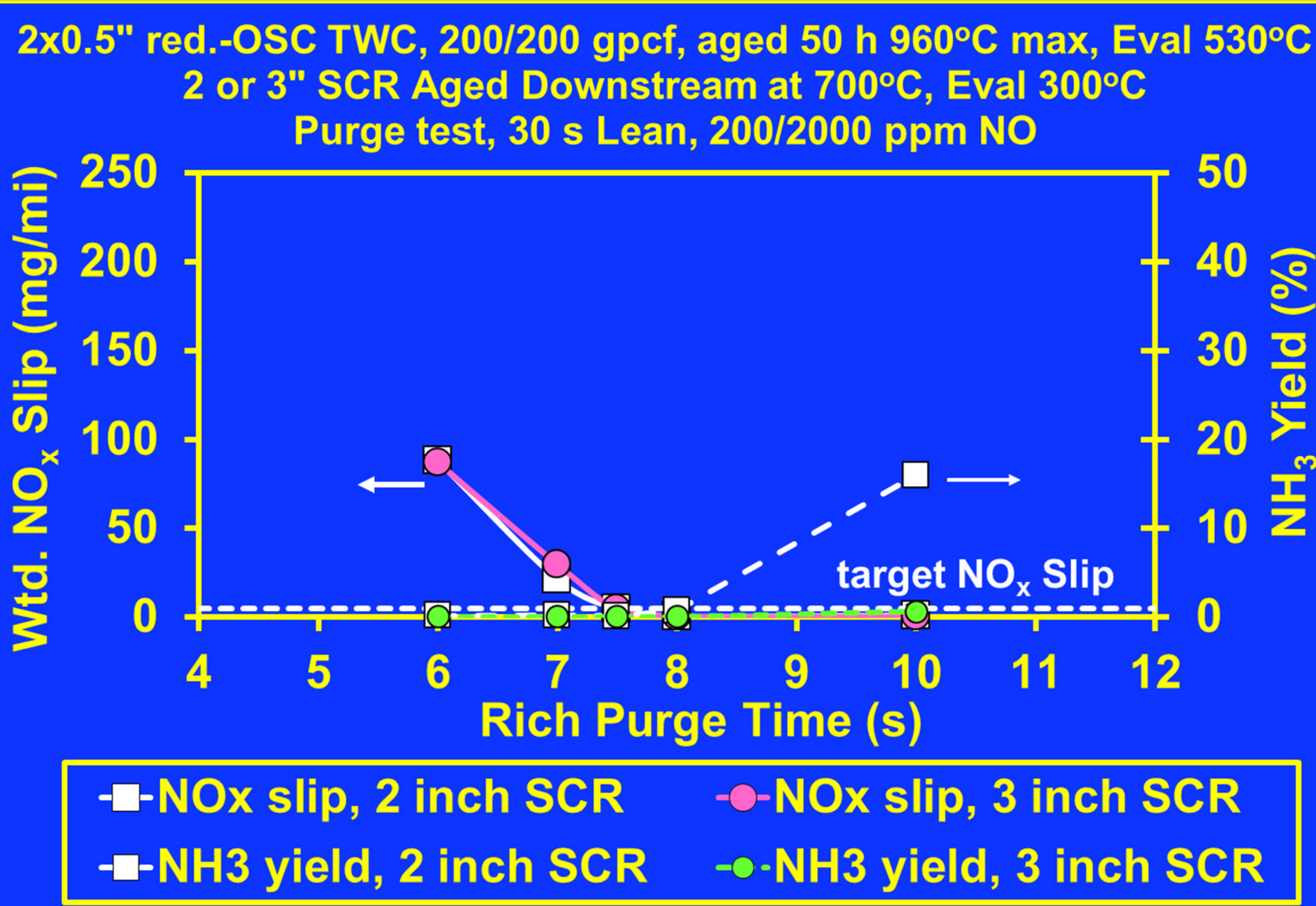
Effect of 4-Mode Aging on NOx Slip & NH3 Yield

2x0.5" red.-OSC TWC, 200/200 gpcf, aged 50 h 960°C max, Eval 530°C
1, 2, or 3" SCR Aged Downstream at 800°C, Eval 300°C
Purge test, 30 s Lean, 200/2000 ppm NO



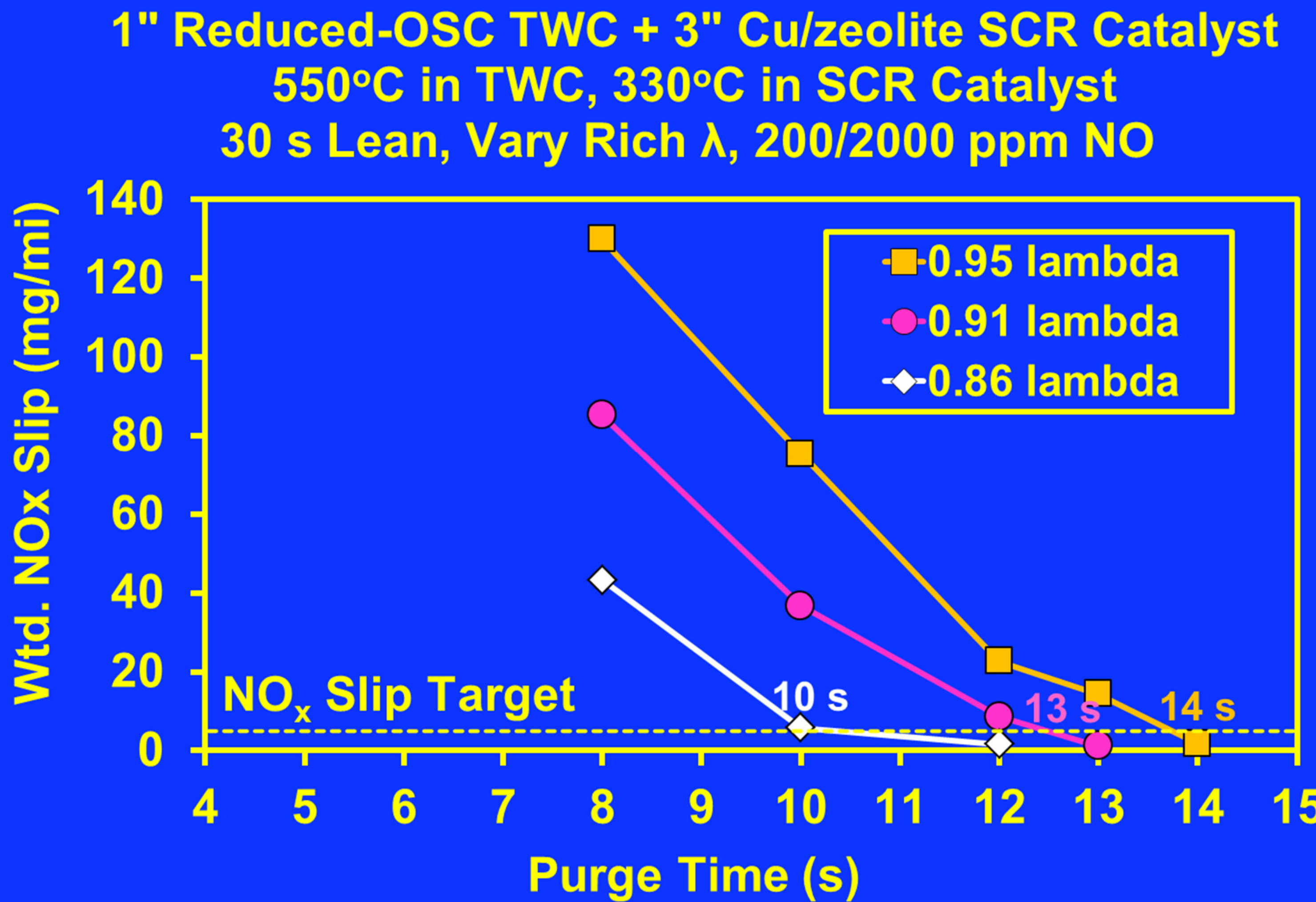
1, 2, or 3" of SCR catalyst did not satisfy NO_x slip target (even with 96% conv). High NH_3 yields suggest low NH_3 storage capacity after aging at 800 C in a lean/stoich/rich environment.

Effect of Thermal Aging on NOx Slip & NH3 Yield



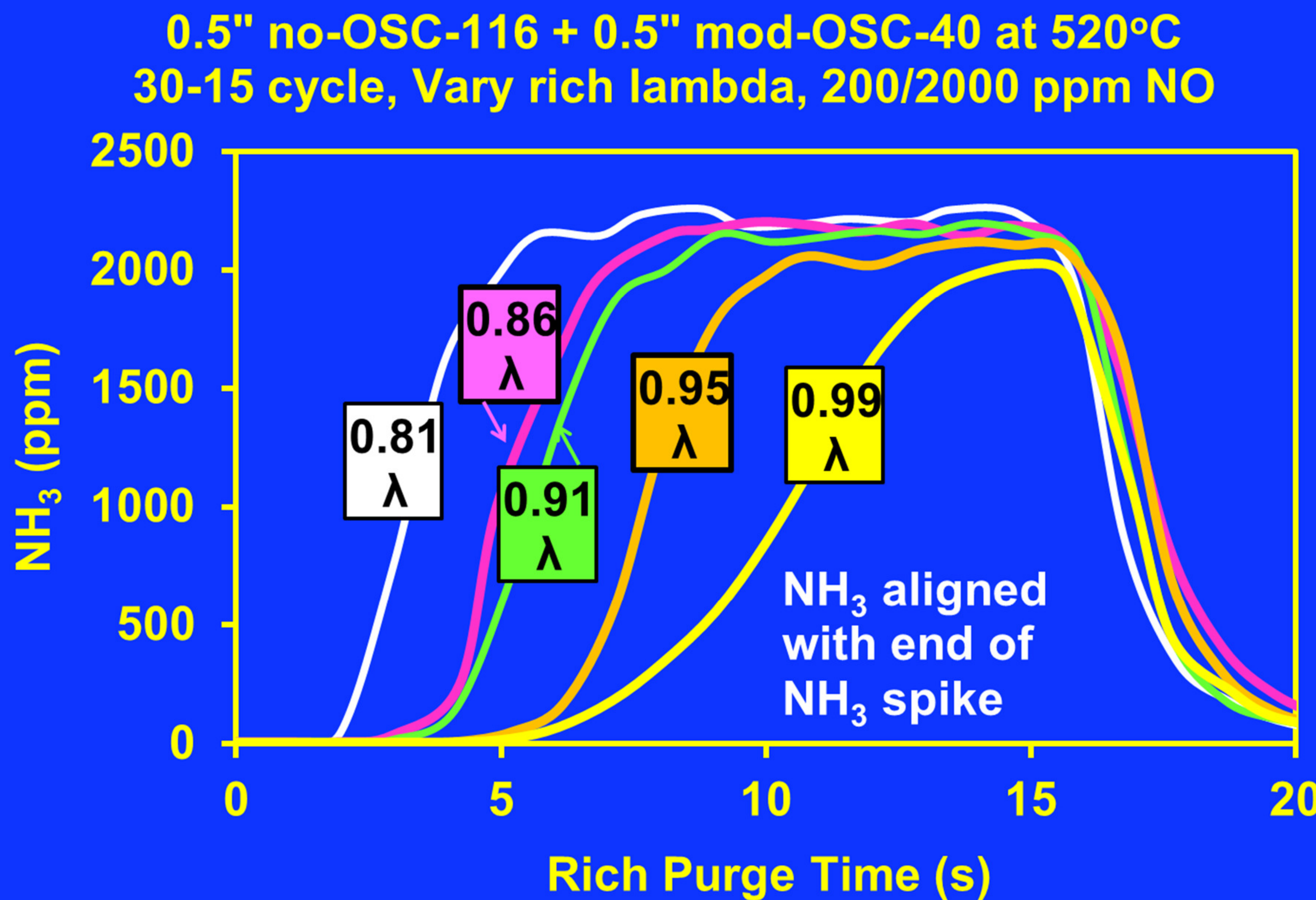
2" satisfied NO_x slip target but had some NH_3 slip with longer purges.
3" of SCR satisfied NO_x slip target with essentially no NH_3 slip.
The max aging temperature of SCR catalyst should be limited to 700 C when aging in a lean/stoich/rich environment.

Effect of Rich Duration & Rich Lambda



Longer purge times needed with less rich purges.

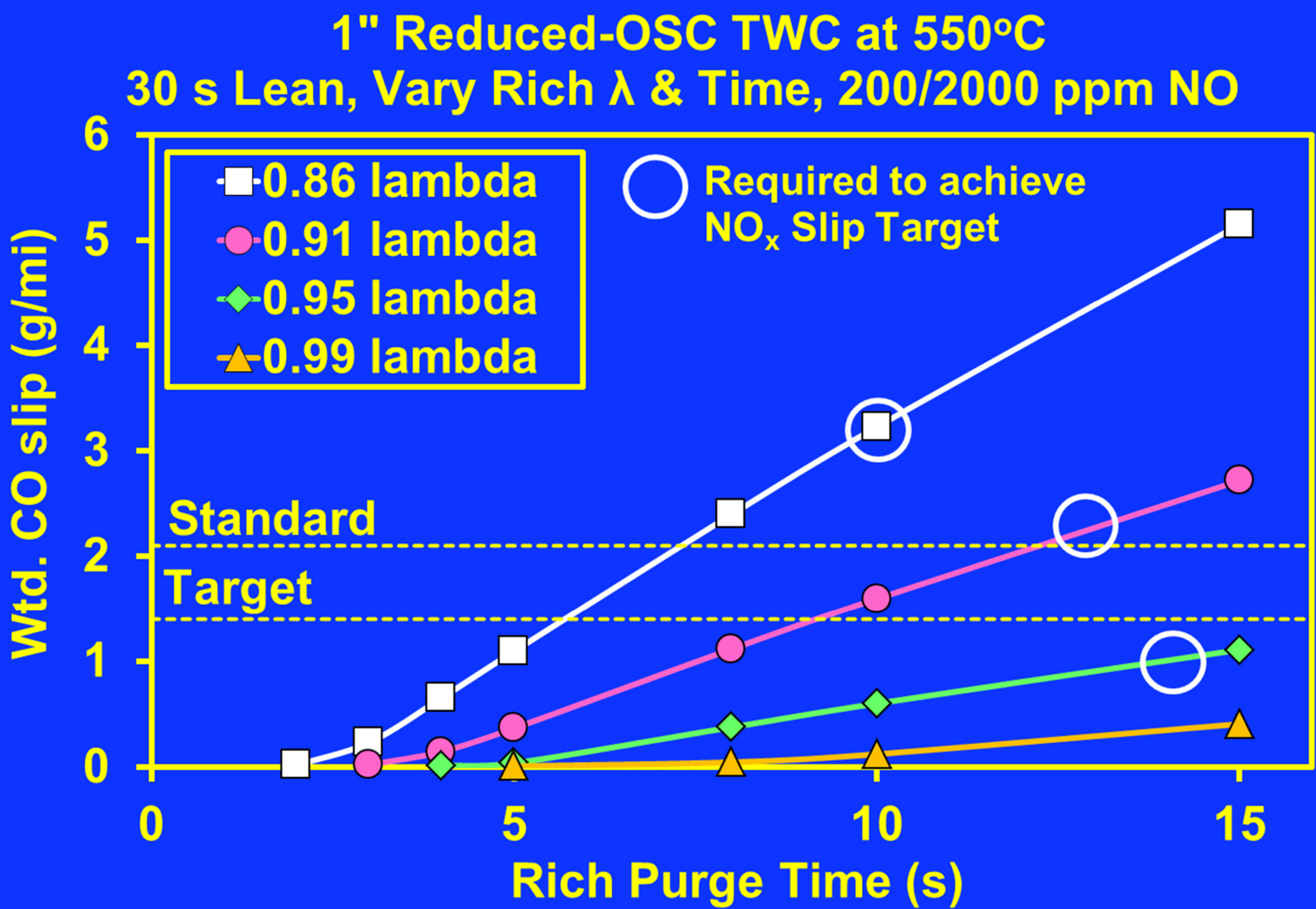
Effect of Rich λ and Duration on NH_3 Make



Longer purges needed because NH_3 generation is delayed due to OSC

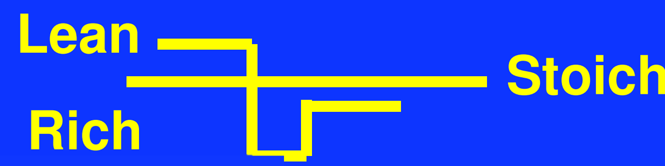
NH_3 yield eventually approaches 100% for all rich lambdas

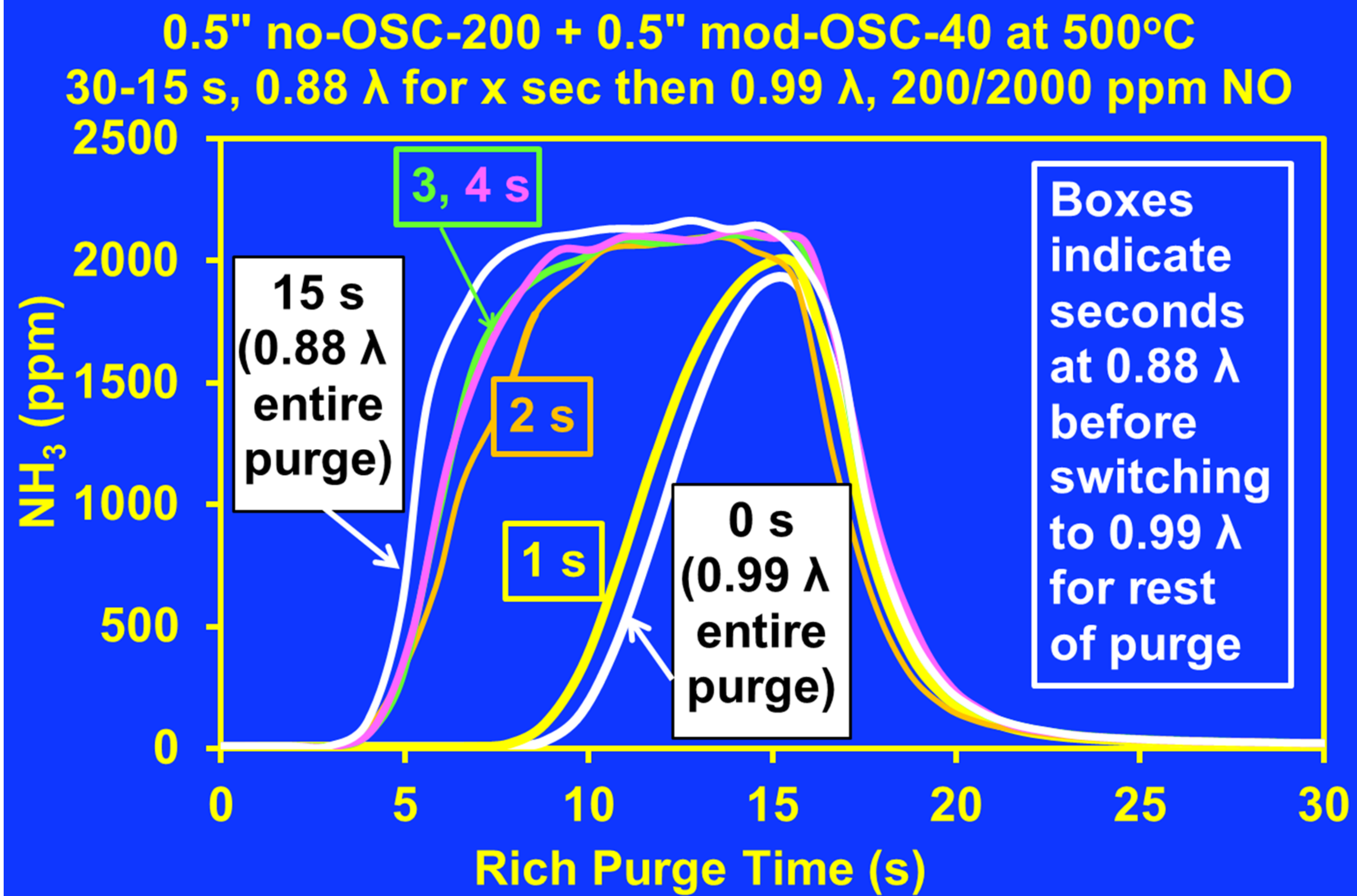
Effect of Rich λ and Duration on CO Slip



Cannot satisfy NOx and CO slip targets simultaneously at 0.86 & 0.91 λ
Both targets satisfied at 0.95 λ, but long purges required (FE)

Two-Step Purge

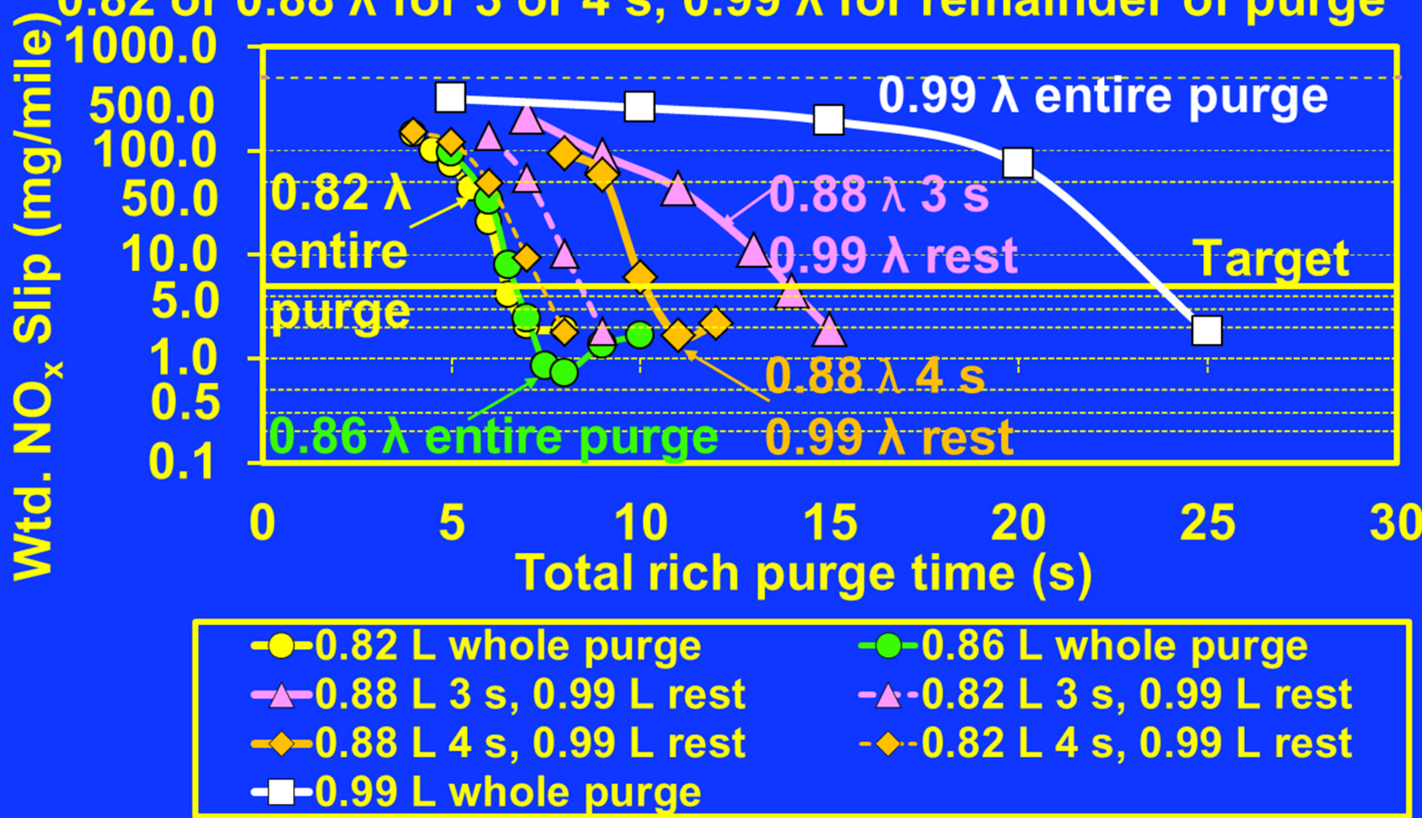




Two-step purge reduces OSC of the TWC quickly then transitions to 0.99 λ to minimize CO and FE penalties while still generating NH_3. 3 or 4 seconds at 0.88 λ required to reduce OSC of CC TWC.

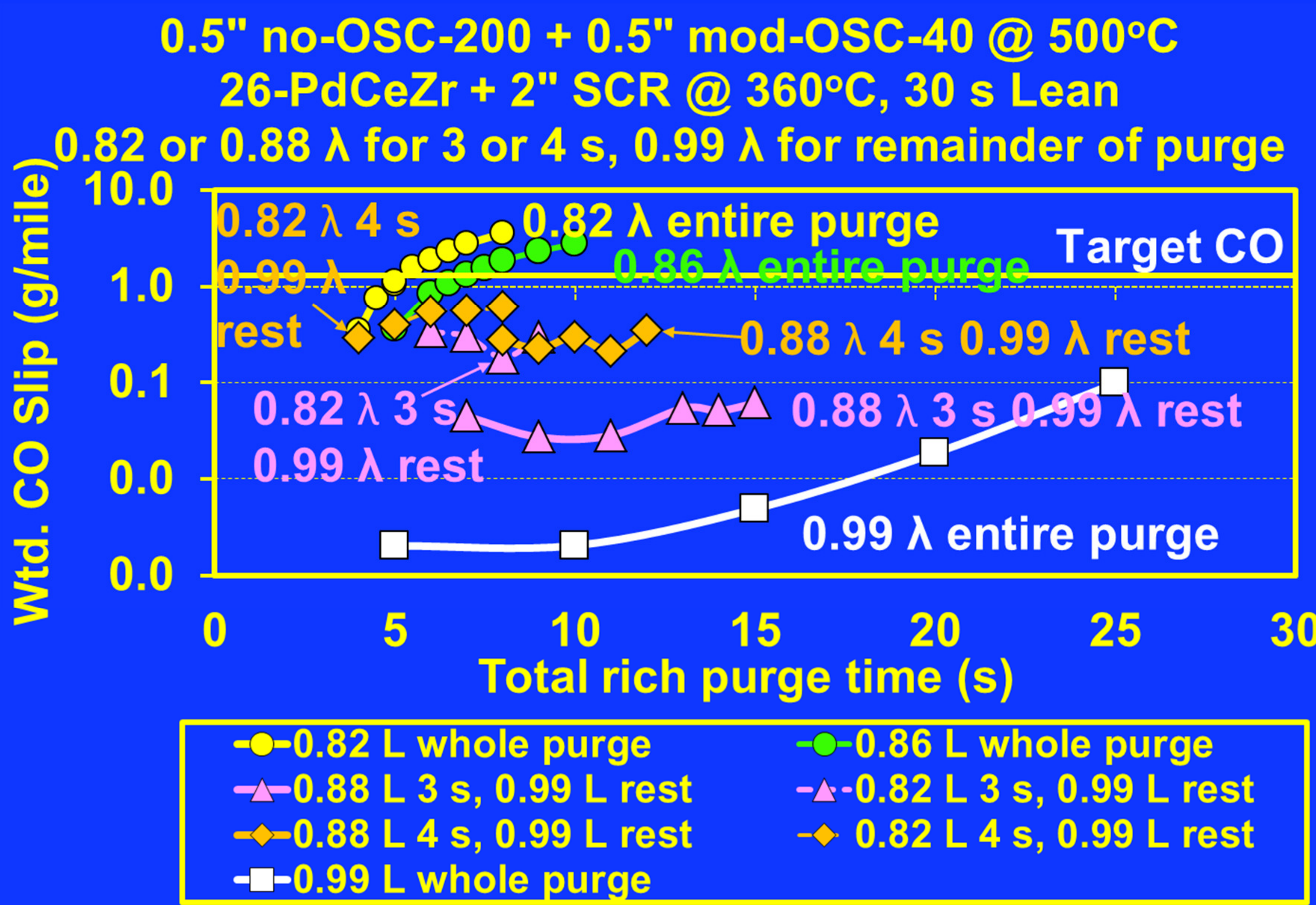
Effect of Two-Step Purge on NOx Slip for CC TWC + U/B TWC + SCR System

0.5" no-OSC-200 + 0.5" mod-OSC-40 @ 500°C
26-PdCeZr + 2" SCR @ 360°C, 30 s Lean
0.82 or 0.88 λ for 3 or 4 s, 0.99 λ for remainder of purge



With continuous 0.99 λ, 23 s purges required to achieve NO_x slip target.
With continuous 0.82 λ, 7 s purges required.
With 0.82 λ for 3 or 4 s then 0.99 λ, 9 or 8 seconds required.

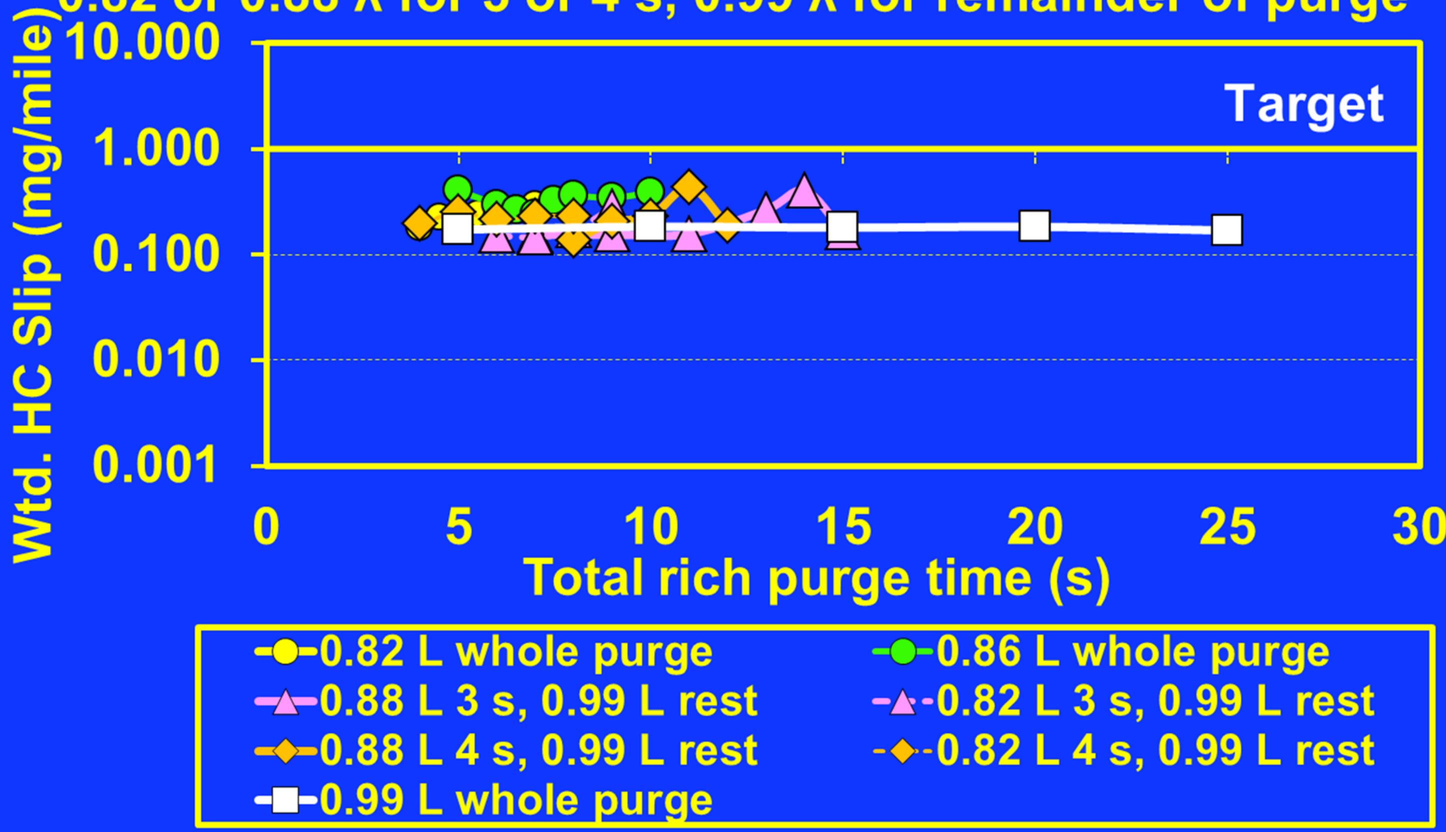
Effect of Two-Step Purge on CO Slip



With continuous 0.82 or 0.86 λ, CO slip target exceeded.
But with two-step purges, CO slip met for all purge times tested.

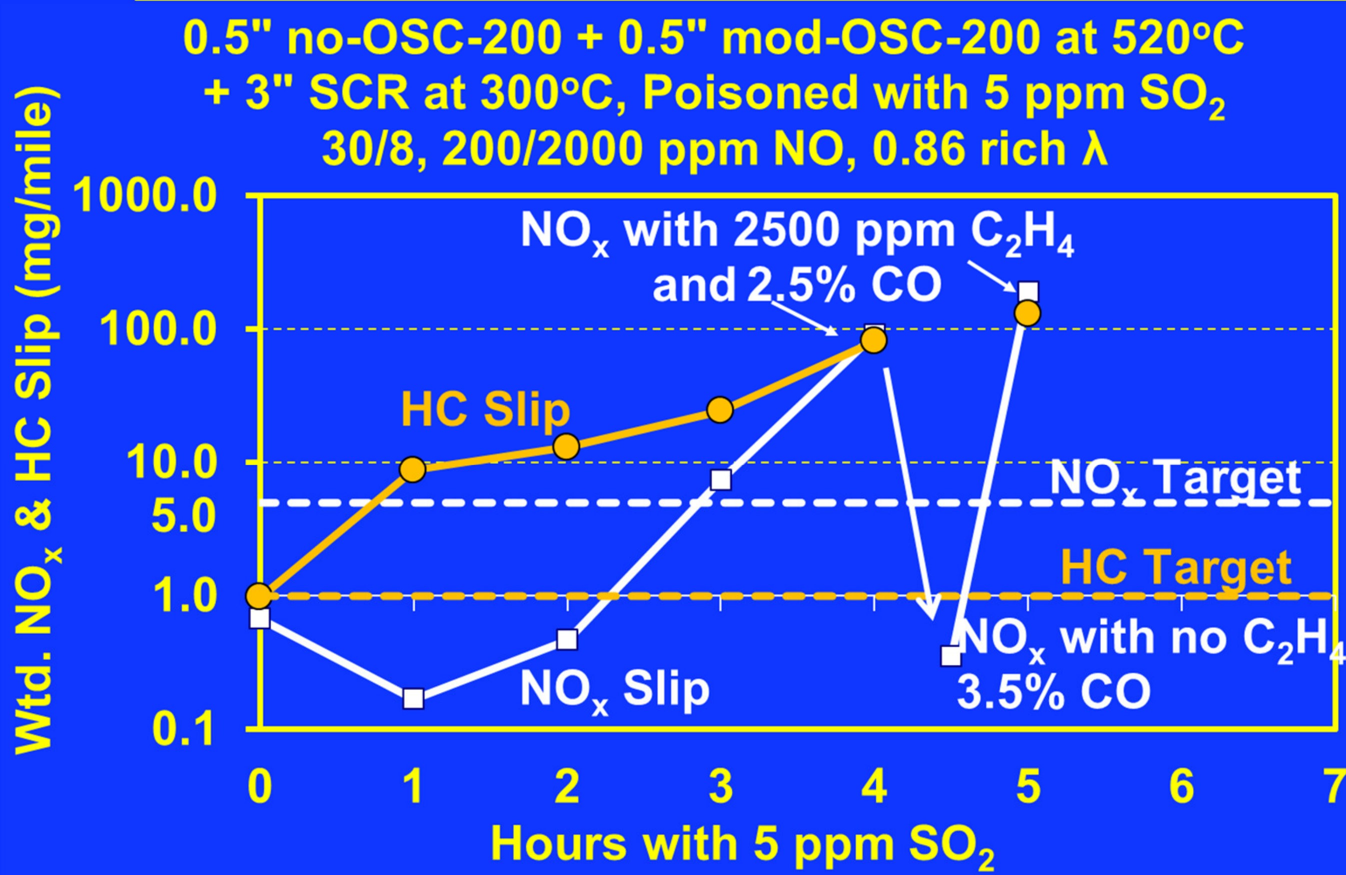
Effect of Two-Step Purge on HC Slip

0.5" no-OSC-200 + 0.5" mod-OSC-40 @ 500°C
26-PdCeZr + 2" SCR @ 360°C, 30 s Lean
0.82 or 0.88 λ for 3 or 4 s, 0.99 λ for remainder of purge



HC slip target met for all conditions. So with optimized formulations, temperatures, optimized feedgas NO levels rich and lean, and the two-step purge, the aged CC TWC + U/B TWC + SCR system met HC, CO, & NO_x targets with reasonable lean/rich times.

Effects of Sulfur Poisoning & Gas Composition on NOx & HC Slip



NOx slip exceeded target after 3 hours. But when C2H4 turned off and replaced with equivalent CO/H2, NOx slip dropped to very low levels. Loss of performance due to reduced steam reforming & NH3 generation.

- ➢ SCR catalyst itself not significantly affected by sulfur

→ Can still provide high NO_x conversion with proper chemistry.

Summary

All the NH_3 is generated from FG NO_x during rich periods

> Need low FG NO_x lean, high FG NO_x rich for reasonable L/R times

The maximum aging temperature of the SCR catalyst needs to be limited to 700 C when the aging includes stoichiometric & rich operation

A two-step purge allowed the CC TWC + U/B TWC + SCR system to satisfy NOx, HC, and CO slip targets

Sulfur poisoning degraded steam reforming activity & NH_3 yield of CC TWC

> SCR catalyst not significantly affected by sulfur, high NO_x conversion with proper exhaust chemistry

It is assumed that, for many customers, the CC TWC would remain naturally desulfated due to periodic exposure to high T rich conditions from rapid heating strategies and high load operation such as in US06

> Active desulfation strategy not required but should be available

TWC+SCR shows promise in achieving Tier 2, Bin 2 emission levels on lean-burn gasoline applications

More details in SAE paper 2015-01-1004