Update on Heavy-Duty Low NO_X Demonstration Programs at SwRI

SOUTHWEST RESEARCH INSTITUTE®

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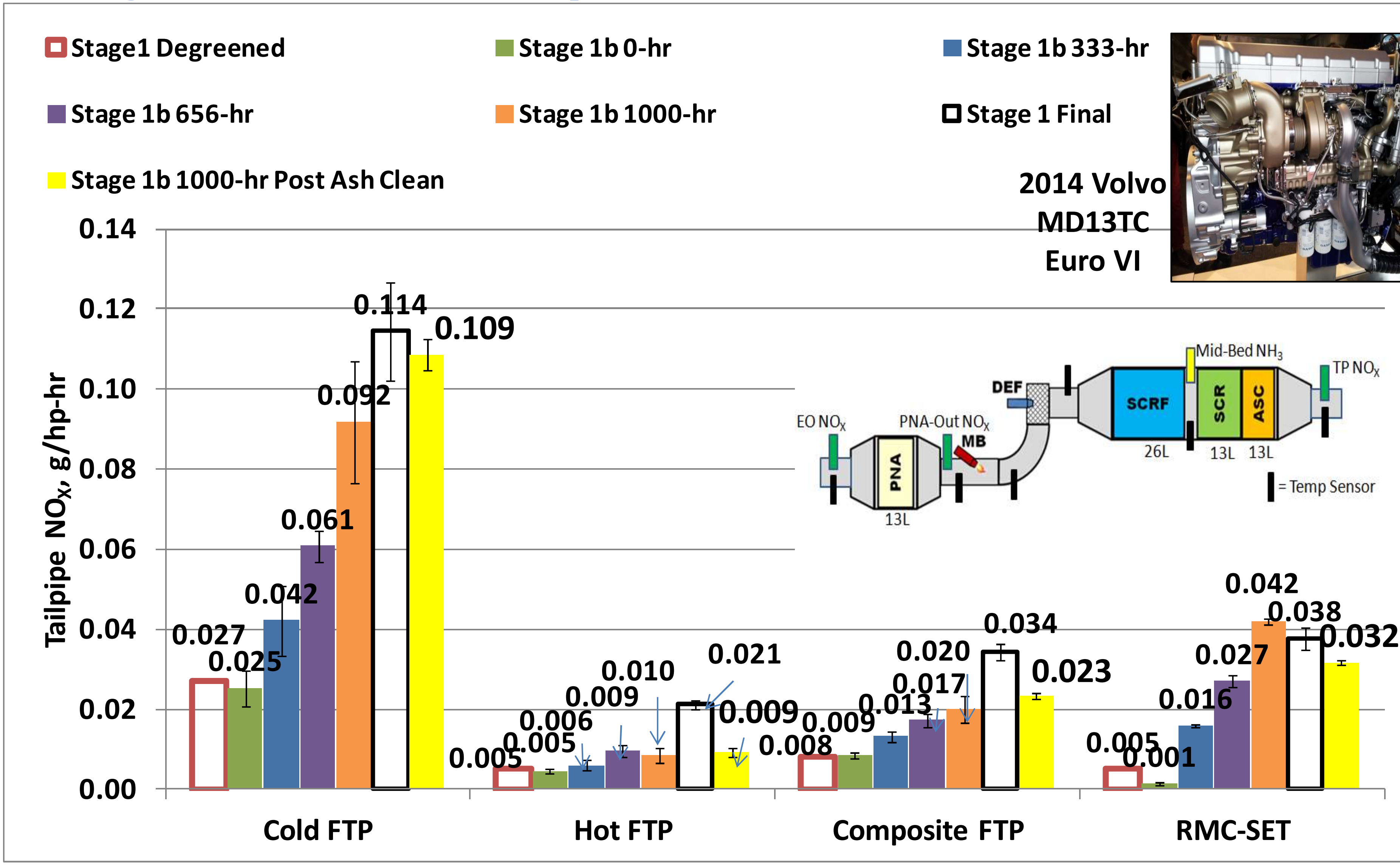
September 26, 2019

CARB Low NO_X Programs at SwRI

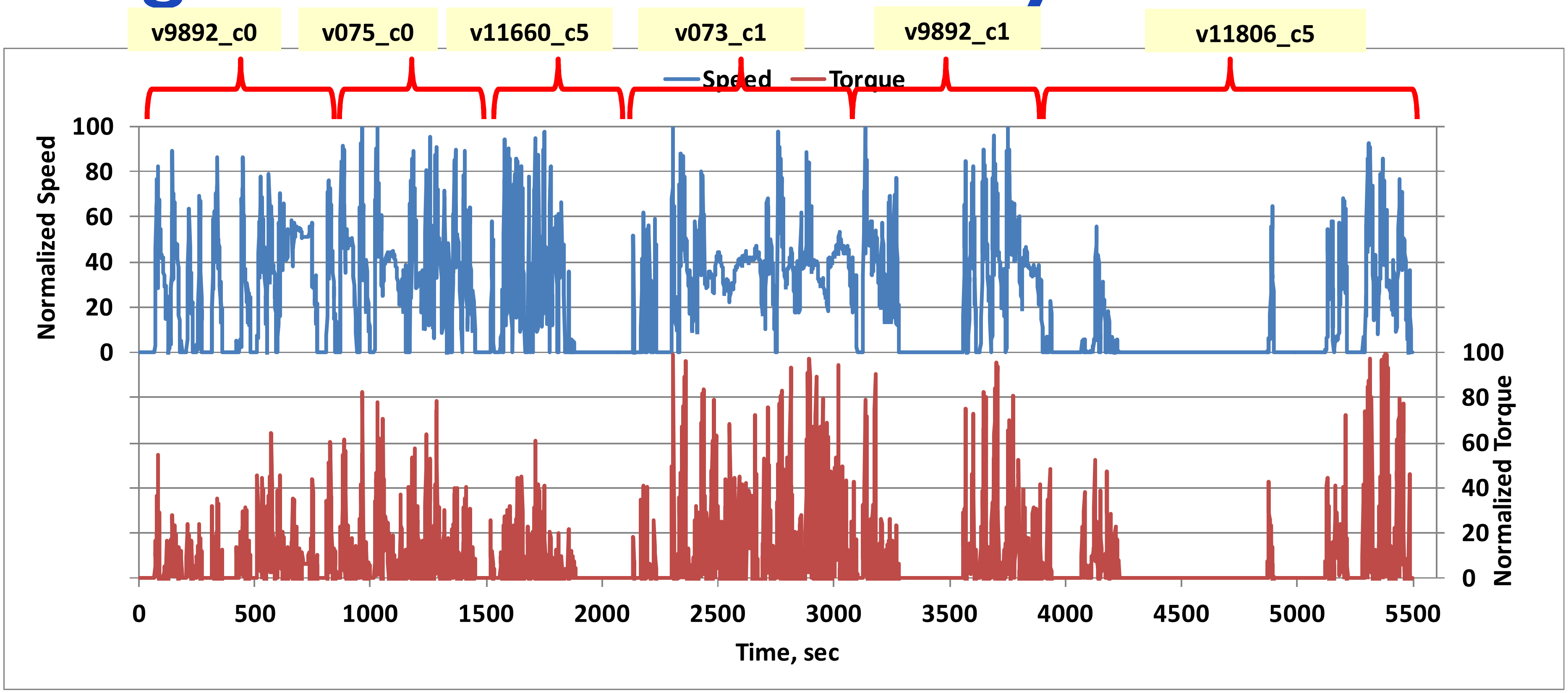
- ***Stage 1*** *– Evaluating Technologies and Methods to Lower Nitrogen Oxide Emissions from Heavy-Duty Vehicles (2014-2017) -* ***COMPLETE***
    - *Initial Technology Evaluation – Diesel and CNG*
    - *Primary focus on Regulatory Cycles*
- **Stage 1b** – Repeat Aging and Evaluation of Stage 1 Hardware (2018-2019) - REPORTING
  - Answer questions from Stage 1 and provide robust parts for Stage 2
- **Stage 2** – Heavy-Duty Low Load Emission Control (2017-2019) - REPORTING
    - Expand previous technology evaluation to low-load and urban operating cycles
    - Evaluation of in-use testing metrics to evaluate emissions at low loads
- **Stage 3** – Further Evaluation and Development of Low NO_X Technologies on 2017 (non-Turbocompound) Engine Platform (2018-2020)
    - Focus on both Low Load (Real world) and Regulatory cycles
  - ***Stage 3b – Engine Hardware Technology Effort organized by SwRI to augment Stage 3***

Stage 1b Results – Updated Data Set with FUL Tests



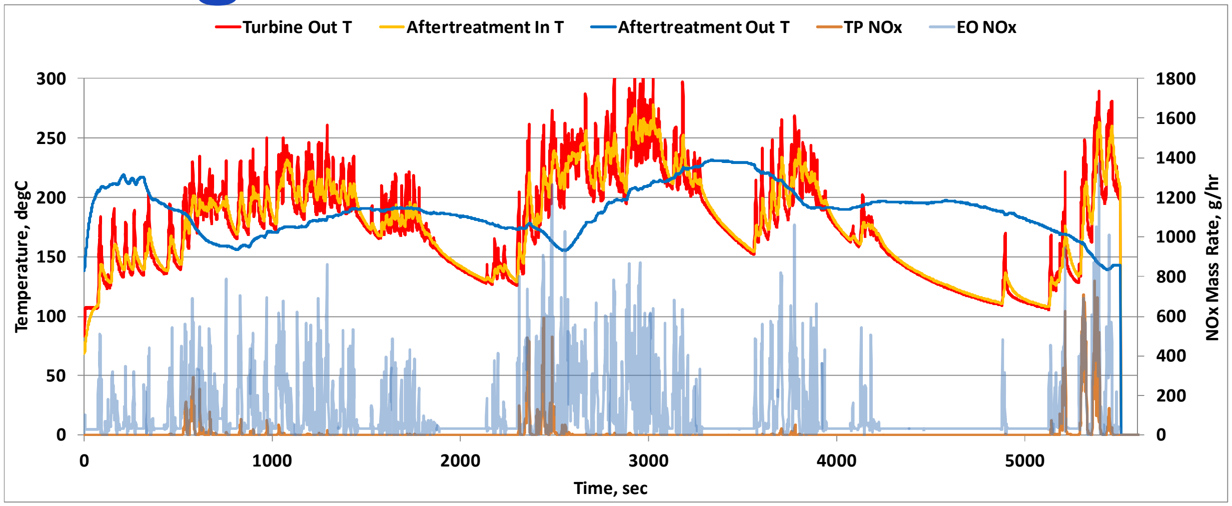
Note: UAF of +0.004 g/hp-hr is added to these to account for infrequent regeneration impact

Stage 2 - Final Low Load Cycle



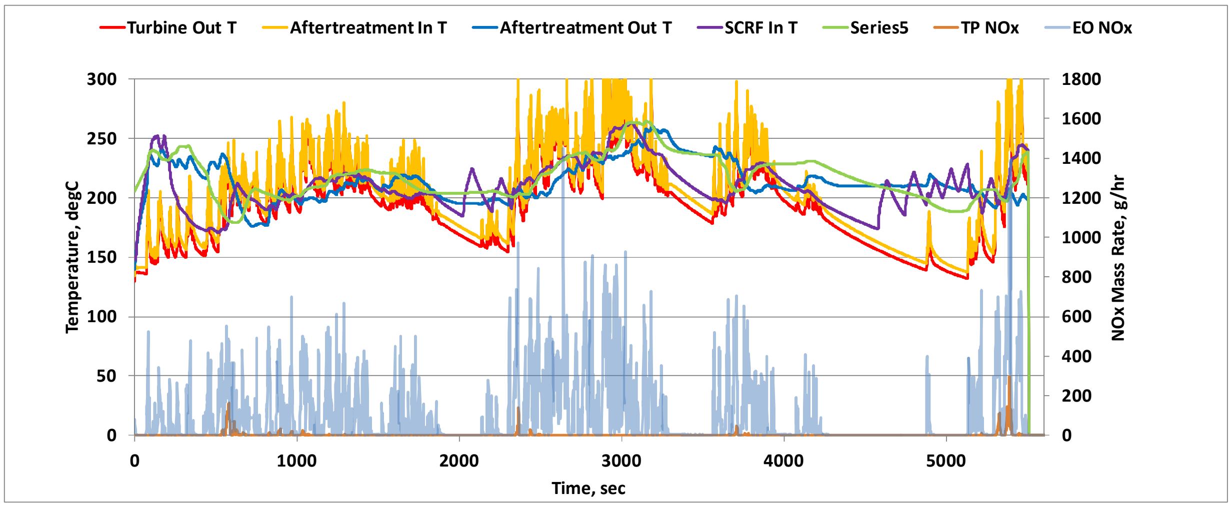
- Developed from real world vehicle operations at Low Load
- Average power generally 7-8% of engine max (with idle load)
- <u>Run with accessory load at idle</u>
  - HHD: 3.5kw, MHD: 2.5kw, LHD: 1.5kw (from EPA GEM defaults)
- TP NO_X Levels on Current Production engines – 0.35 to 1.5 g/hp-hr
  - average ~ 1 g/hp-hr

Stage 2 - LLC Performance on Stage 1 / 2 Engine



Stage 2 - Baseline EU 6 System

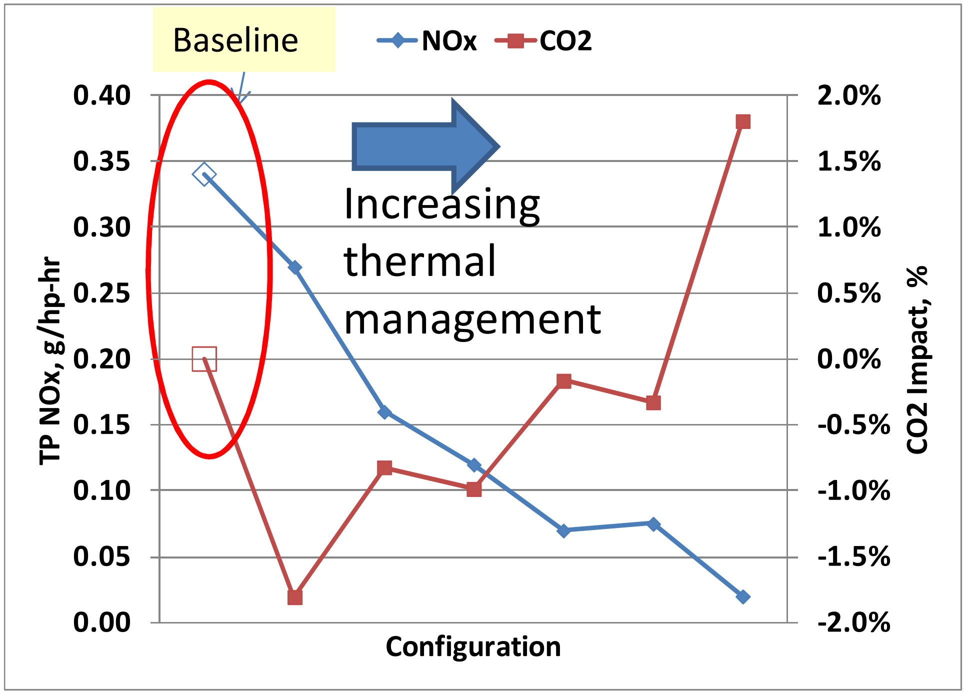
- Overall 90% conversion
- EO NO_X = 3.4 g/hp-hr
- TP NO_X = 0.34 g/hp-hr
- CO_2 = 607 g/hp-hr

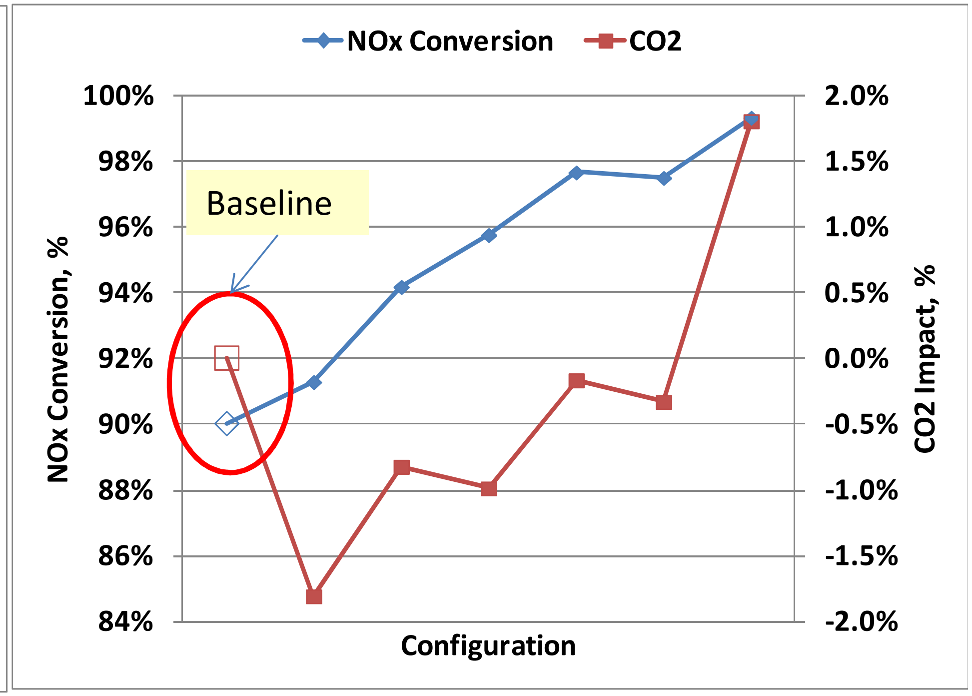


Stage 2 - Low NO_X Engine

- Overall 97.5% conversion
- EO NO_X = 3.0 g/hp-hr
- TP NO_X = 0.07 g/hp-hr
- CO_2 = 608 g/hp-hr

Updated Stage 2 LLC Result Comparison

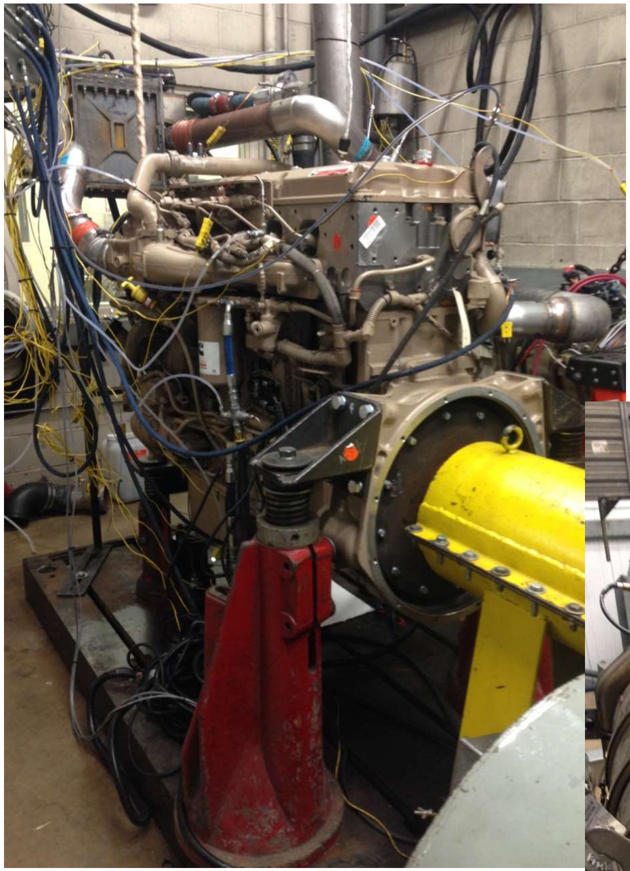




- Stage 1b Baseline MD13TC EU6 - 90% conversion on LLC
- Without thermal management, 91% conversion and CO_2 is improved by 2% on LLC
- Highest level of thermal management shows 2% CO_2 penalty for 0.02 g/hp-hr NO_X on LLC
- "Optimized" thermal management at 0.07 g/hp-hr NO_X is fuel consumption neutral

Stage 3 Low NO_X Demonstration Program

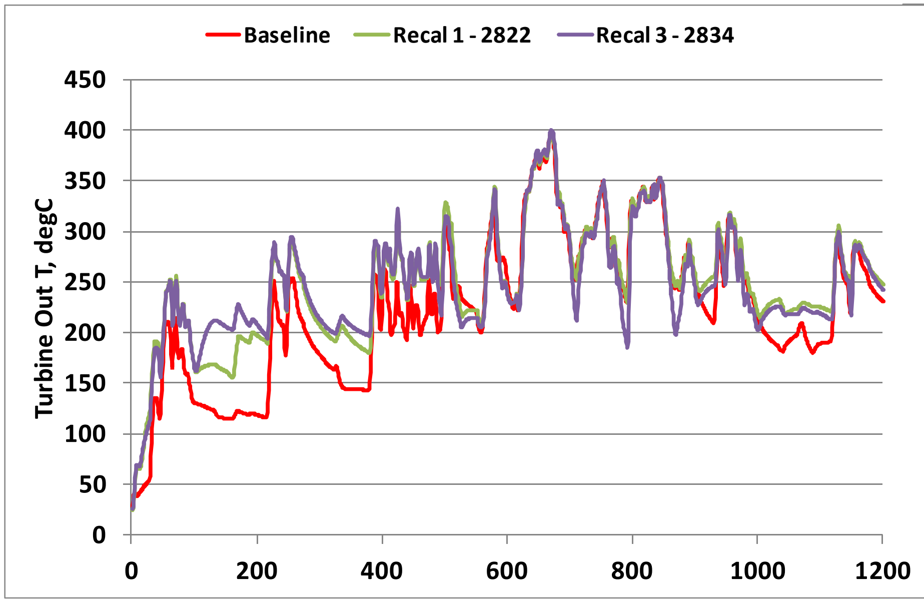
- **Examine potential for Low NO_X on a platform that is more representative of broader market in 2017+**
  - Production 2017 Cummins X15
  - More representative of typical U.S. GHG approach
- **Integrate both Regulatory and Low Load Cycles at the start**
  - Program targets are 0.02 g/hp-hr on regulatory cycles <u>and</u> control on Low Load cycles

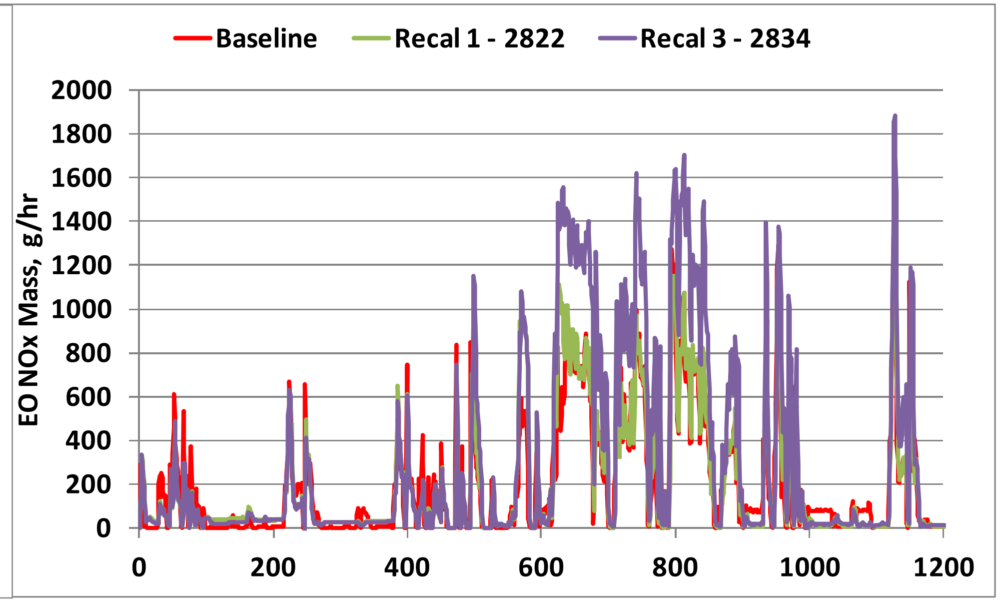


2017 Cummins X15

Production Aftertreatment (replaced for Low NO_X)

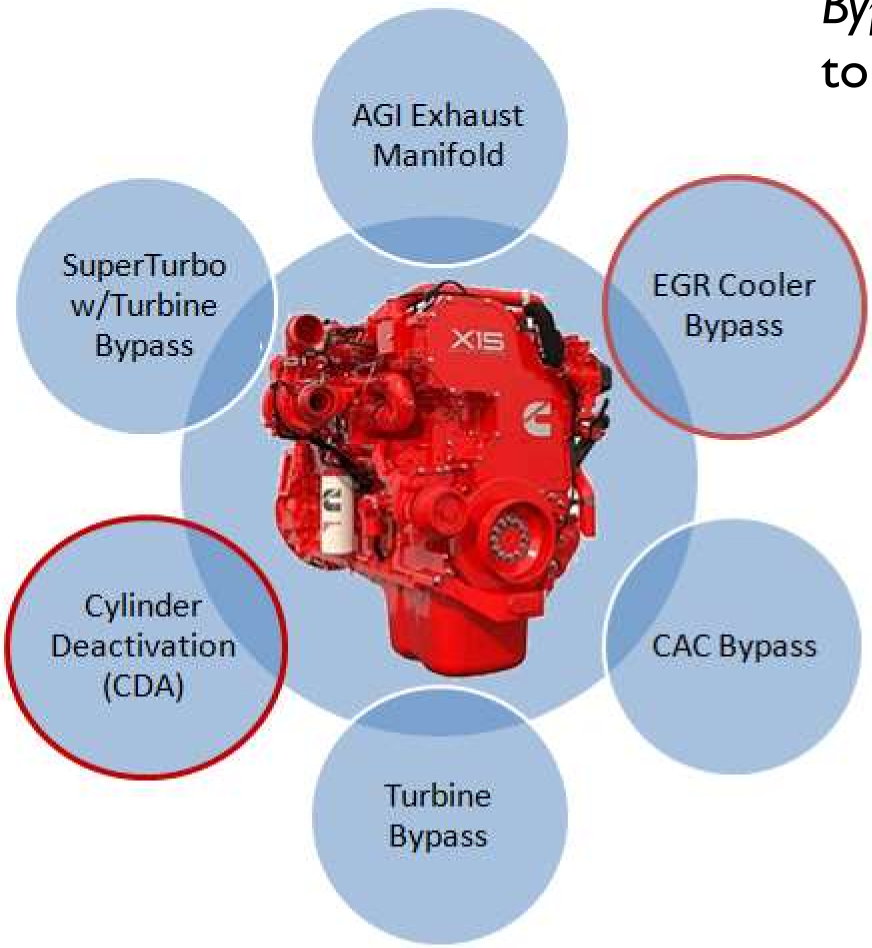
Stage 3 – Modified Engine Calibration (Cold FTP Example)



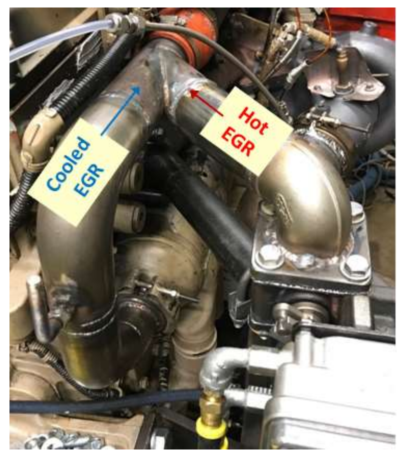


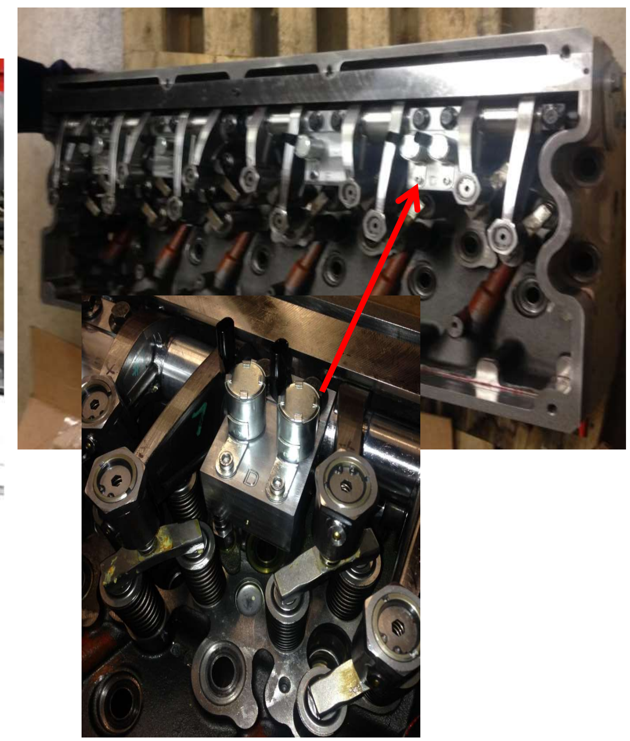
- 2017 Cummins X15 – stock engine hardware
- Modified Calibration Elements – Modified EGR, VGT, multiple injections, elevated idle, etc...
- Elevated T and Reduce EO NO_X early (some GHG cost)
- Higher EO NO_X later for (mitigate some of GHG cost)
- Note that Cold-FTP Recal 3 has +4% impact on CO_2 (+0.6% to Composite)

Stage 3b – Additional Engine Hardware Evaluated



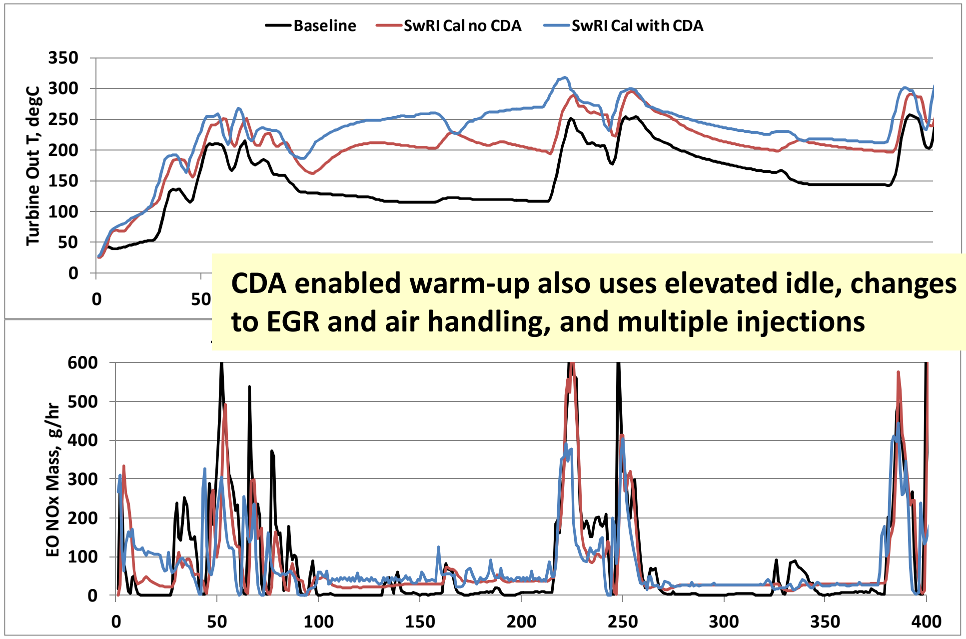
- **Cylinder Deactivation (CDA)** and *EGR Cooler Bypass* selected is final choices to carry forward to Stage 3 demonstration
    - Hardware evaluations indicated sufficient value to justify hardware cost





Stage 3 - Using CDA to Improve AT System Conditions and Fuel Consumption

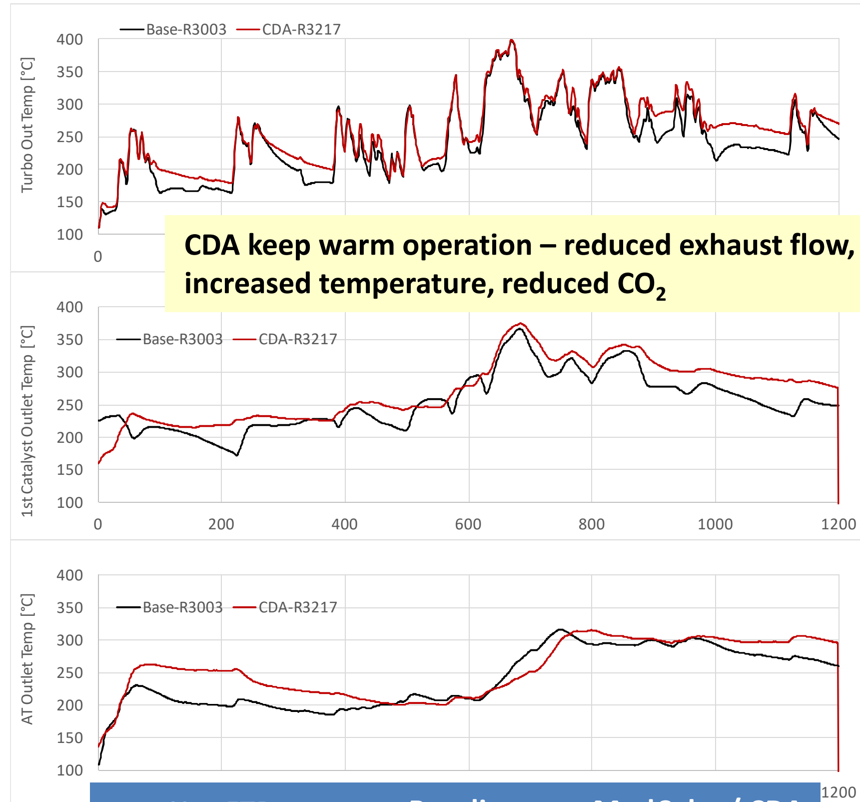
Cold-Start FTP ("Get Hot")



CDA enabled warm-up also uses elevated idle, changes to EGR and air handling, and multiple injections

Cold FTP	Baseline	ModCal	ModCal w/ CDA
CO_2 g/hp-hr	531	**552**	**538**
% from baseline	n/a	**+ 4.0%**	**+ 1.3%**
Weighted % from base	n/a	**+ 0.5%**	**+ 0.2%**
EO NO_X, g/hp-hr	2.0	**3.2**	**3.0**

Hot-Start FTP ("Stay Hot")

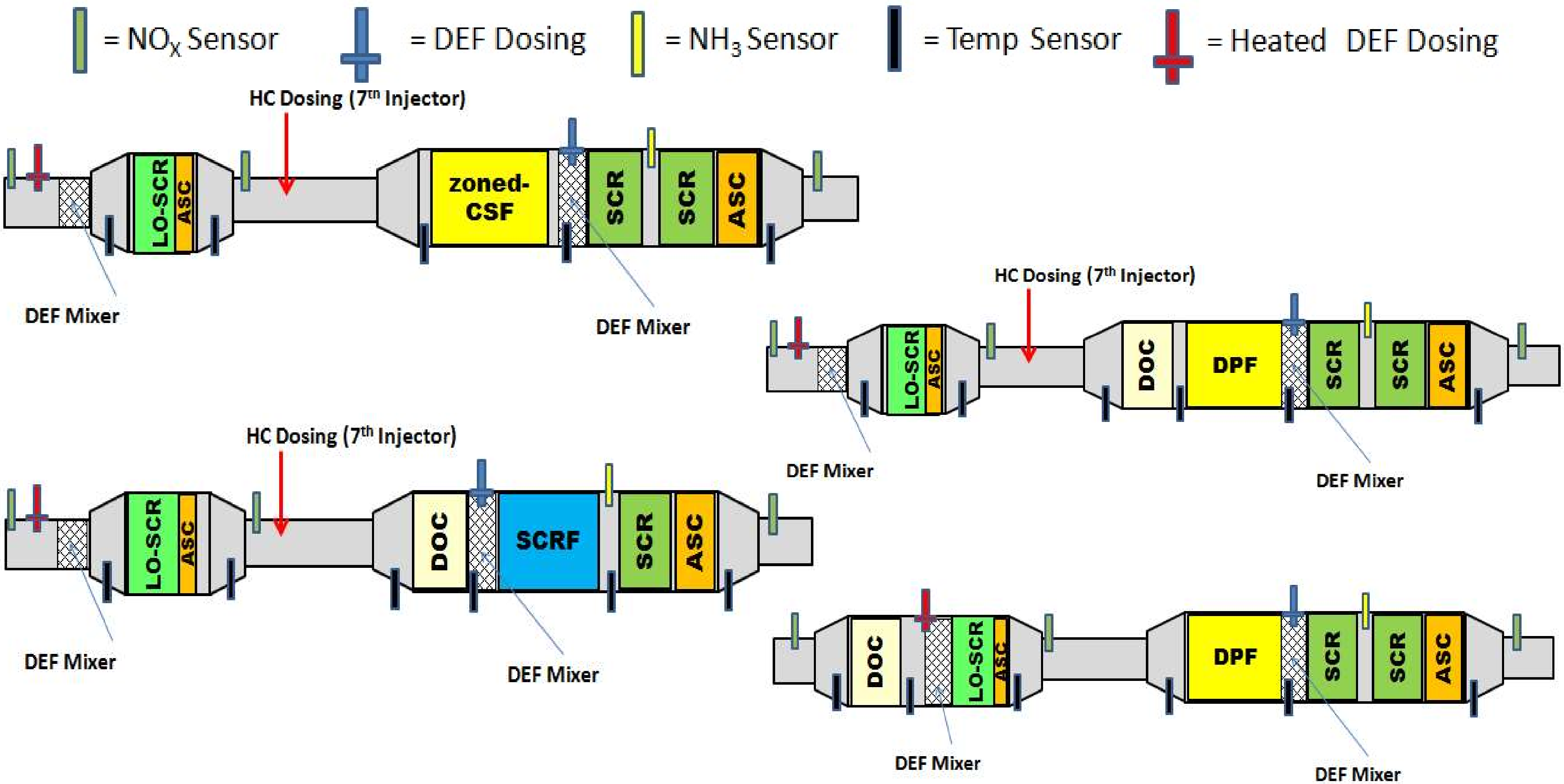


CDA keep warm operation – reduced exhaust flow, increased temperature, reduced CO_2

Hot FTP	Baseline	ModCal w/ CDA
CO_2 g/hp-hr	504	495
% from baseline	n/a	**- 1.5%**
Weighted % from base	n/a	**- 1.3%**
EO NO_X, g/hp-hr	2.9	3.5

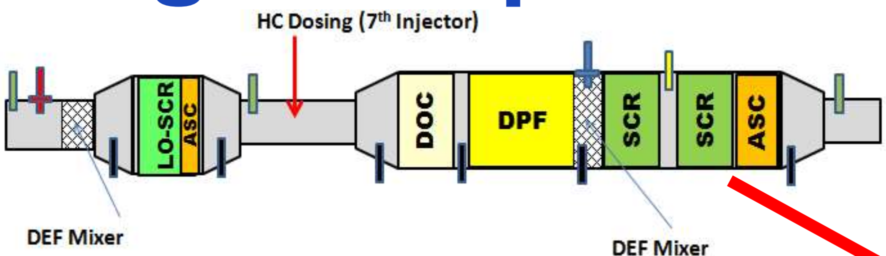
Stage 3 Aftertreatment – Configurations Examined

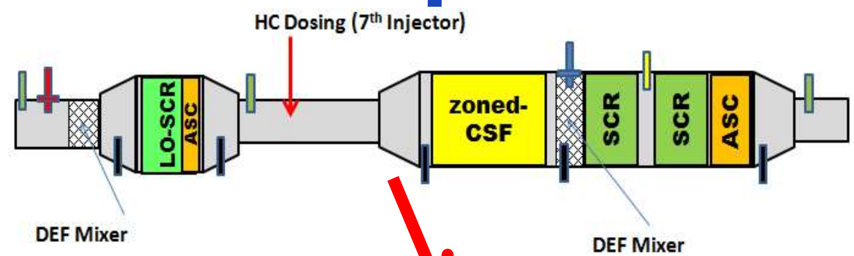
Integration and Evaluation Complete



- Development Aged parts – hydrothermally aged to 435,000 miles FUL (Current Data)
- Final Aged parts – thermal and chemical aging to 435,000 miles FUL using DAAAC protocol (Final Demonstration) – 10X acceleration factor

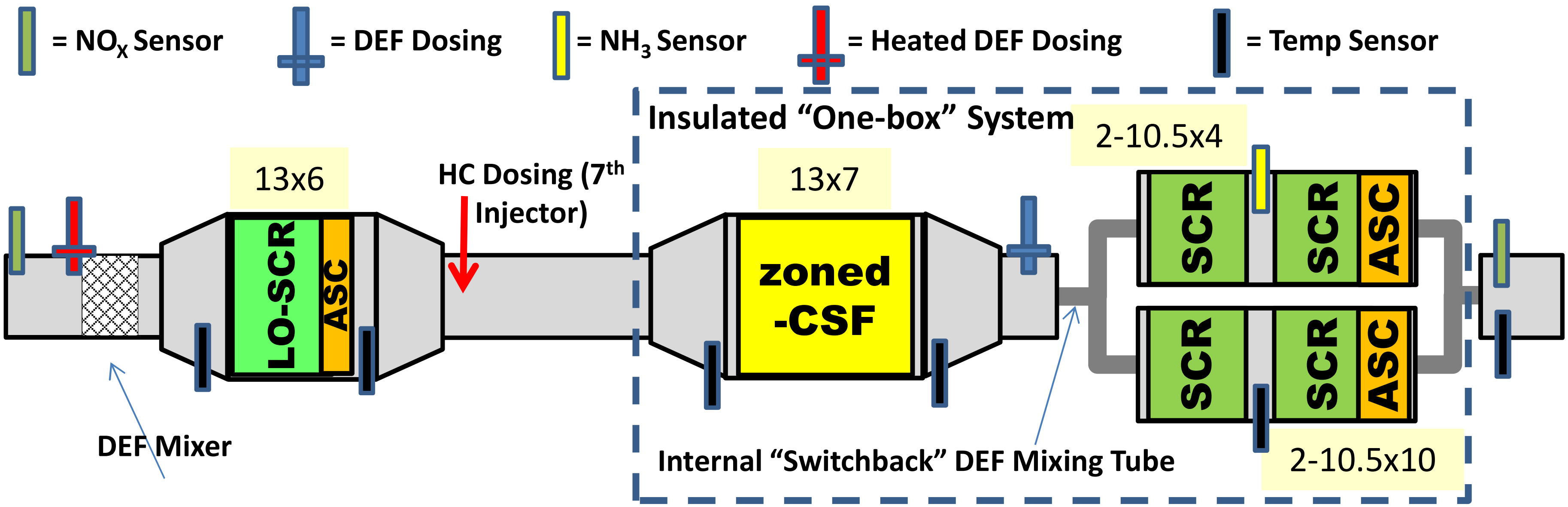
Stage 3 - Updated System Comparisons





	Baseline	Config 2B	Config 1A
Cold FTP NO_X	0.27	0.043	0.054
Cold FTP CO_2	531	542	545
Hot FTP NO_X	0.14	0.014	0.012
Hot FTP CO_2	505	500	502
LLC NO_X	1.4	0.12 / 0.053	0.16 / 0.036
LLC CO_2	624	593 / 609	614 / 633
Backpressure	24	36	25
RMC-SET NO_X	0.15	-	0.026 (no optimization at all and no upstream help)
RMC-SET CO_2	454	- (but likely higher)	455

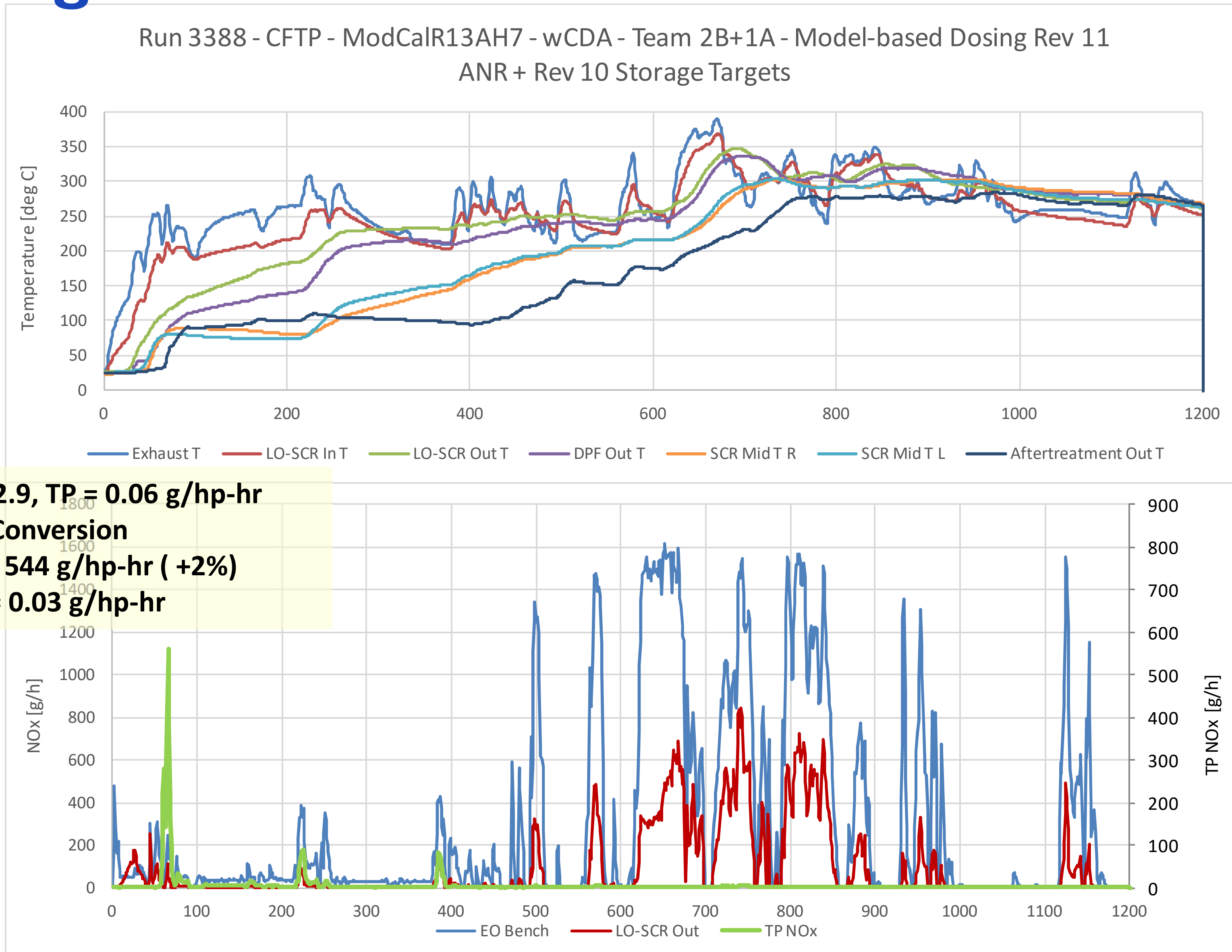
Stage 3 - Final Aftertreatment System Schematic (Hybrid of 2B + 1A)



- Zone coated CSF for reduced thermal inertia upstream of dsSCR
- Need 7th injector to avoid HC exposure on LO-SCR
- Similar deSO_X questions for LO-SCR

LOSCR	13x6	400/4	with ASC zone coated
zonedCSF	13x7	300/7 HAC	DOC coating front CSF coating back
SCR	2-10.5x4	600	dual parallel paths
SCR-ASC	2-10.5x10	600	dual parallel paths, with ASC zone coated

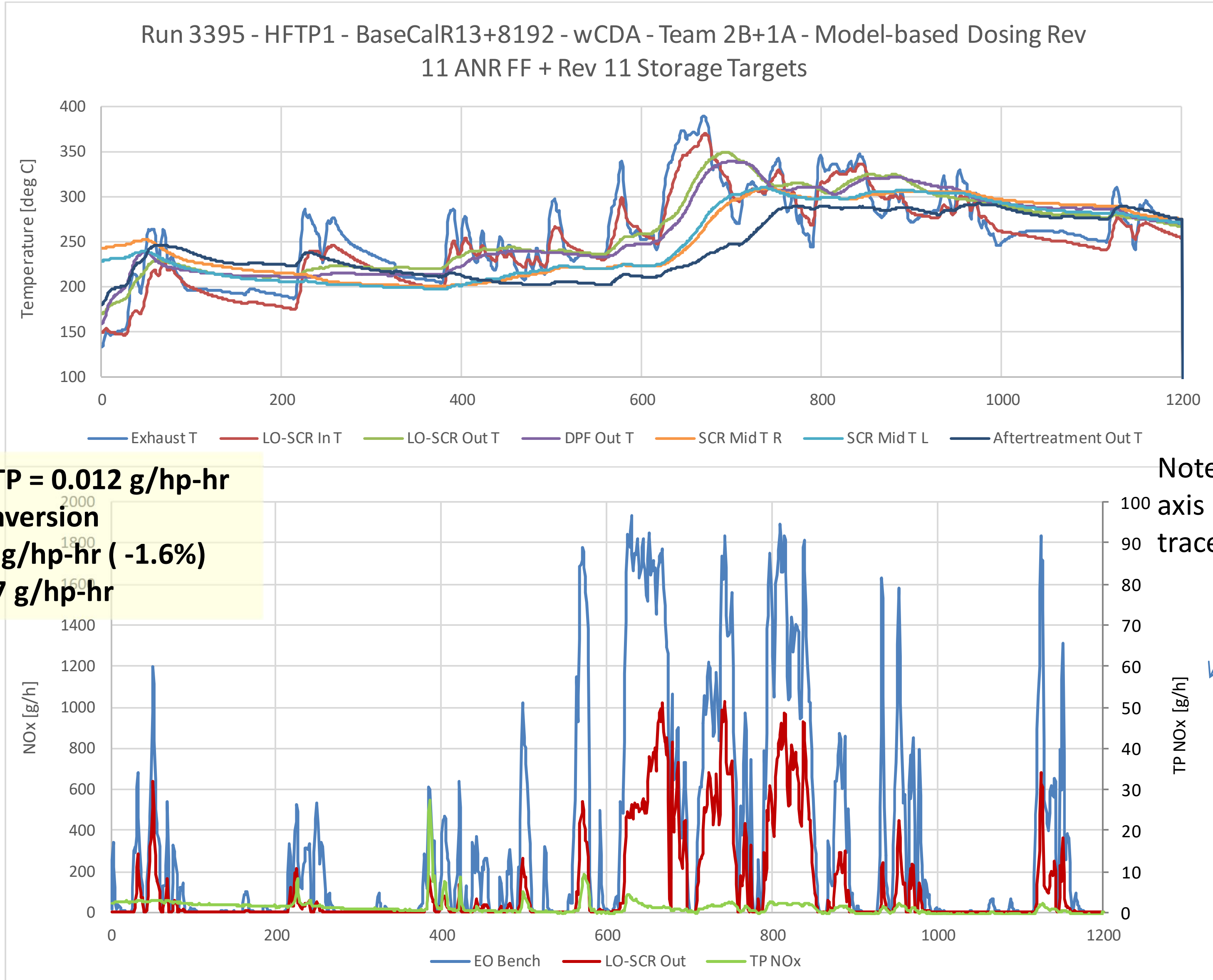
Stage 3 - Cold FTP Performance – 2B+1A



EO = 2.9, TP = 0.06 g/hp-hr
98% Conversion
CO_2 = 544 g/hp-hr (+2%)
N_2O = 0.03 g/hp-hr

Note TP lower axis (green trace)

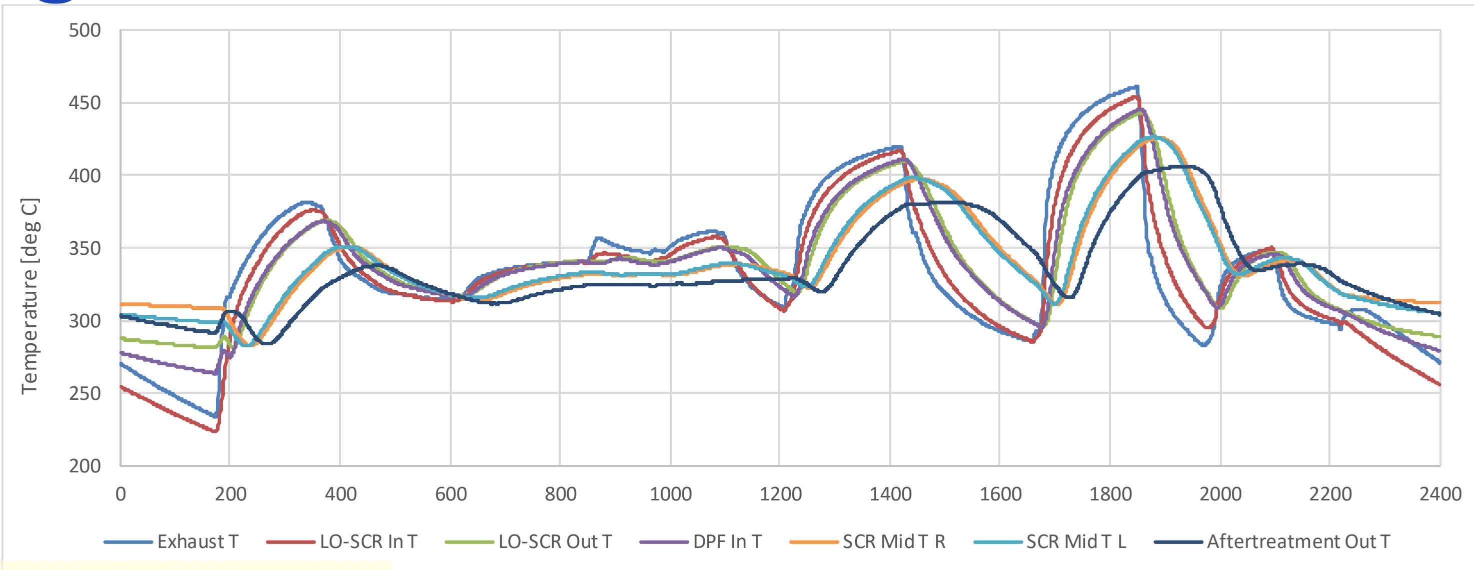
Stage 3 - Hot FTP Performance – 2B+1A



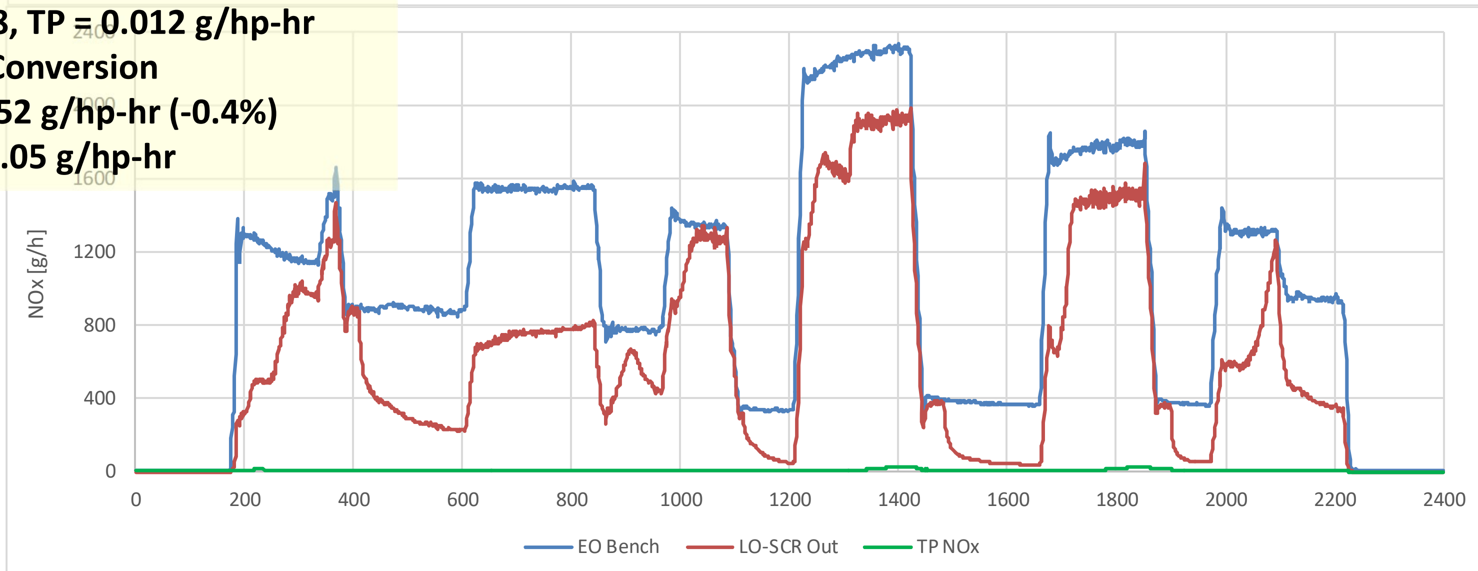
EO = 3.4, TP = 0.012 g/hp-hr
99.6% Conversion
CO_2 = 496 g/hp-hr (-1.6%)
N_2O = 0.07 g/hp-hr

Note TP lower axis (green trace)

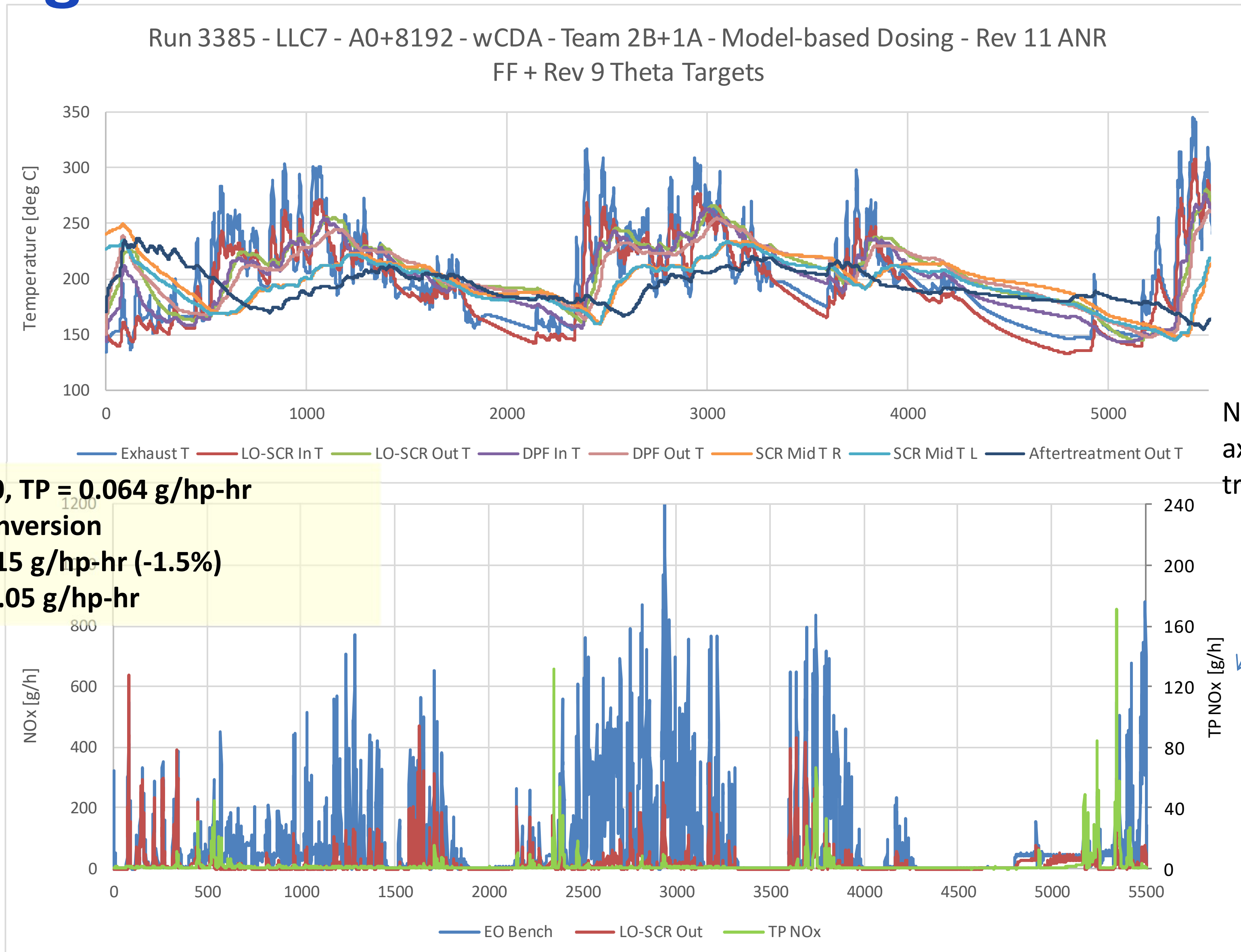
Stage 3 - RMC-SET Performance – 2B+1A



EO = 3.8, TP = 0.012 g/hp-hr
99.6% Conversion
CO_2 = 452 g/hp-hr (-0.4%)
N_2O = 0.05 g/hp-hr



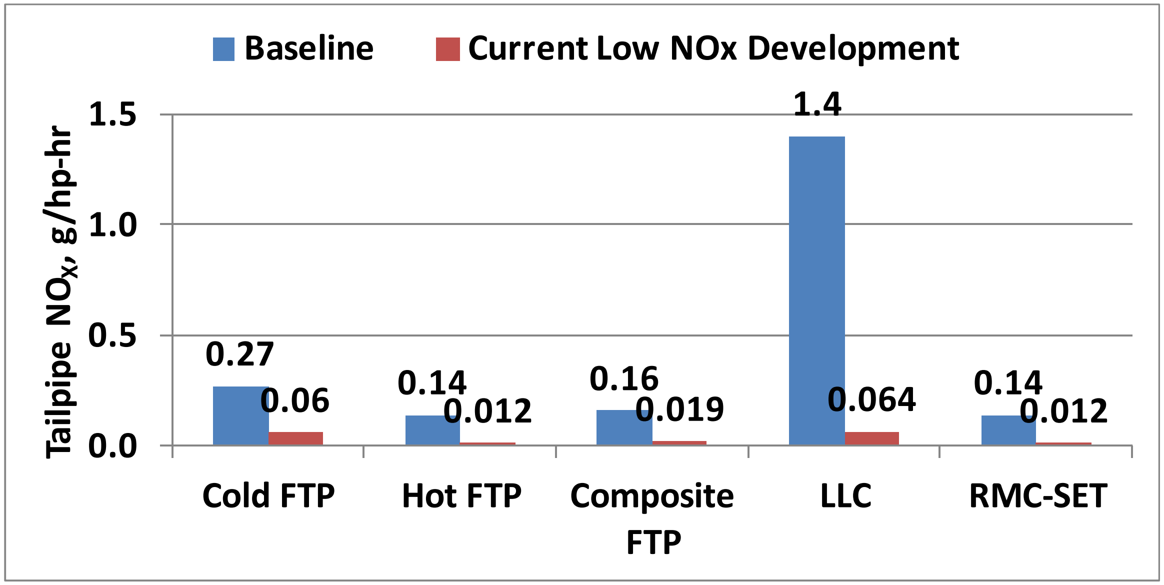
Stage 3 - LLC Performance – 2B+1A

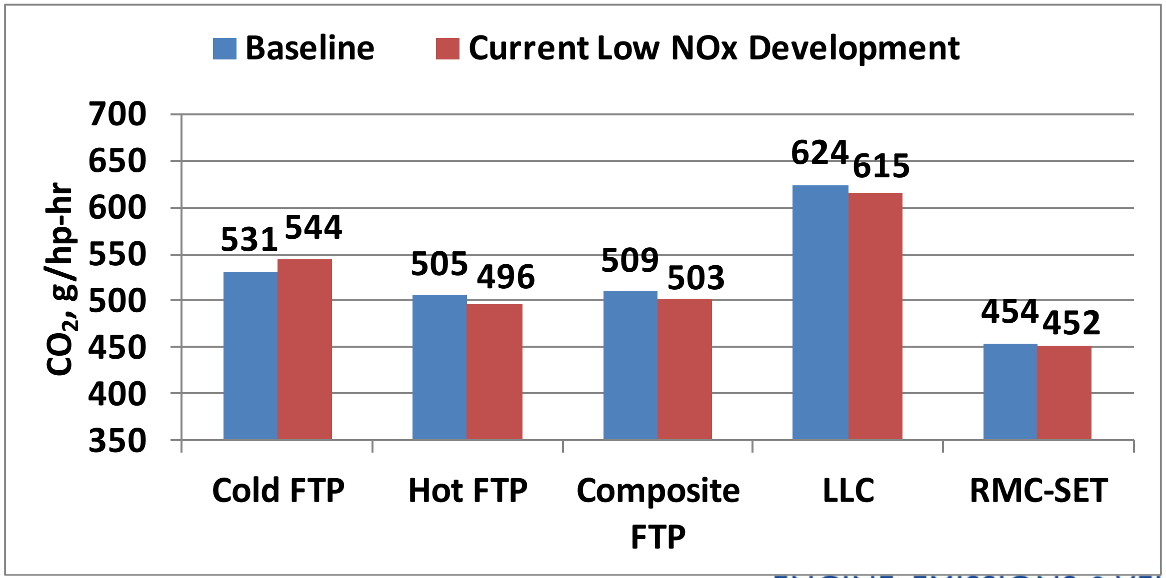


EO = 3.0, TP = 0.064 g/hp-hr
98% Conversion
CO_2 = 615 g/hp-hr (-1.5%)
N_2O = 0.05 g/hp-hr

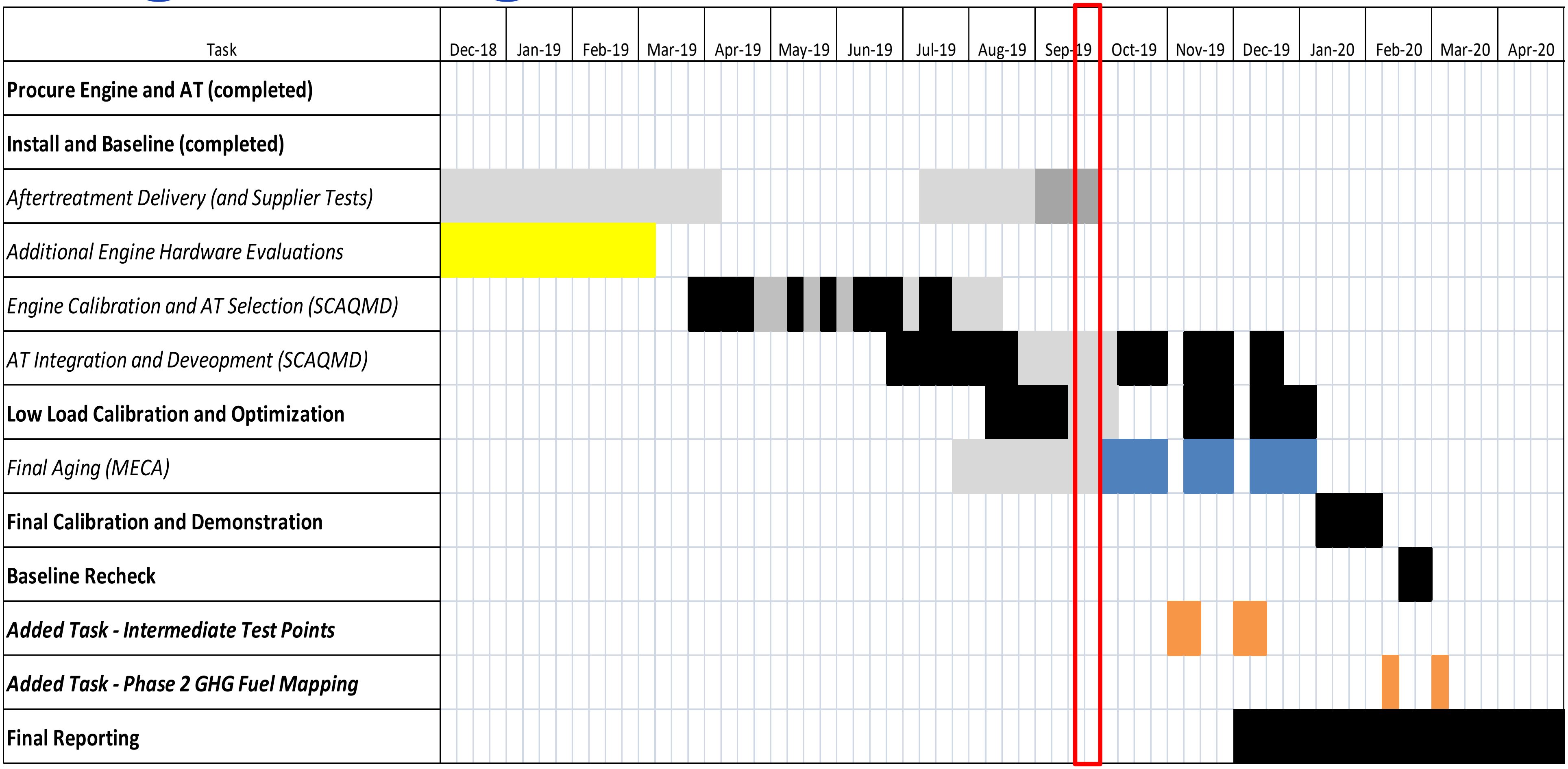
Note TP lower axis (green trace)

Stage 3 Low NO_X – Current Development Status





Stage 3 - Program Timeline and Schedule



- Full Technical Program Completion February 2020
- Results on Final Aged parts Jan-Feb 2020
- Draft Report March 2020

Acknowledgments

- California Air Resources Board (CARB)
- South Coast Air Quality Management District (SCAQMD)
- U.S. EPA
- Manufacturer's of Emission Controls Association (MECA)
- SwRI CHEDE VII Consortium
- OEM Partners
  - Volvo (Stage 1 / 1b / 2)
  - Cummins (Stage 3)
- Program Advisory Group stakeholders
- National Renewable Energy Lab (NREL)
- All of the MECA supplier member companies who supplied hardware and engineering support

Appendix – Backup Materials

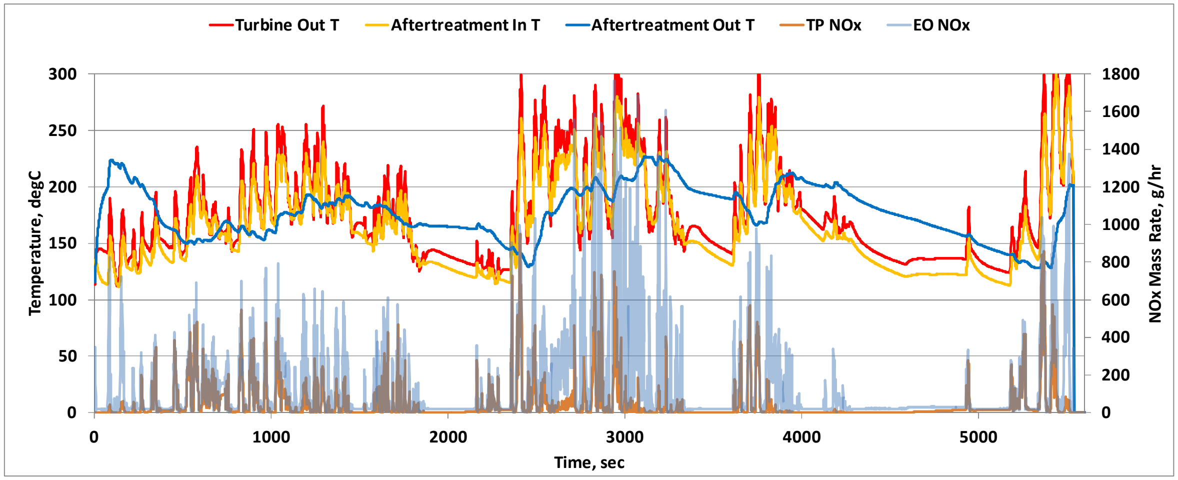
Stage 1b Final Conclusions

- Generally observed degradation in Stage 1b was smaller than for Stage 1
  - FTP: **Stage 1b = 0.023 g/hp-hr** versus Stage 1 = 0.034 g/hp-hr
  - RMC-SET : **Stage 1b = 0.032 g/hp-hr** versus Stage 1 = 0.038 g/hp-hr
    - pre-ash cleaned was at 0.042 g/hp-hr
  - Canning failure and subsequent issues did have a significant impact on system performance (normal versus abnormal degradation identified)
  - Note: +0.004 Upward Adjustment Factor (UAF) should be added to both results to account for emissions due to infrequent regeneration

	BSCO2, g/hp-hr			
	Cold	Hot	Composite	RMC
Baseline Engine	574.2	542.6	547.4	457.7
Final ULN Config	604.4	548.8	558.2	463.6
% change	5.3%	1.1%	**2.0%**	**1.3%**
Mini-burner air	0.4%	0.2%	**0.2%**	
Increased SCRF Regeneration			**0.3%**	**0.3%**
Total FTP CO2 Impact			**2.5%**	**1.6%**

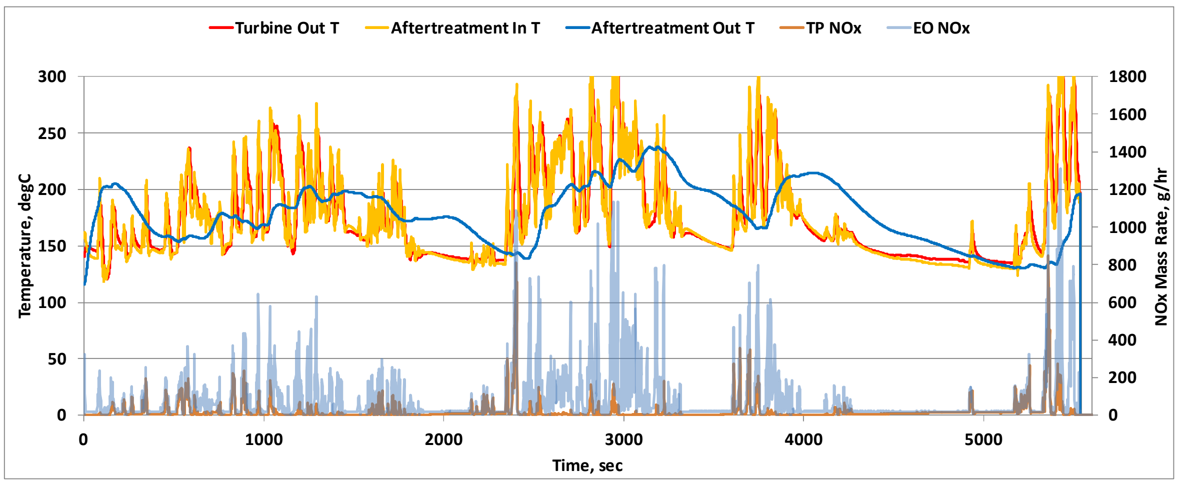
- RMC-SET performance was heavily influenced by ash cleaning
  - reduced temperature and backpressure post ash cleaning
  - evidence of precious metal contamination on SCRF – appears to be removable but better cleaning procedure needs to be adopted

Stage2 - Final Low Load Cycle on Current Production Engines



Engine A - 2017

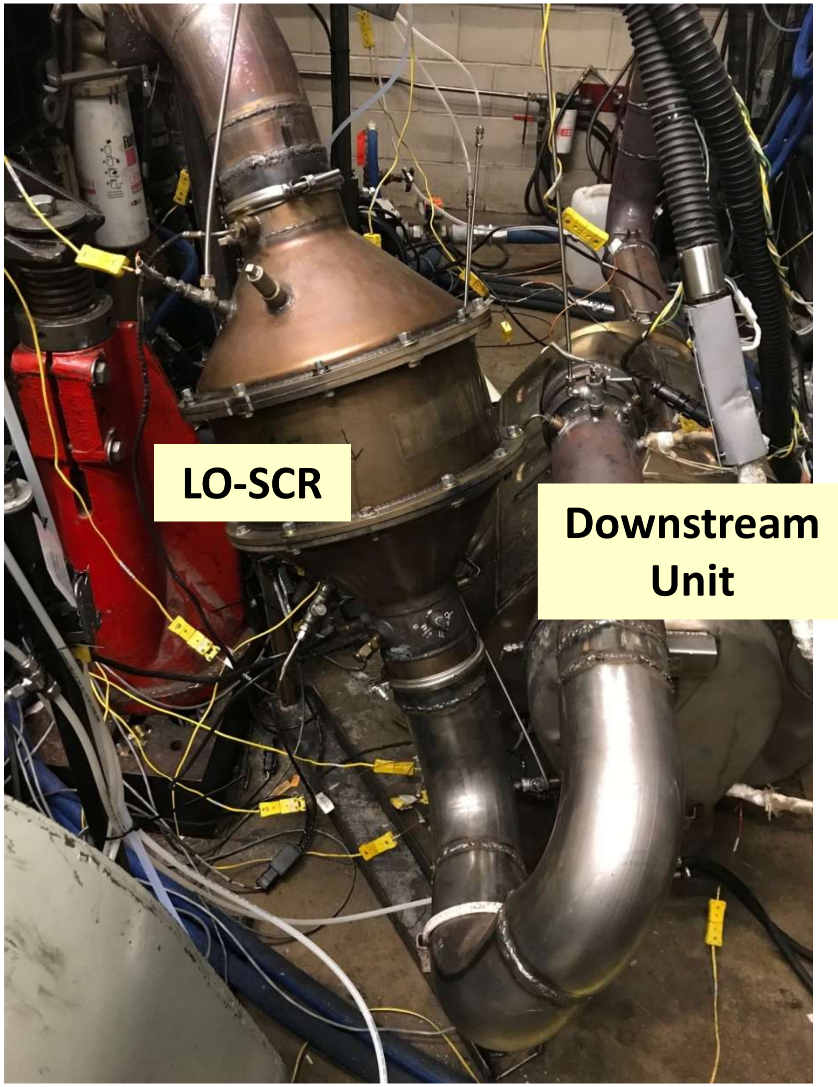
- Overall 64% conversion
- EO NO_X = 4.2 g/hp-hr
- TP NO_X = 1.5 g/hp-hr
- CO_2 = 613 g/hp-hr

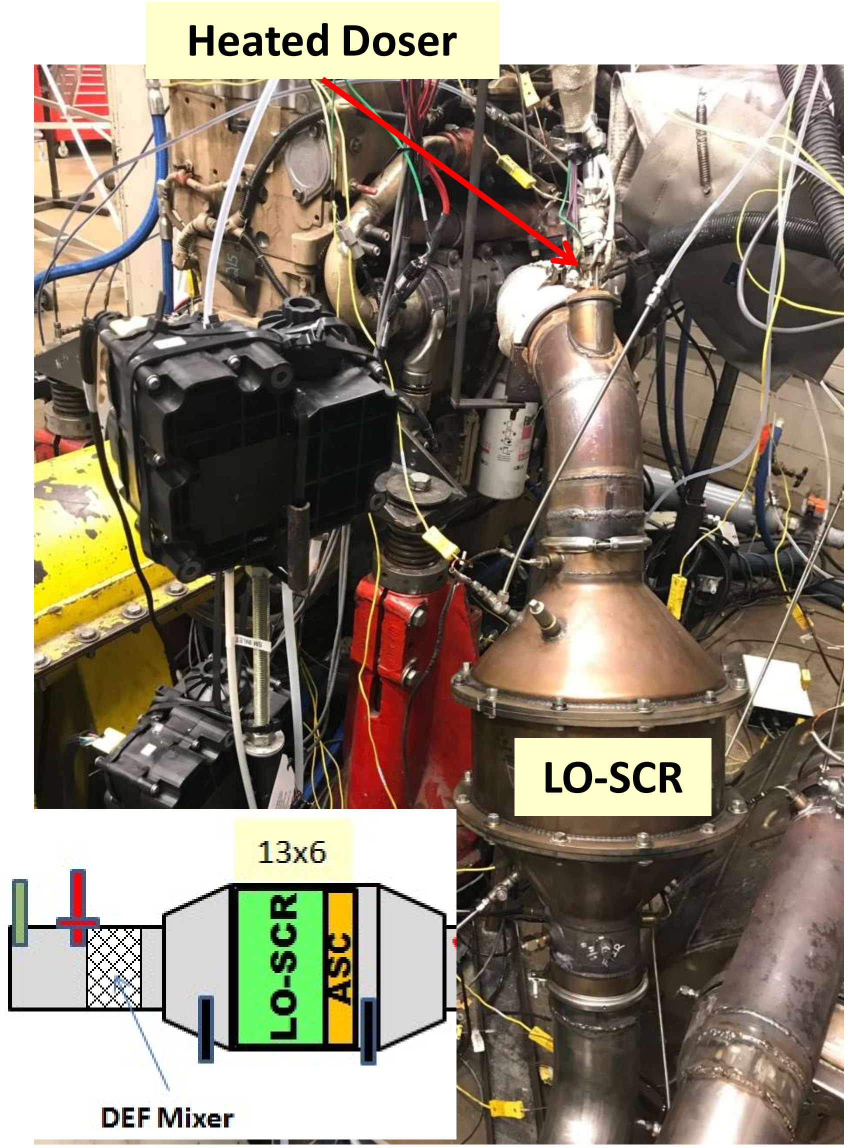


Engine B - 2018

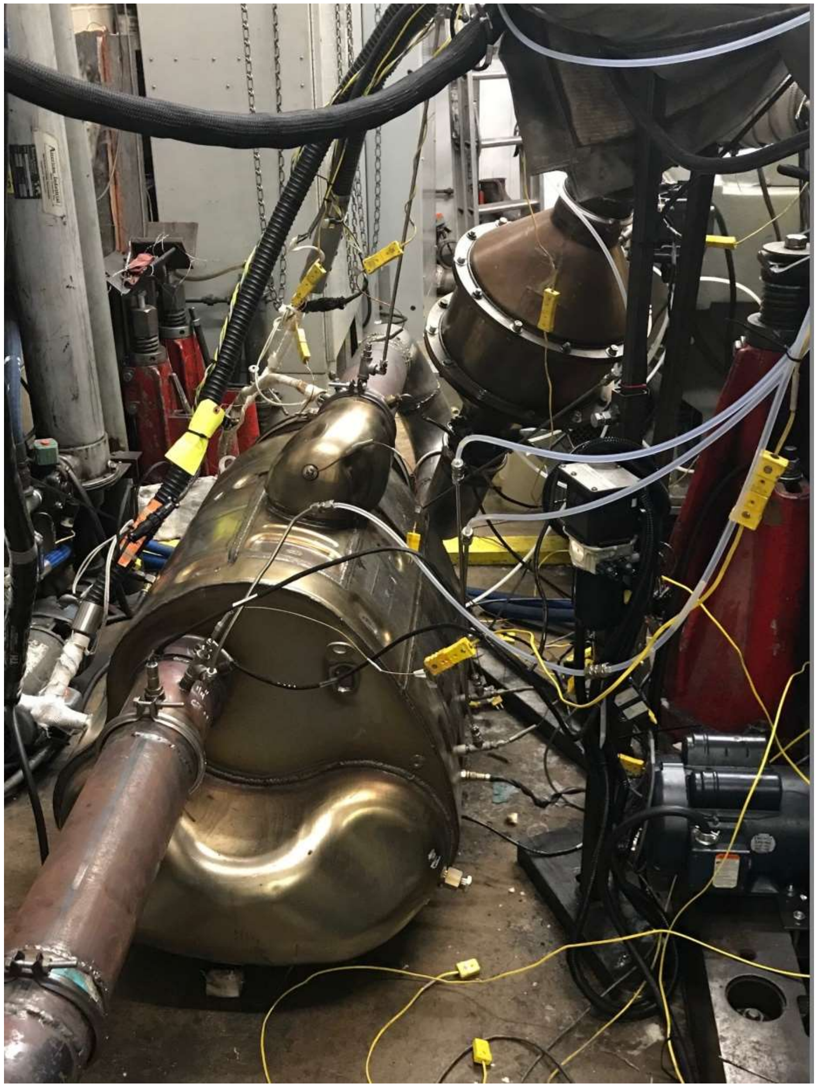
- Overall 74% conversion
- EO NO_X = 3.2 g/hp-hr
- TP NO_X = 0.8 g/hp-hr
- CO_2 = 710 g/hp-hr

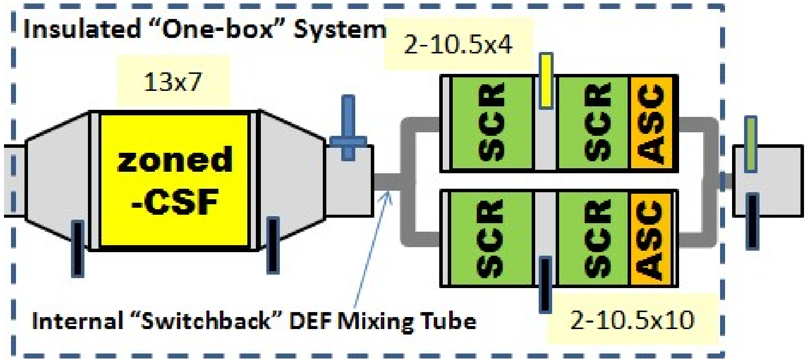
Stage 3 Final Configuration – Overall and Upstream

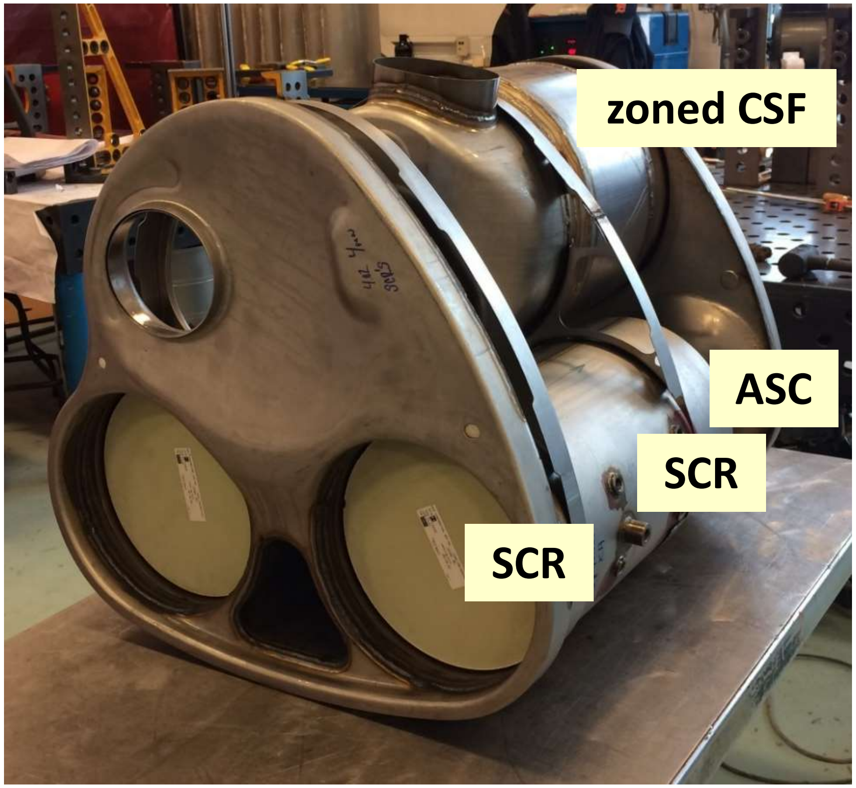




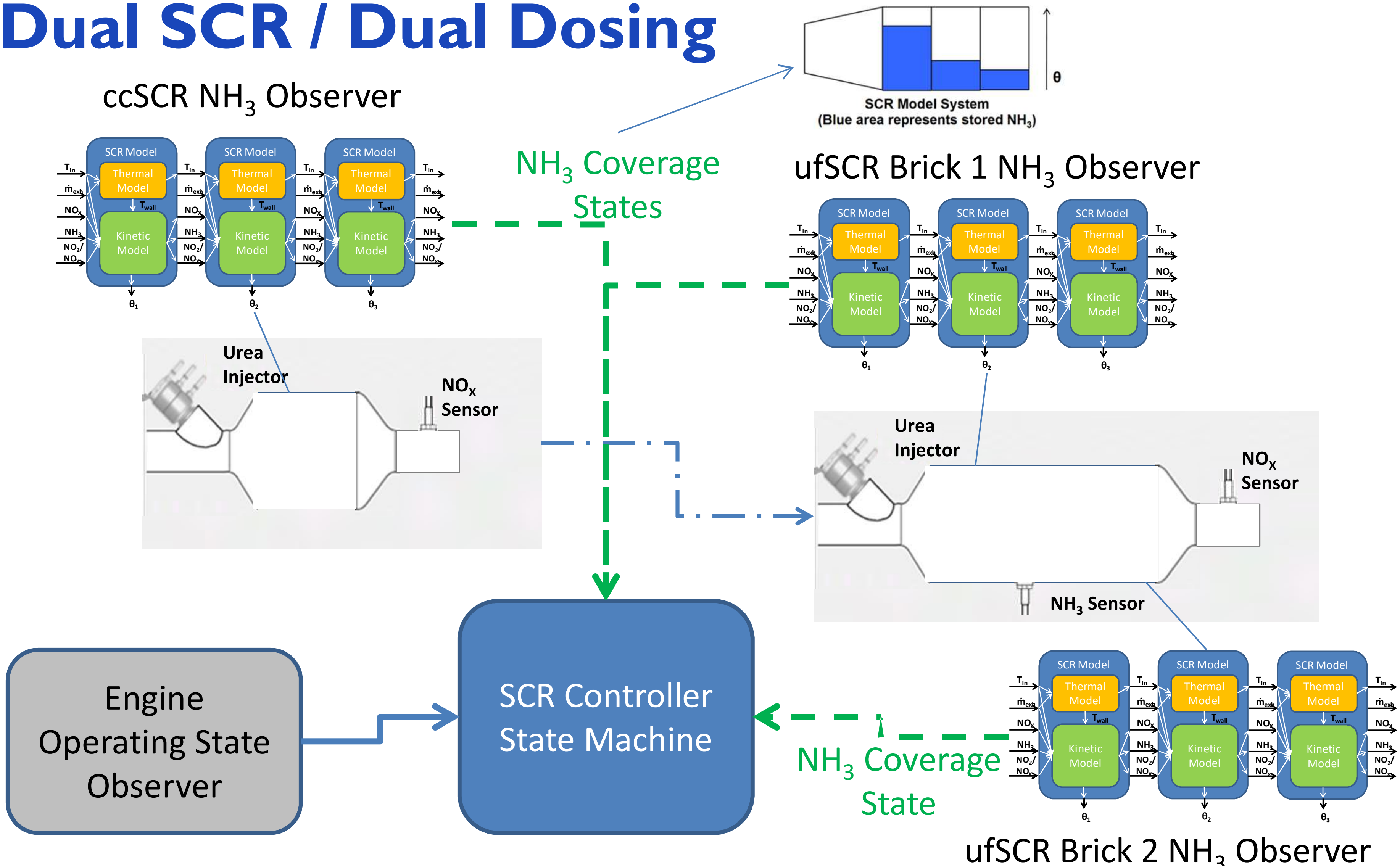
Stage 3 - Final Configuration - Downstream Package





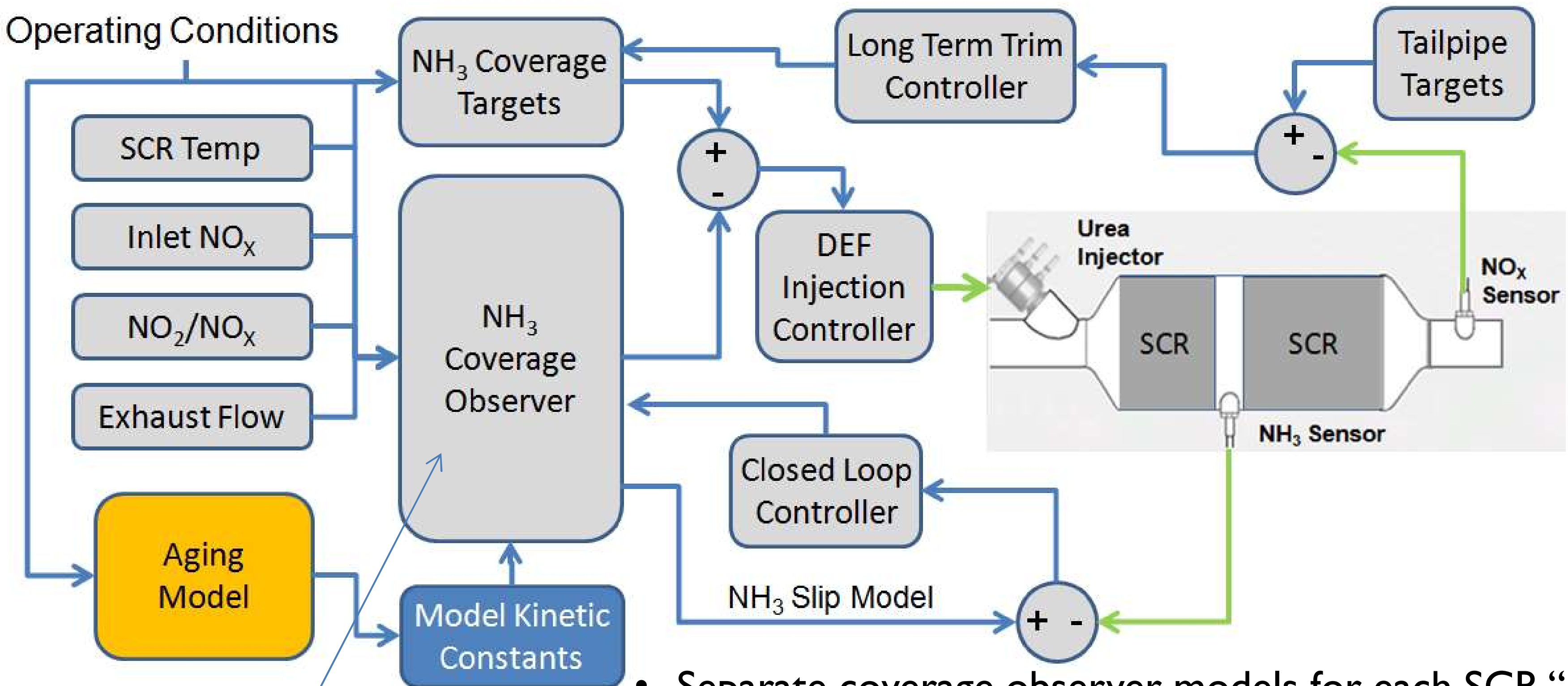


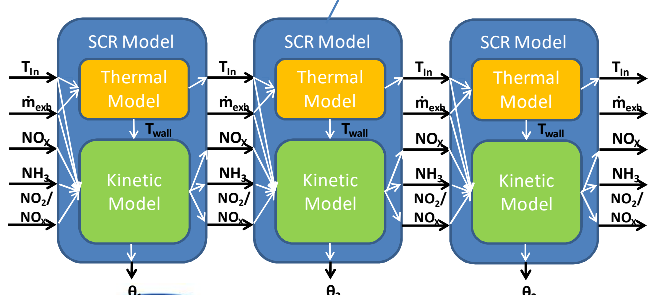
Stage 3 - Overall SCR Controller Schematic
Dual SCR / Dual Dosing



ECM Compatible, Production Oriented Controls Approach

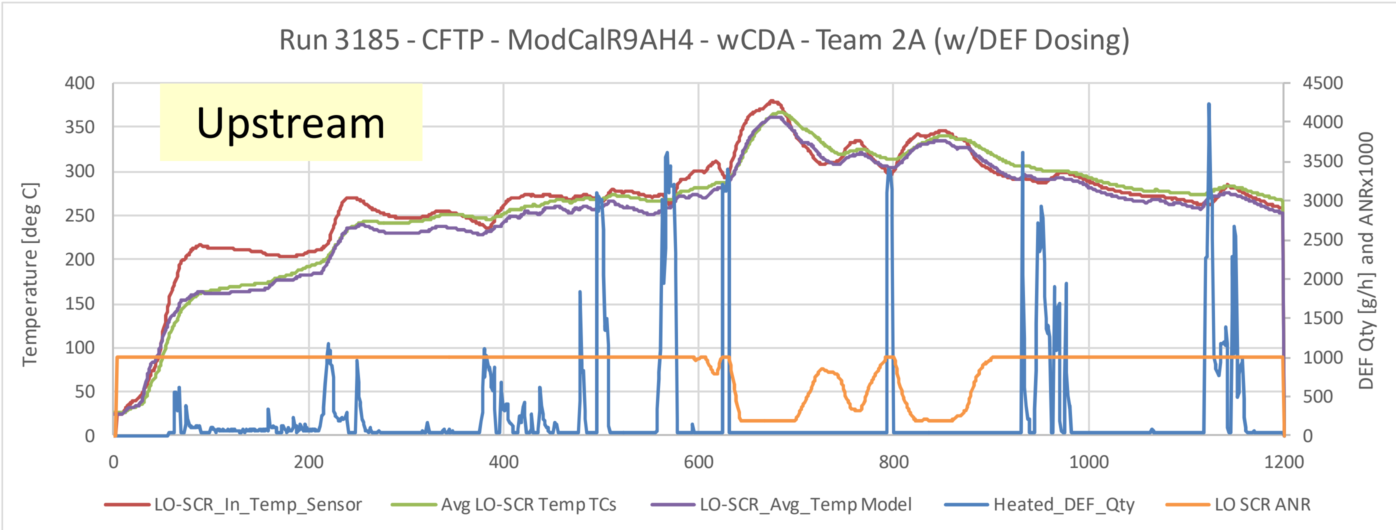
Stage 3 - Control Structure Example for Downstream Catalyst / Doser (ufSCR)

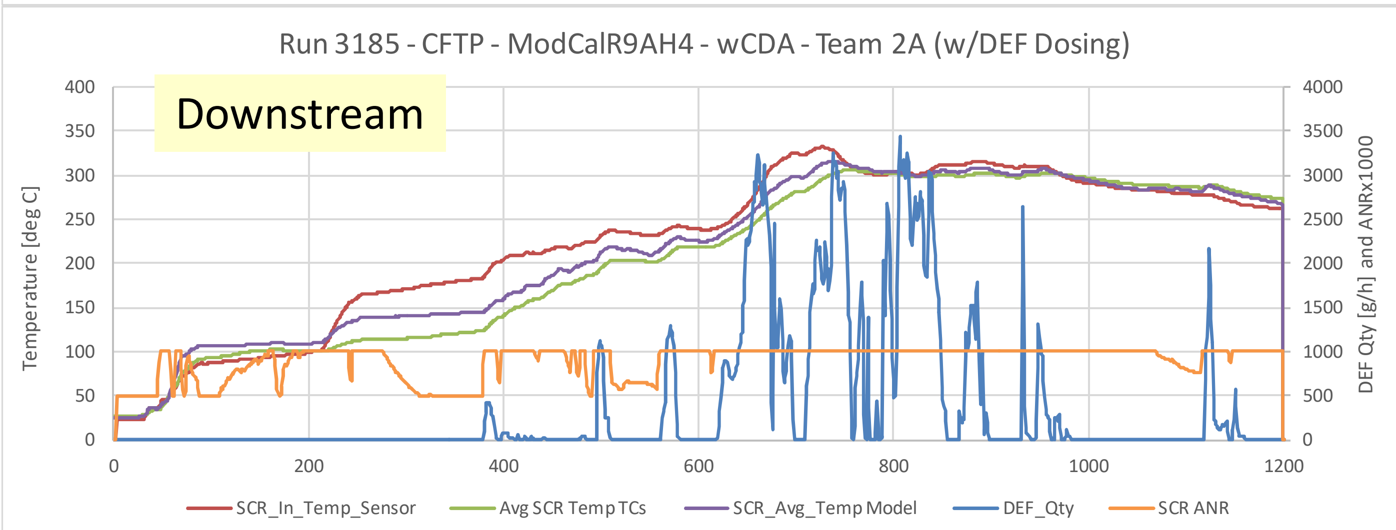




- Separate coverage observer models for each SCR "brick"
- Real-time feedback via NH_3 sensor (maintain >99.5% conversion)
- Primary calibration parameters are controller gains and coverage targets
  - Same calibration used for FTP, RMC-SET, LLC, etc.

Stage 3 - Dual Dosing Approach – Cold FTP Example





- Upstream (heated) dosing dominates early dosing
- Both system active in transition
- Downstream dosing dominates high temperature with AT warm
- Upstream dosing comes back into play as system cools to prepare storage