Aftertreatment System Durability for Future Low NO_X Engines

SOUTHWEST RESEARCH INSTITUTE®

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Agenda

- Defining Durability versus Robustness
- Regulatory Requirements
- Durability Challenges and System Demands
- Low NO_X Durability Example (CARB Stage 3 Engine)
- Assessing Aftertreatment Durability
  - Accelerated Aging Methodology (DAAAC)
- Facilities for Accelerated Aging
- Summary and Conclusions

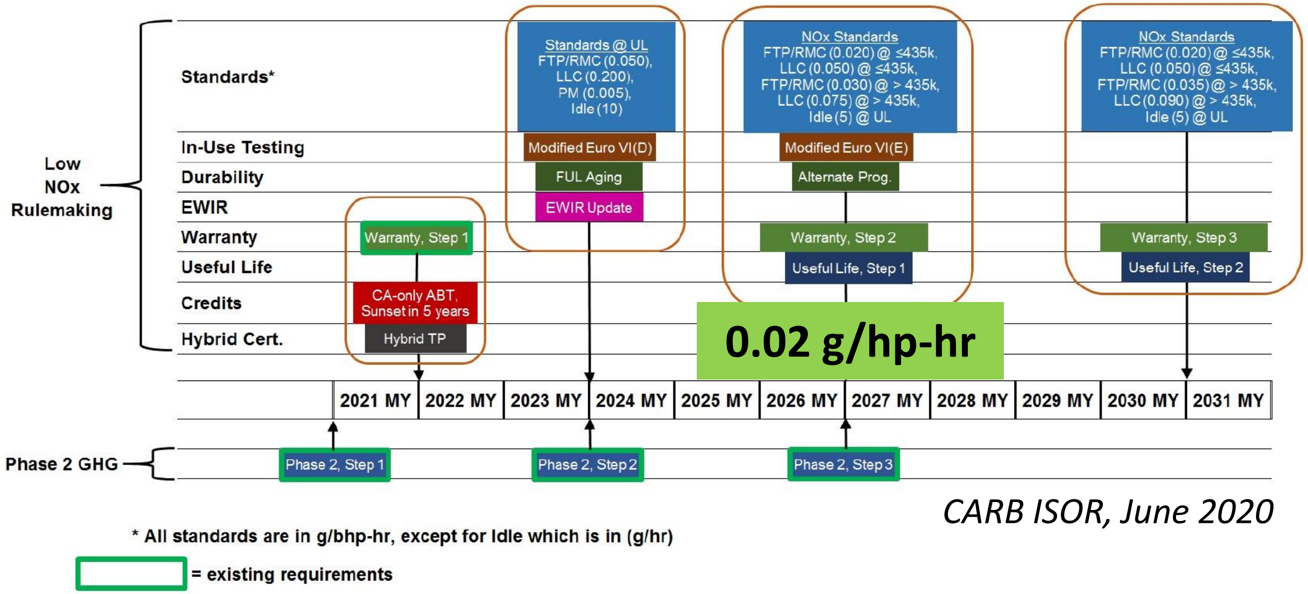
Definitions

- Durability and Robustness are not the same thing
  - Proper system design can improve both

- **Durability** describes the resistance of a system to "normal" modes of degradation
  - A system can degrade and still be within normal operating limits
  - Normal degradation is expected – we can design for this
  - Proper design for good durability means understanding field operations and conditions
  - Durability can be helped by feedback controls and long-term trim functions

- **Robustness** describes the resistance of a system to "abnormal" modes of degradation
  - Generally associated with a system failure
  - Abnormal degradation is not expected – we cannot easily predict failures
  - Proper design for robustness means understanding potential system failure modes (FMEA)
  - Diagnostics are the primary defense against failure in use – spot failures and limit the damage

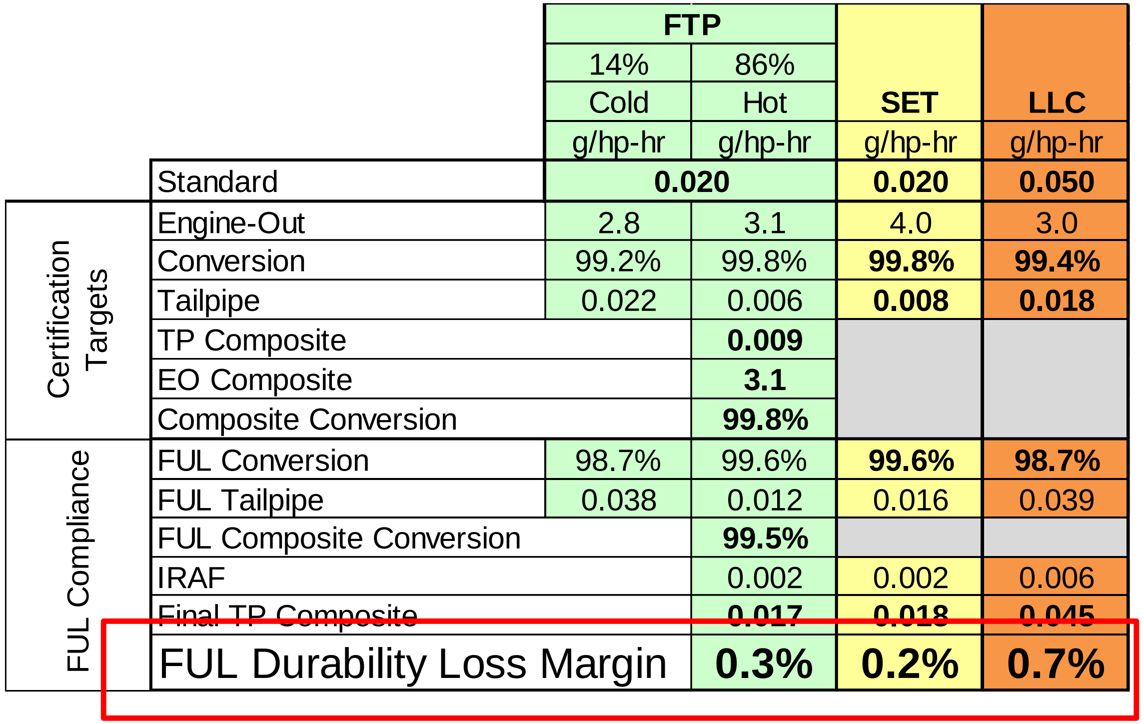
Requirements - Simultaneous NO_X and CO_2 Reduction



CARB ISOR, June 2020

* All standards are in g/bhp-hr, except for Idle which is in (g/hr)

🟩 = existing requirements



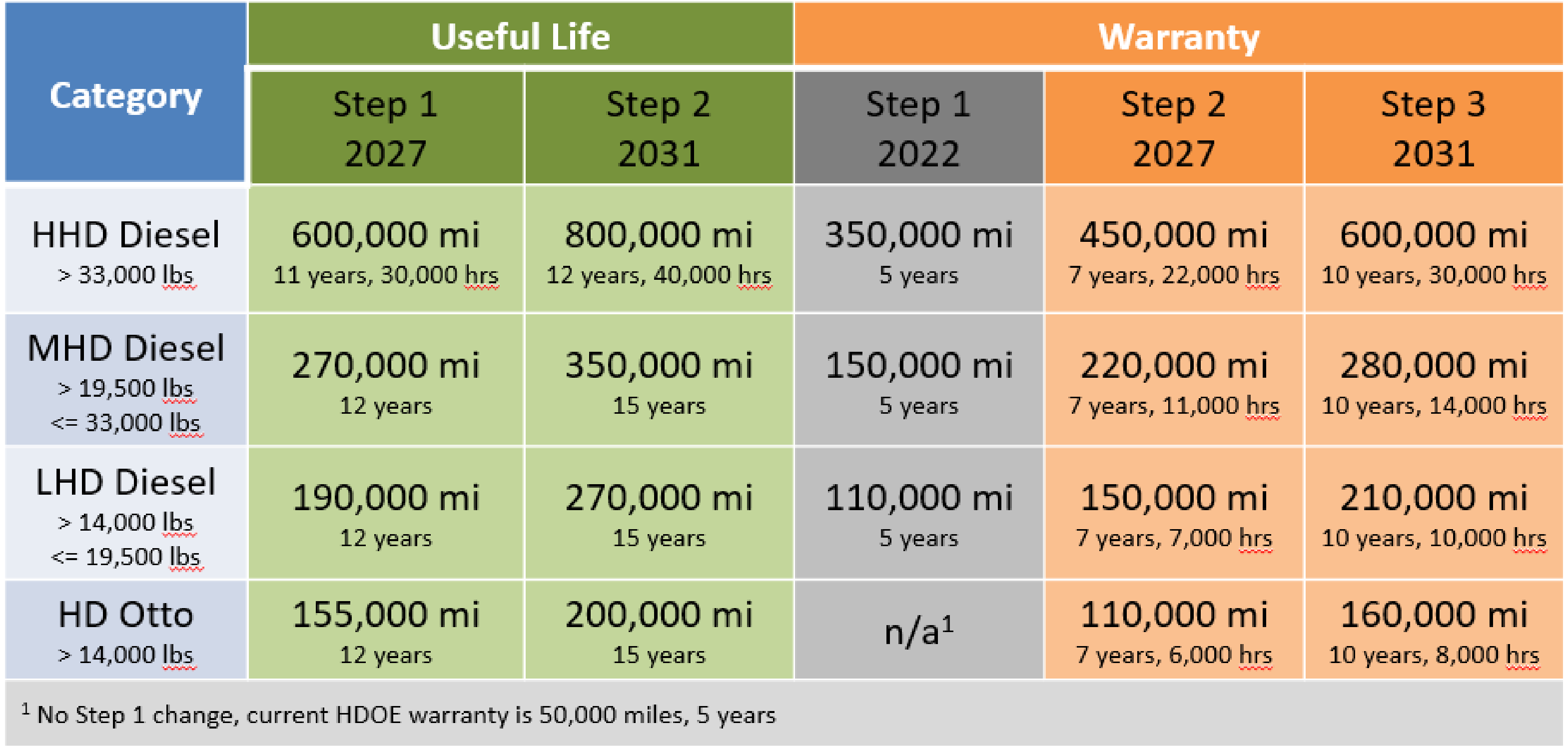
		FTP		SET	LLC
		14% Cold	86% Hot		
		g/hp-hr	g/hp-hr	g/hp-hr	g/hp-hr
	Standard	0.020		0.020	0.050
Certification Targets	Engine-Out	2.8	3.1	4.0	3.0
	Conversion	99.2%	99.8%	**99.8%**	**99.4%**
	Tailpipe	0.022	0.006	**0.008**	**0.018**
	TP Composite		**0.009**		
	EO Composite		**3.1**		
	Composite Conversion		**99.8%**		
FUL Compliance	FUL Conversion	98.7%	99.6%	**99.6%**	**98.7%**
	FUL Tailpipe	0.038	0.012	0.016	0.039
	FUL Composite Conversion		**99.5%**		
	IRAF		0.002	0.002	0.006
	Final TP Composite		**0.017**	**0.018**	**0.045**
	FUL Durability Loss Margin		**0.3%**	**0.2%**	**0.7%**

- Meeting Upcoming Regulatory Targets will Require Simultaneous Reductions on NO_X and CO_2
- This will increase the requirement for Aftertreatment performance and durability

- Aftertreatment Conversion Efficiency Demand is > 99.5% at end-of-life
- Margin for Loss of Conversion ~ 0.25% (0.7% at low load)

Requirements - Increased Full Useful Life Periods

CARB Increased FUL Requirements from Low NO_X Rule



Category	Useful Life		Warranty		
	Step 1 2027	Step 2 2031	Step 1 2022	Step 2 2027	Step 3 2031
HHD Diesel > 33,000 lbs	600,000 mi 11 years, 30,000 hrs	800,000 mi 12 years, 40,000 hrs	350,000 mi 5 years	450,000 mi 7 years, 22,000 hrs	600,000 mi 10 years, 30,000 hrs
MHD Diesel > 19,500 lbs <= 33,000 lbs	270,000 mi 12 years	350,000 mi 15 years	150,000 mi 5 years	220,000 mi 7 years, 11,000 hrs	280,000 mi 10 years, 14,000 hrs
LHD Diesel > 14,000 lbs <= 19,500 lbs	190,000 mi 12 years	270,000 mi 15 years	110,000 mi 5 years	150,000 mi 7 years, 7,000 hrs	210,000 mi 10 years, 10,000 hrs
HD Otto > 14,000 lbs	155,000 mi 12 years	200,000 mi 15 years	n/a[1]	110,000 mi 7 years, 6,000 hrs	160,000 mi 10 years, 8,000 hrs

[1] No Step 1 change, current HDOE warranty is 50,000 miles, 5 years

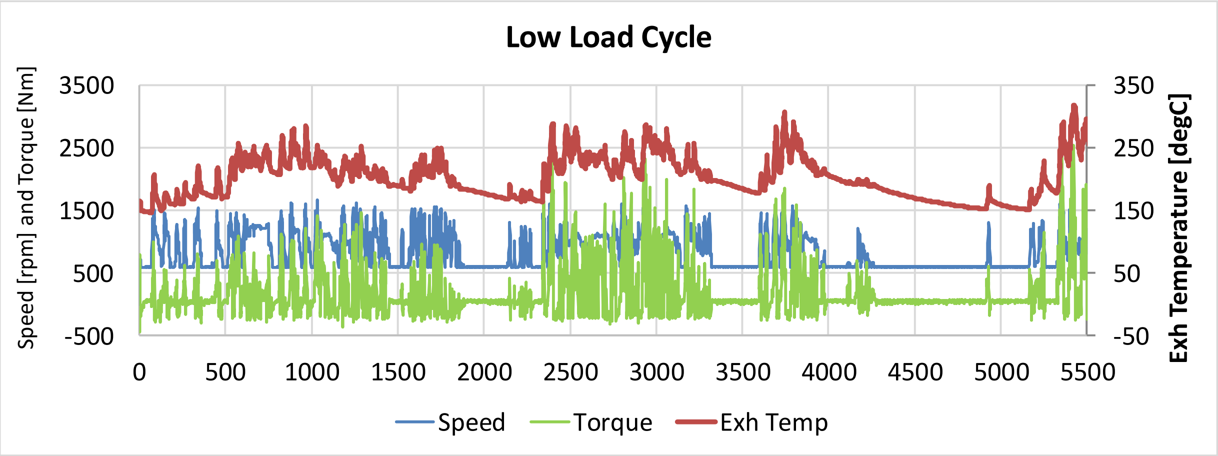
- Current Diesel FUL: HHD = 435,000 MHD = 185,000 LHD = 110,000
- Current Otto FUL = 110,000 miles

- CARB Low NO_X Omnibus extended FUL ~ X2
- EPA is also examining extending FUL requirements
- More stringent in-use requirements also increases demand for real Aftertreatment durability

Class 8 Durability Increase from 700000 km to 1290000 km by 2031

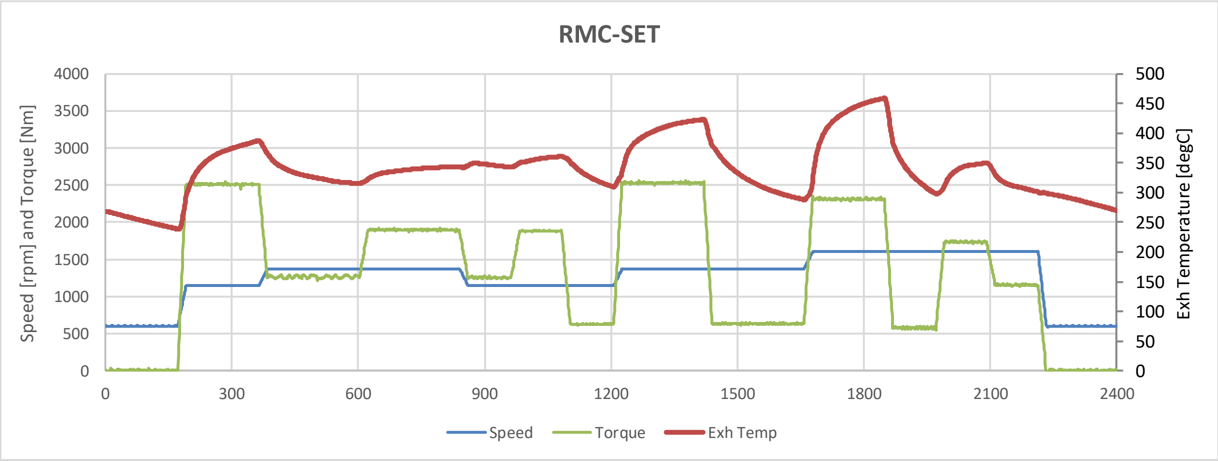
SCR Durability Challenges

Low Load



- Low Temperature Conversion on intermittent high load transients
- Durability challenge = maintain Low T Conversion
  - Chemical poisons
  - Sulfur management
  - Maintain DOC NO-NO_2 feed-gas performance
  - High T exposure impact on storage

High Load



- Very High Conversion at High Flow and NO_X Rates
- Durability Challenge = maintain high T selectivity of NH_3 oxidation
  - High Temperature Durability
  - Slip Catalyst Selectivity
- Manage storage capacity changes to prevent excessive slip

Other Key System Elements for Aftertreatment Durability at Low NO_X

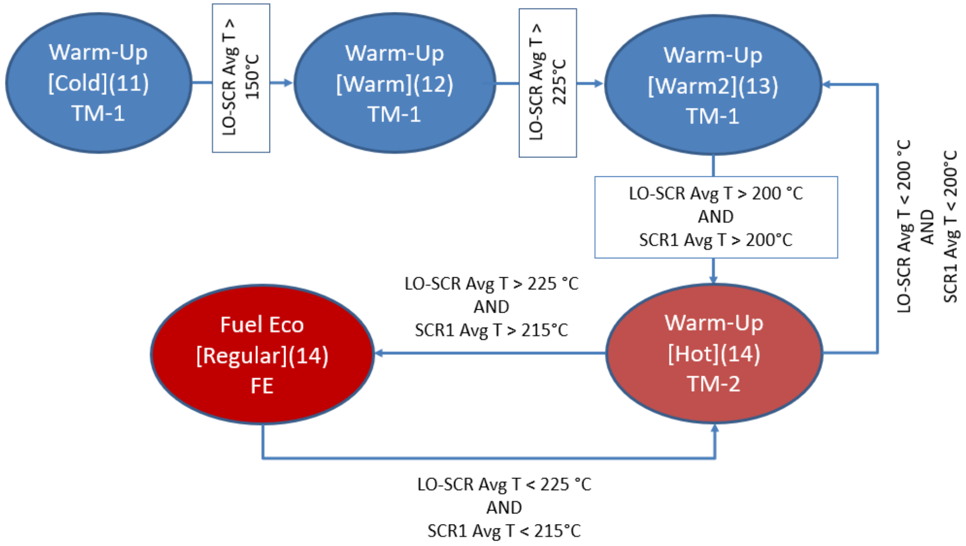
- Very good DEF evaporation and mixing
  - especially for high load, high NO_X conditions with high DEF demand

- Sensors and Actuators
  - accurate sensors that are stable over time (NO_X and NH_3)
  - repeatable and reliable DEF and HC dosing

- Good regeneration controls
  - Periodic regenerations and deSO_X events will be needed
  - Preventing excessive localized temperatures is critical to maintain Aftertreatment Durability

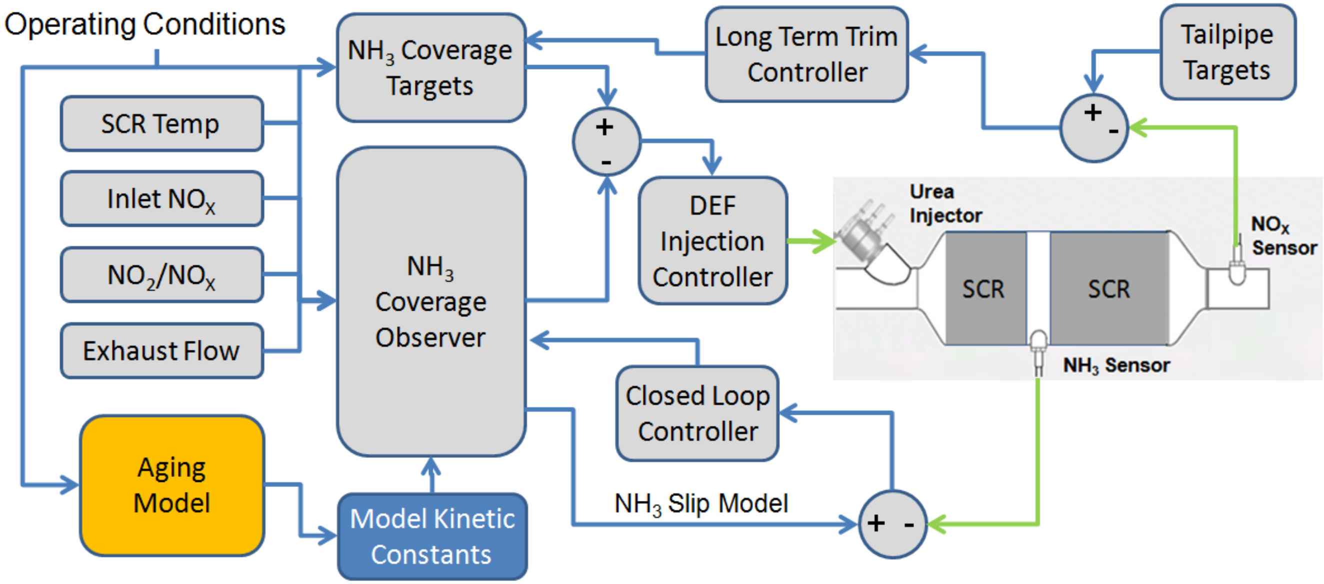
The Role of Controls in Aftertreatment Durability

Engine – Thermal Management



- Better thermal management control results in higher system temperatures
- Aftertreatment less affected by low temperature conversion losses due to chemical poisoning

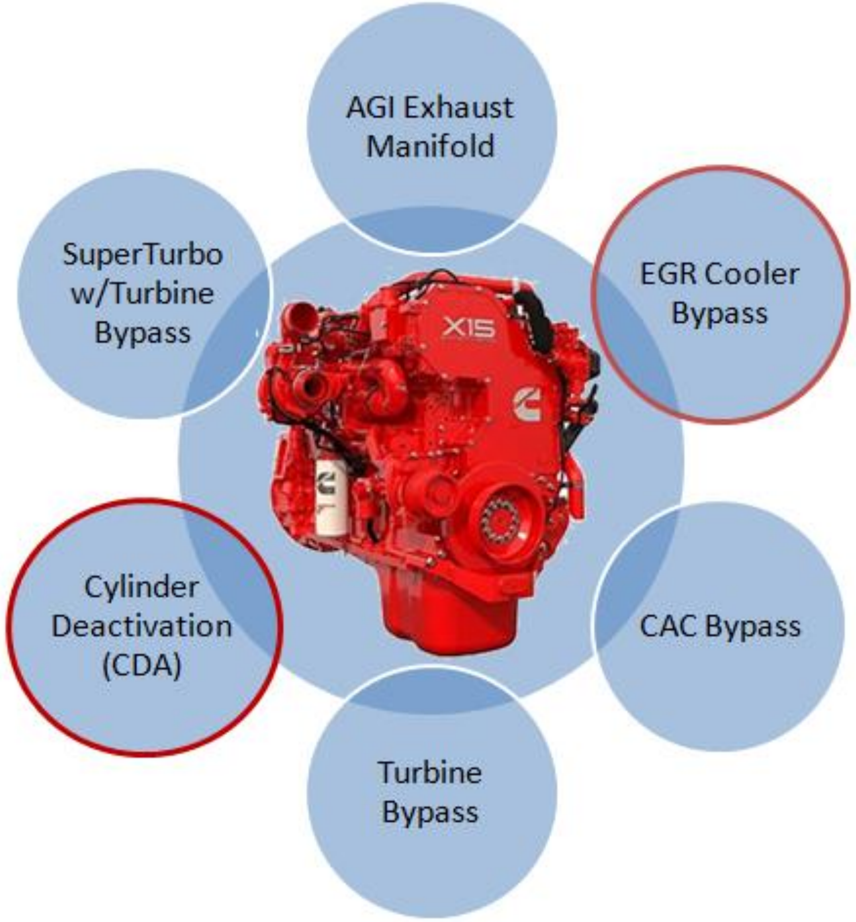
Aftertreatment – Model Based DEF Dosing Controls



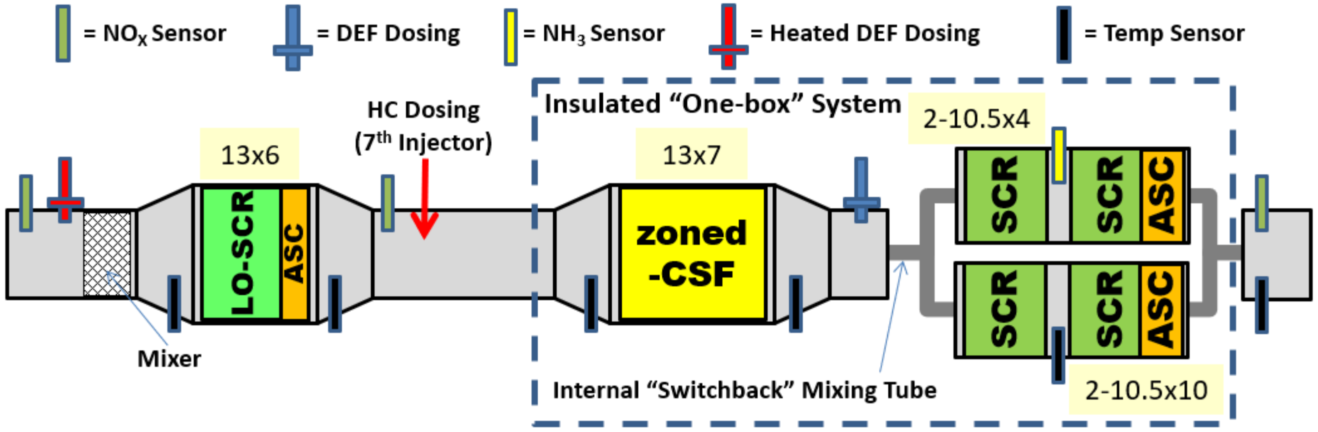
- Model-based controls for improved flexibility
- High Speed Feedback too maintain precision at high NO_X conversion (> 99.5%)
- Long-term trim to compensate for model-input errors
- Catalyst aging model

Stage 3 Low NO_X Engine Example

2017 Cummins X15 Engine with Eaton CDA Hardware

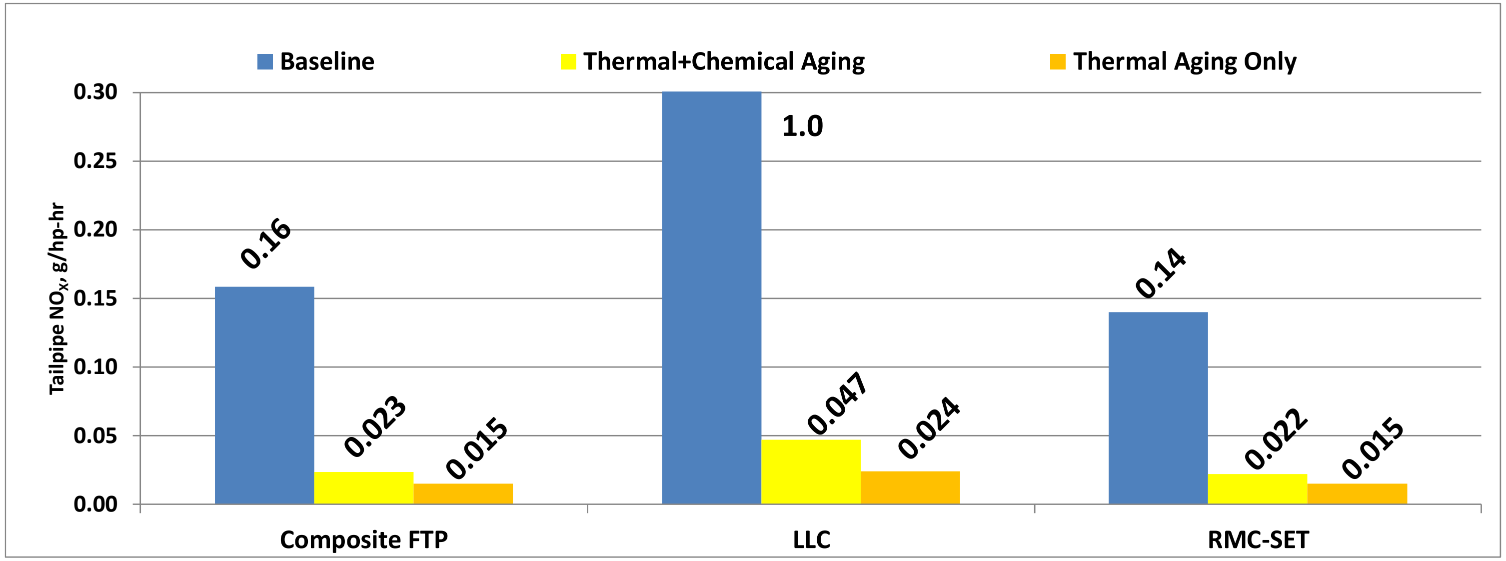


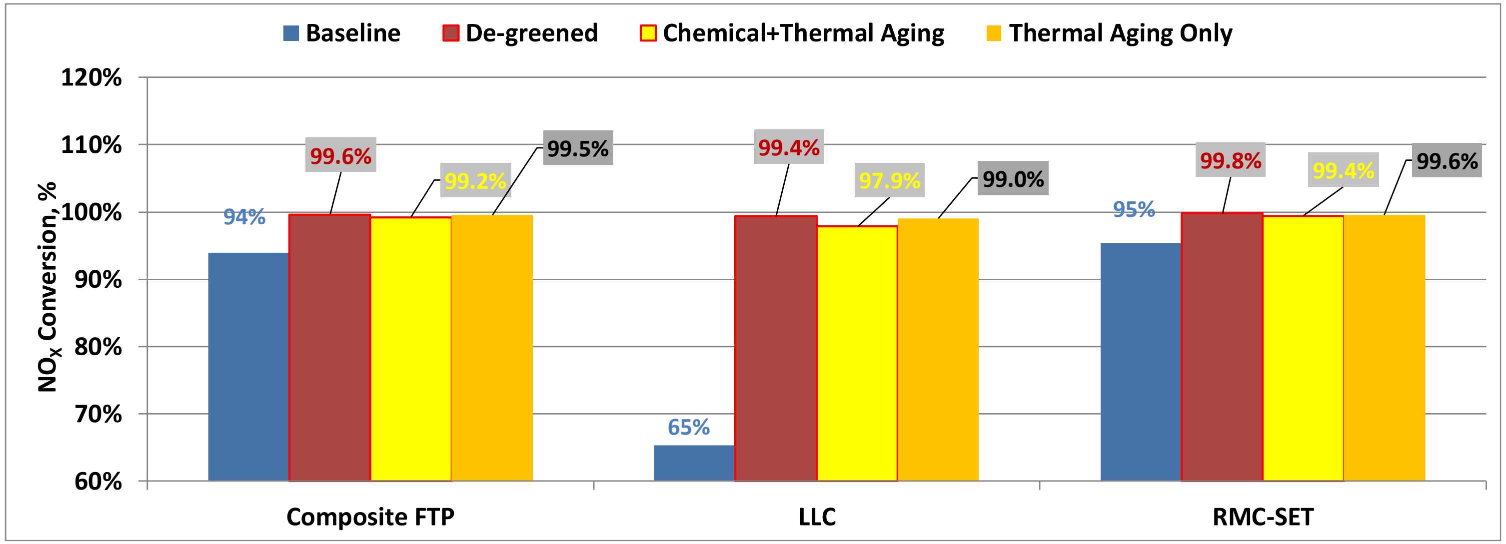
Advanced Low NO_X Aftertreatment (Dual SCR-Dual Dosing)



Advanced Cu-zeolite based SCR catalysts for low temperature performance and high temperature durability

Stage 3 Demonstration System Durability





- Values shown as tested
  - 0.002 added to FTP/RMC for IRAF (regeneration adjustment, “k-factor”)
  - 0.006 added to LLC for IRAF
- Margin available to standard as calibrated = 0.2% for FTP/RMC and 0.7% for LLC
- Degradation with Full Aging (Thermal + Chemical) ~ 0.4% for FTP/RMC and 1.5% for LLC
- Thermal aging only not sufficient, especially at lower temperatures

Stage 3 System - Opportunities for Further Improvement in Durability of NO_X Performance

- Move to traditional DOC + DPF architecture
  - Better long-term NO-NO_2 oxidation (downstream SCR feedgas)
  - More robust and likely slightly better CO_2
- Further improvement in downstream mixing
- Small Increase in downstream catalyst volume for high load points
- Catalyst Formulation
  - More low temperature chemical poisoning resistance
  - Better long-term high temperature selectivity of NH_3 oxidation
- Further Controls Improvement - Catalyst Aging Model
- Target = Reduce Aging Impact by Half

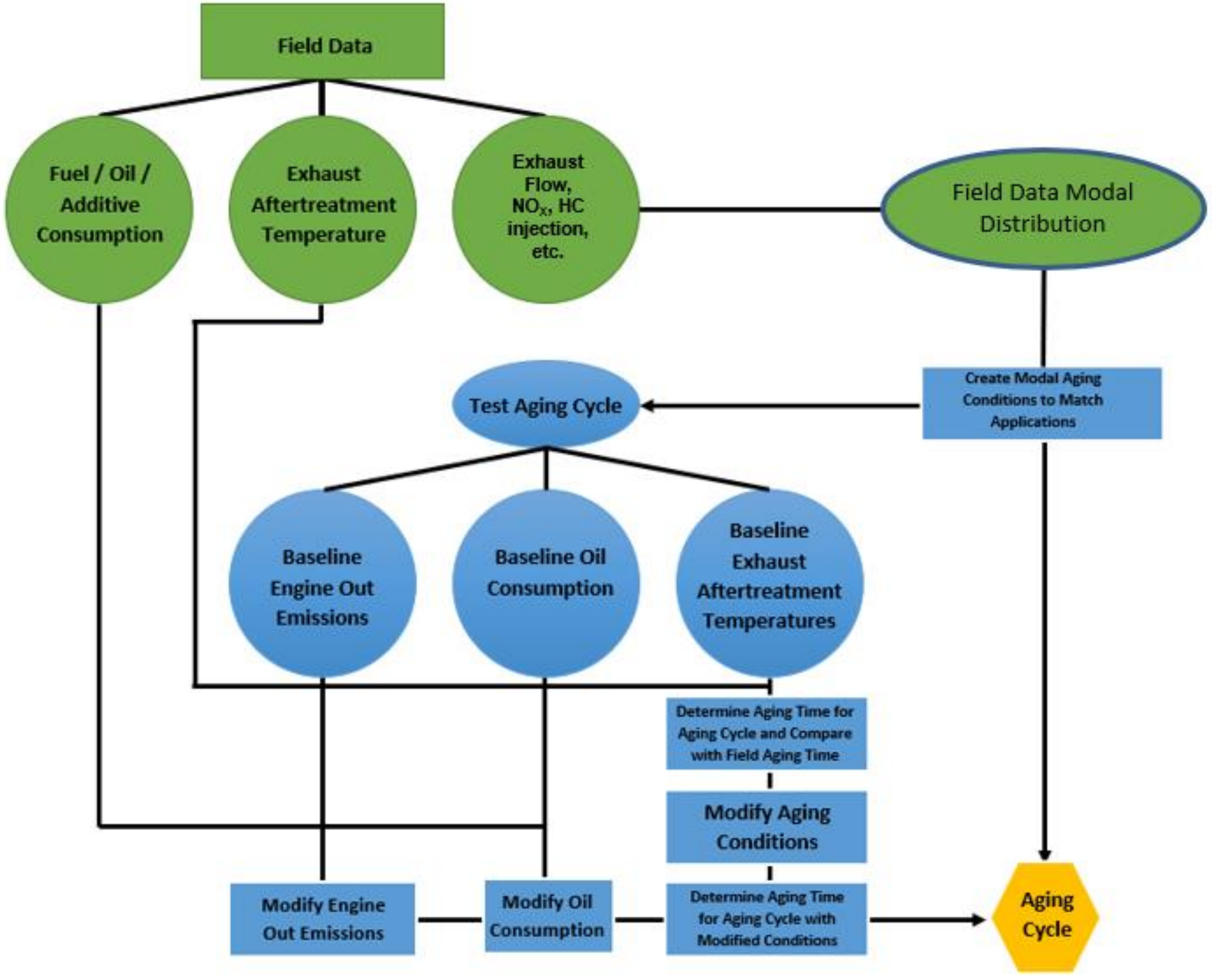
Assessing Aftertreatment Durability

- Laboratory Assessment of Durability is Important for Multiple Reasons
  - Certification – pre commerce demonstration of system design (Due Diligence)
  - Development – aged parts are needed to understand necessary design margins

- Traditional Approaches
  - Normal Engine Aging
    - Full Useful Life – very time consuming (10000 hours FUL for heavy-duty on-road)
    - Partial Life – still time consuming and requires extrapolation which has been shown to be inaccurate
    - These issues will get worse with increased FUL (20000 hours FUL for heavy-duty on-road)
  - Hydrothermal Aging (Oven)
    - Not representative of real-world aging
    - Does not accurately capture key mechanisms for Low NO_X

- Accelerated aging methodology that captures all aspects of aging

DAAAC (Diesel Aftertreatment Accelerate Aging Cycles) Protocol


Field Data

Fuel / Oil / Additive Consumption

Exhaust Aftertreatment Temperature

Exhaust Flow, NO_x, HC injection, etc.

Field Data Modal Distribution

Create Modal Aging Conditions to Match Applications

Test Aging Cycle

Baseline Engine Out Emissions

Baseline Oil Consumption

Baseline Exhaust Aftertreatment Temperatures

Determine Aging Time for Aging Cycle and Compare with Field Aging Time

Modify Aging Conditions

Modify Engine Out Emissions

Modify Oil Consumption

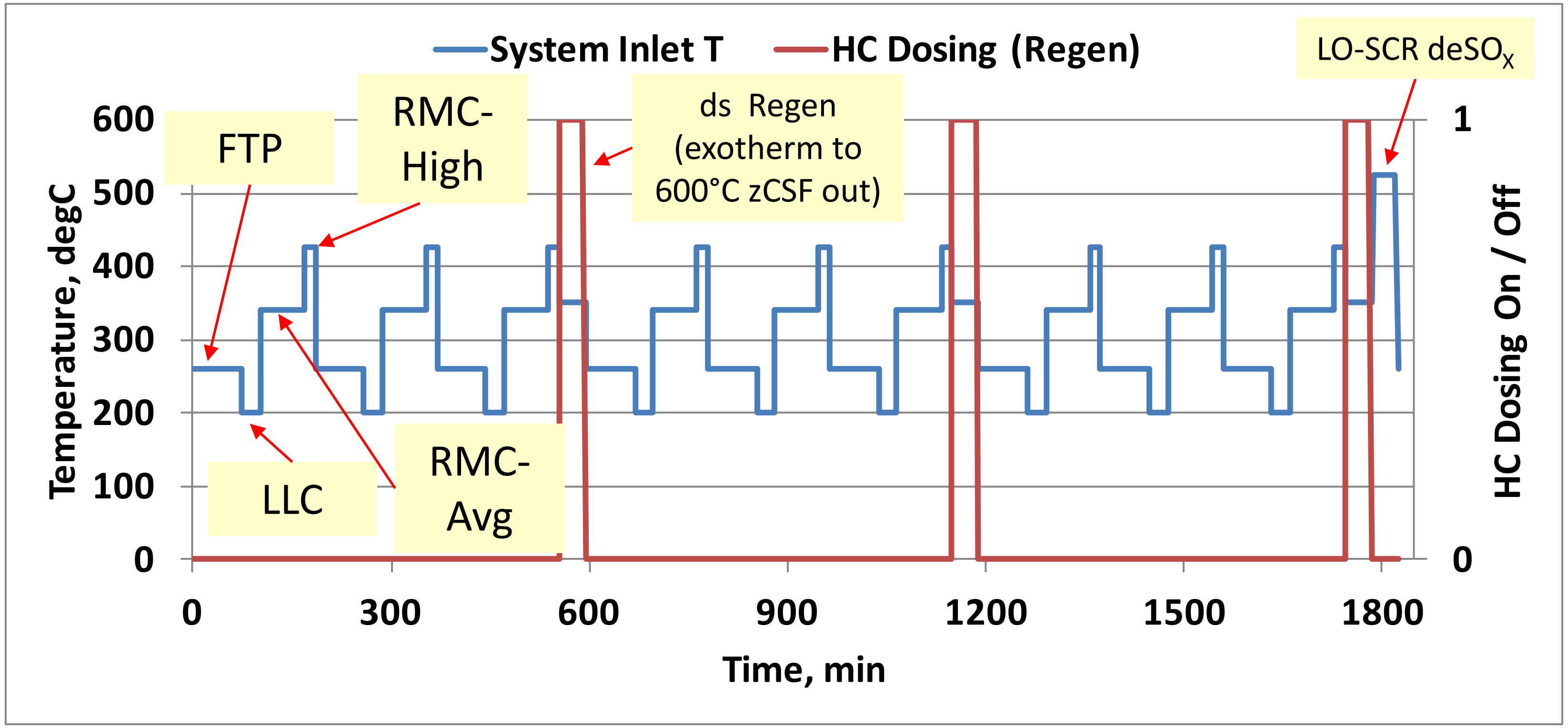
Determine Aging Time for Aging Cycle with Modified Conditions

Aging Cycle

- DAAAC Protocol is a method of generating representative, accelerated aging cycles based on **field** data
  - Not one specific cycle
  - Target is 10X acceleration
  - Aftertreatment-centric approach
- Thermal, Chemical, and Physical Aging Incorporated
- Conditions relevant to field
  - Aging temperatures are not beyond normal field maximums
  - Regenerations conducted in similar fashion to real application
  - Representative normal oil formulations

Stage 3 Low NO_X Demonstration

DAAAC-Based Accelerated Aging Cycle (equivalent to 300 field hours)



1000 Hours DAAAC Aging

=

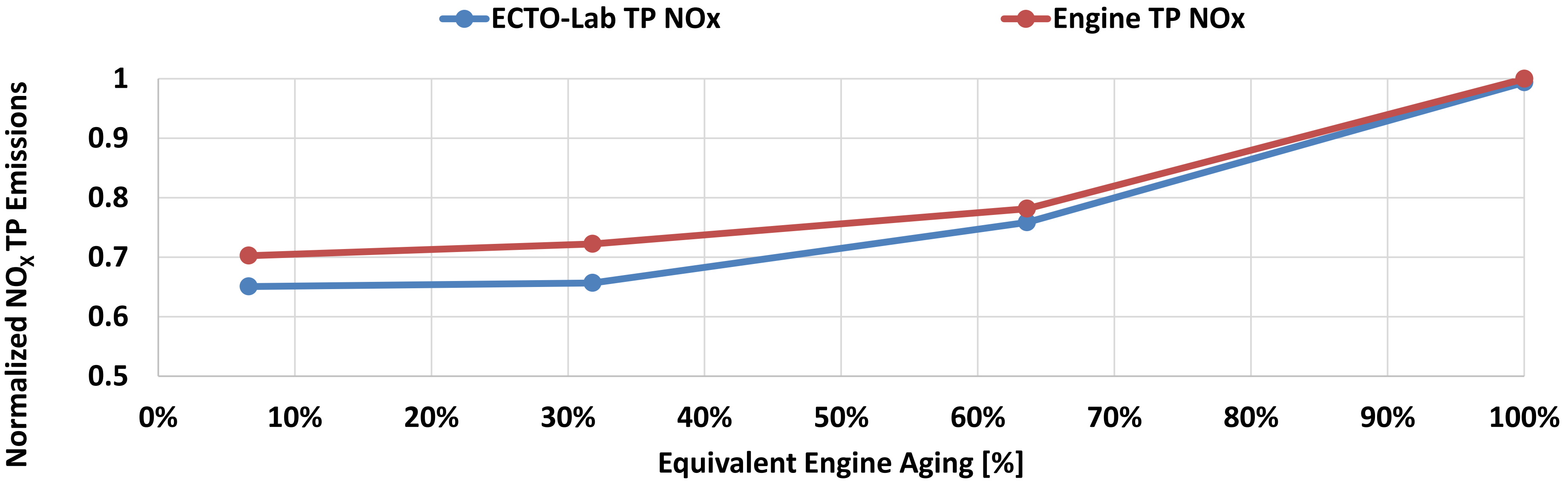
10000 Hours Field Aging
(700,000 km)

- Regeneration 30 min every 100 hours at 600°C zCSF Outlet Temperature
  - Regeneration using actual exotherm via 7th injection fuel injection in front of zCSF
- LO-SCR long-term deSO$_X$ 30 min every 300 hours at 525°C LO-SCR Inlet T (later modified to 550°C)
- Oil exposure at 10X (combination of modified engine and fuel doping)
- Sulfur exposure at 10X (extra sulfur doped in fuel ~ 2.5ppm SO_2 in exhaust)
- Chemical exposure – 138 kg oil, 183 g/L sulfur on LO-SCR – peak filter ash load 35 g/L reached every 500 hours

ECTO-Lab (Burner) Aging Using DAAAC Correlation with Engine-Based Deterioration Factor

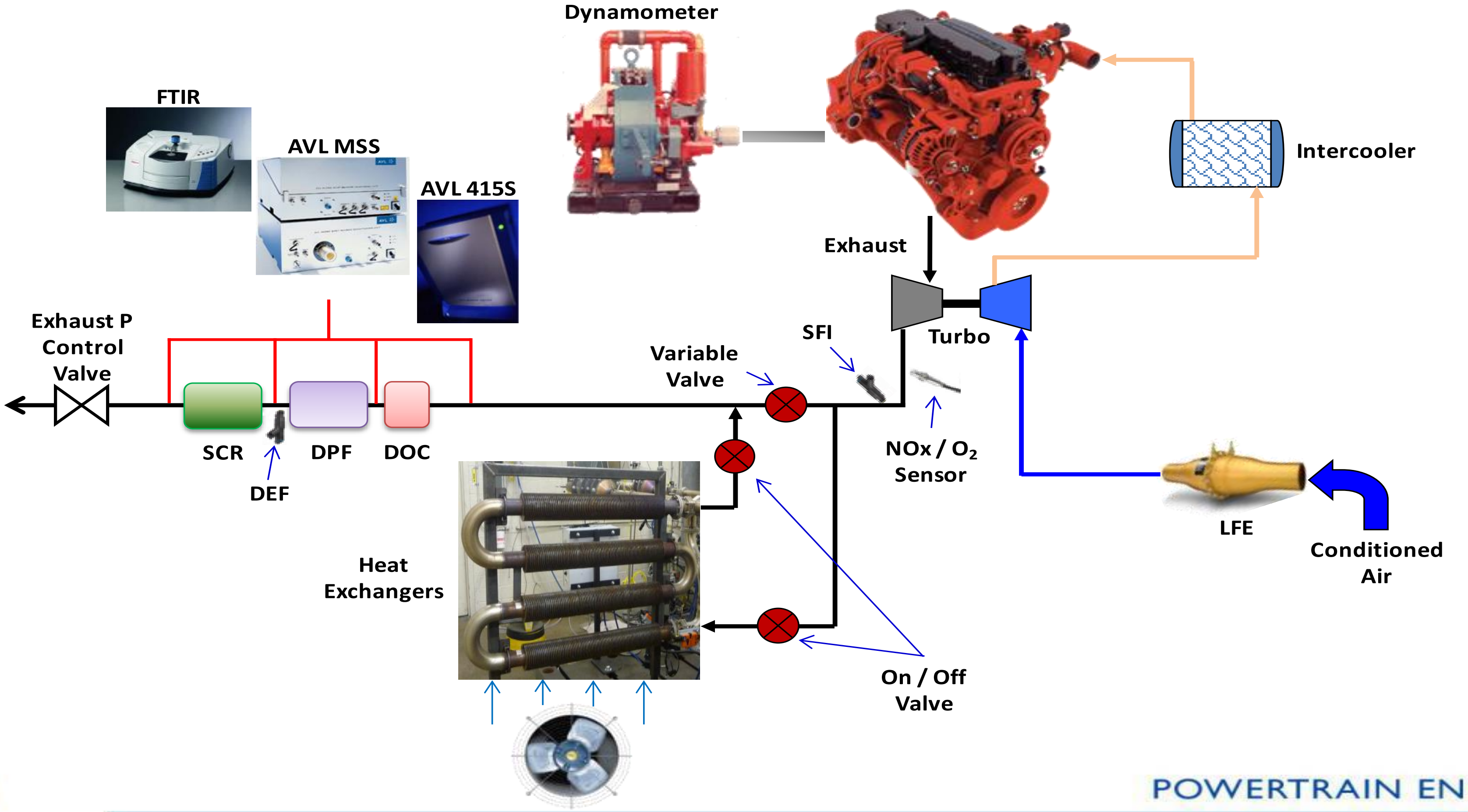
- As Shown Below, the End Result is an ECTO-Lab Aged System That Successfully Replicates the Performance of the Engine Aged System
  - With Oil and Sulfur Exposure
  - But DAAAC was conducted in 1 / 10th the amount of time

- The ECTO-Lab Aged System is Within 1% of the Engine Aged System

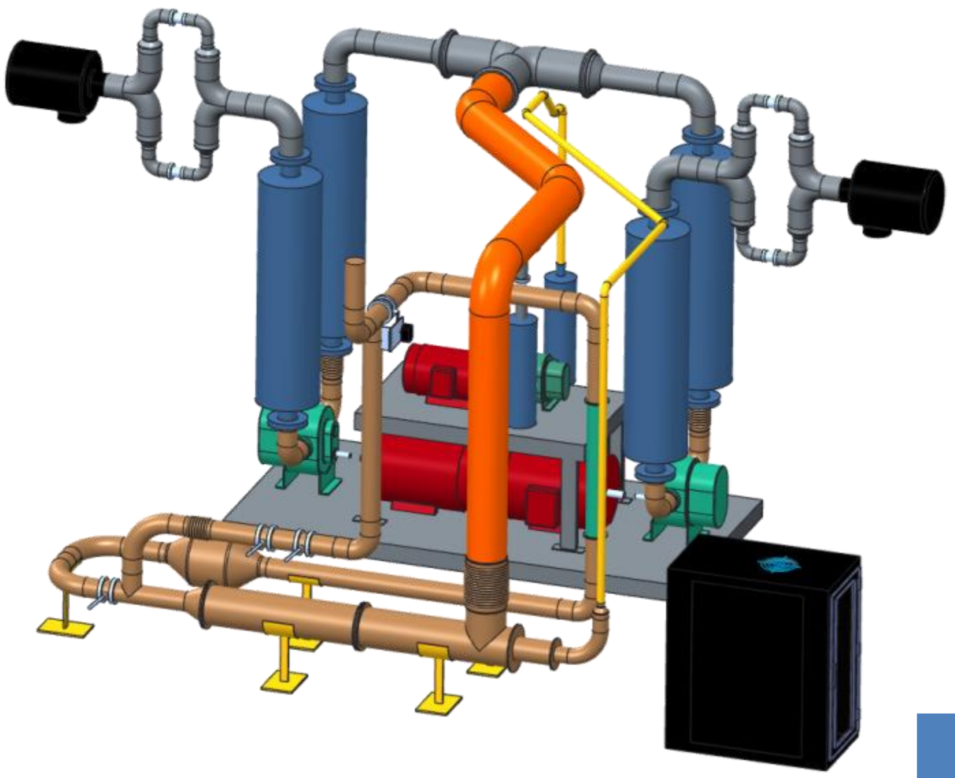


SwRI Engine-Based DAAAC Platform

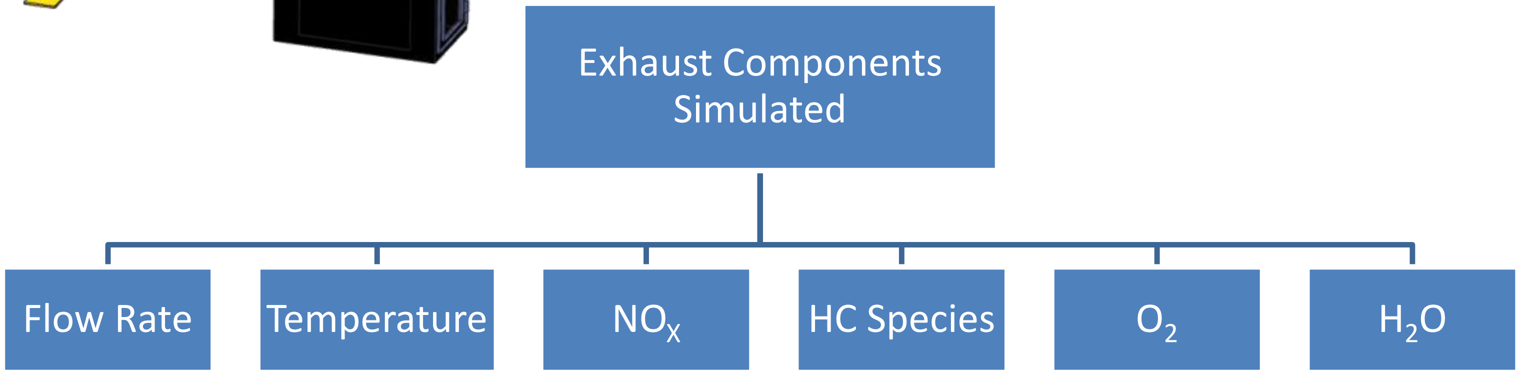
- Highly flexible engine bench used to evaluate age and evaluate diesel aftertreatment components and sensors
- DAAAC modified bench aging engine for increased oil consumption



SwRI Burner-Based DAAAC Platform - ECTO-Lab^{TM}



- SwRI's Exhaust Composition Transient Operation Laboratory^{TM} (ECTO-Lab^{TM}) is a Computer Controlled, Burner-Based Reactor Used to Replicate Stoichiometric and Lean Exhaust Conditions of Conventional SI and CI Engines
- Exhaust Simulation Capabilities Enables Calibration and Validation Efforts on Full-Size Components
- Oil Injection and SO_2 injection for DAAAC acceleration of chemical poisoning (10X)
- Can be used for DAAAC Aging and OBD Part Generation



Exhaust Components Simulated

Flow Rate

Temperature

NO_X

HC Species

O_2

H_2O

Summary and Conclusions

- Aftertreatment Durability is Critical for meeting Future Low NO_X Standards
  - New Standard are Increasing Demand for Durable High NO_X Conversion > 99.5%
- Aftertreatment Durability Requires a Systems Approach
  - Catalyst Formulation
  - Aftertreatment Design
  - Engine Calibration
  - Controls
- Stage 3 Demonstration Indicates Potential but More Work Needed on Aftertreatment Durability to Insure Sufficient Margins
- New Approaches to Accelerated Aging of Diesel Aftertreatment are Needed to Properly Assess Durability
  - SwRI DAAAC Protocol Meets this Need
  - Specialized Facilities for DAAAC Accelerated Aging are Available

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