Aftertreatment Accelerated Aging Protocol and Applicability for Future Regulatory Compliance

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Background

- In 2020, CARB adopted the Heavy-Duty Low NO_X Omnibus Ruling
  - New low load certification cycle
  - Decreased tailpipe NO_X emissions
  - Extended durability and warranty requirements
  - Extended durability tailpipe NO_X emissions
  - **New certification procedures requiring OEMS to certify with aftertreatment systems at full useful life**

- Similar regulatory updates are expected from EPA and other government agencies, but with potential differences in targets

CARB Low NO_X Omnibus – Standards for 2024 – 2026

	CARB Standards	
	Diesel	Otto
FUL Mileage	**435,000 miles**	
NO_X	g/hp-hr	
FTP	0.050	0.050
RMC-SET	0.050	--
LLC	0.200	--
Idle	10	--
PM, g/hp-hr	0.005	

- OBD NO_X threshold to stay at 0.40 g/hp-hr
- OBD PM threshold to stay at 0.03 g/hp-hr

CARB Low NO_X Omnibus –Standards for 2027 and Beyond, HHD Diesel Engines

	2027 – 2030		2031 +	
	IUL	FUL	IUL	FUL
Mileage	**435,000 miles**	**600,000 miles**	**435,000 miles**	**800,000 miles**
NO_X	g/hp-hr			
FTP	0.020	0.035	0.020	0.040
RMC-SET	0.020	0.035	0.020	0.040
LLC	0.050	0.090	0.050	0.100
Idle, g/hr	5	5	5	5
PM, g/hp-hr	0.005			

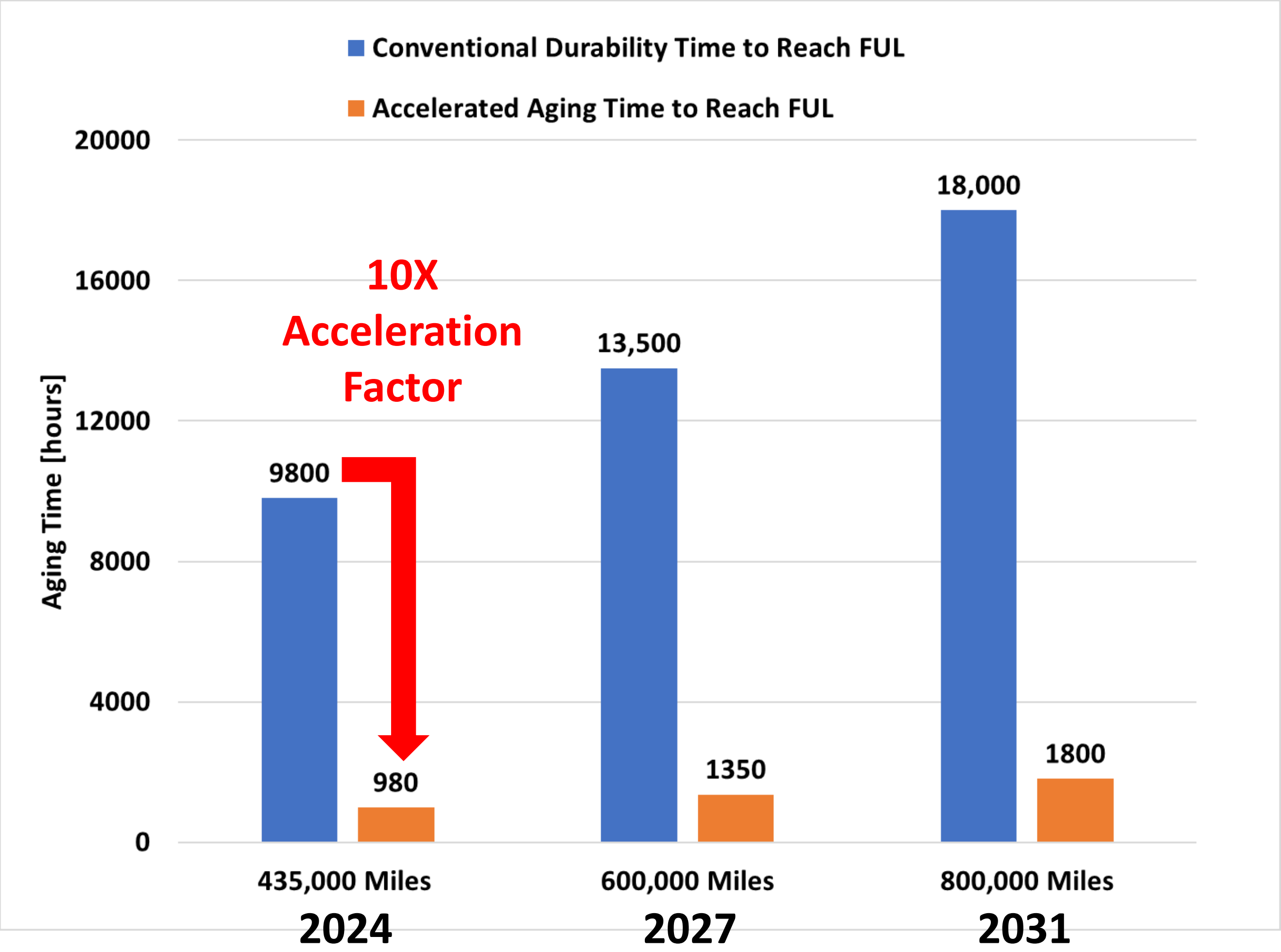
- OBD NO_X threshold to stay at 0.40 g/hp-hr
- OBD PM threshold to stay at 0.03 g/hp-hr

Potential Pathways to Generate FUL Aftertreatment Systems - Example

1. Durability experiment – HHDD: **9,800 hours** (435,000 miles)
2. Durability with accelerated aging – HHDD: **5,500 hours** (435,000 miles)
3. Accelerated aging only – HHDD: **980 hours** (435,000 miles)

Primary Intended Service Class	Current UL (miles)	DDP Procedures
LHDD	**110,000**	Age EAS on dynamometer to FUL using pathway 1 or 2 cycles **(≈ 2,500* hours)**
MHDD	**185,000**	Age EAS on dynamometer to FUL using pathway 1 or 2 cycles **(≈ 4,200* hours)**
HHDD	**435,000**	Two possible options: • Age EAS on dynamometer for 4,600 hours using pathway 1 or 2 cycles, and then age aftertreatment only using accelerated aging for ½ UL(≈600 hours DAAAC). Age for 300 additional dyno hours **(≈ 5,500* hours).** This option requires NOx sensor data submittal. • Age EAS on dynamometer to FUL using pathway 1 or 2 cycles **(≈ 9,800* hours)**, or

Potential Accelerated Aging Times for Future Regulation

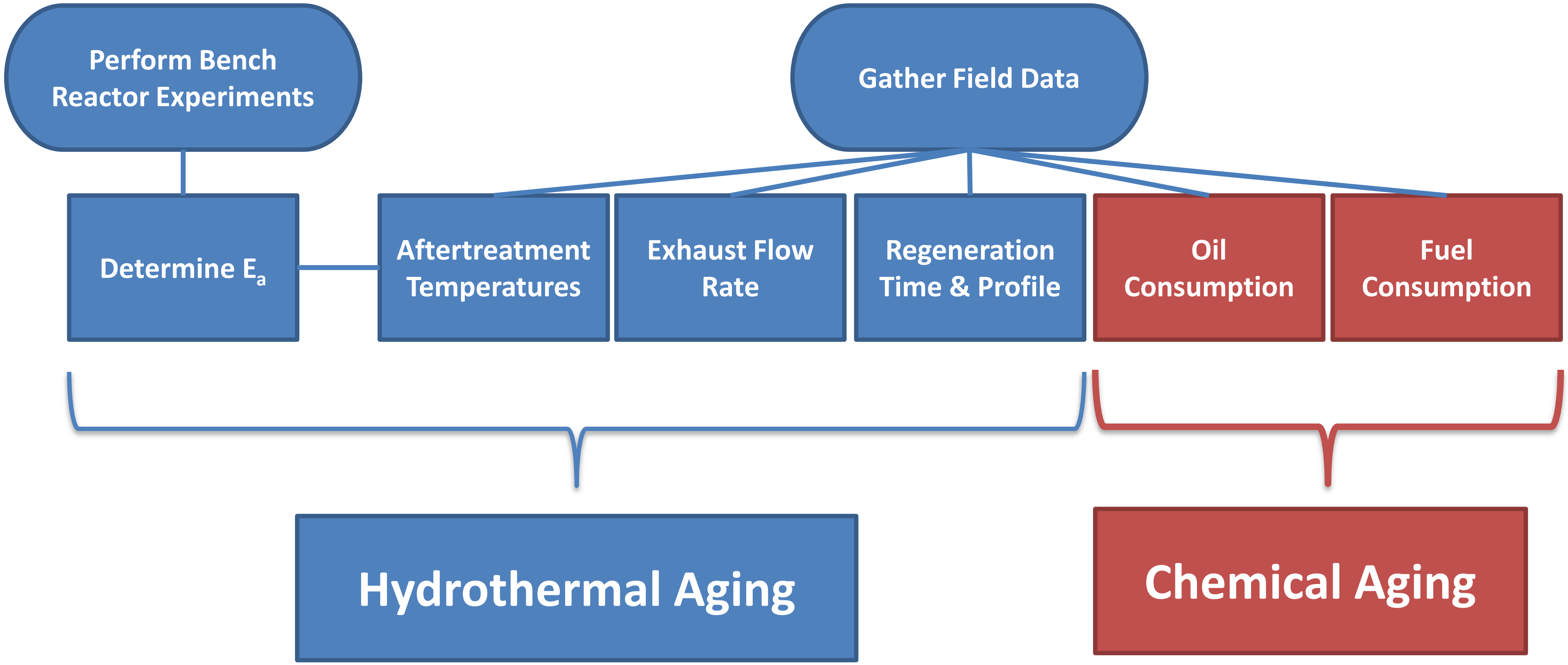


Diesel Aftertreatment Accelerated Aging Cycles (DAAAC)

- DAAAC is a protocol intended to accelerate aftertreatment aging utilizing field representative exhaust conditions
  - 10X acceleration factor: 9800 hours → 980 hours
  - Aftertreatment is aged as a completed system
  - DAAAC is **NOT** a cycle

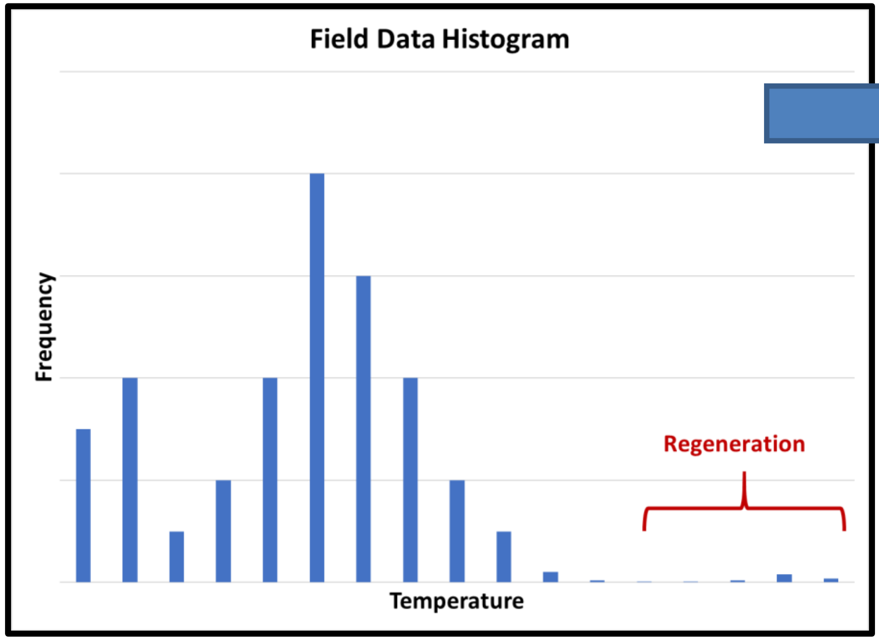
- Primary deactivation mechanisms considered:
  - **Hydrothermal aging**
    - High temperature exhaust conditions such as regeneration
  - **Lubricant derived poisons**
    - Engine oil consumption
  - **Sulfur exposure**
    - Fuel and engine oil consumption

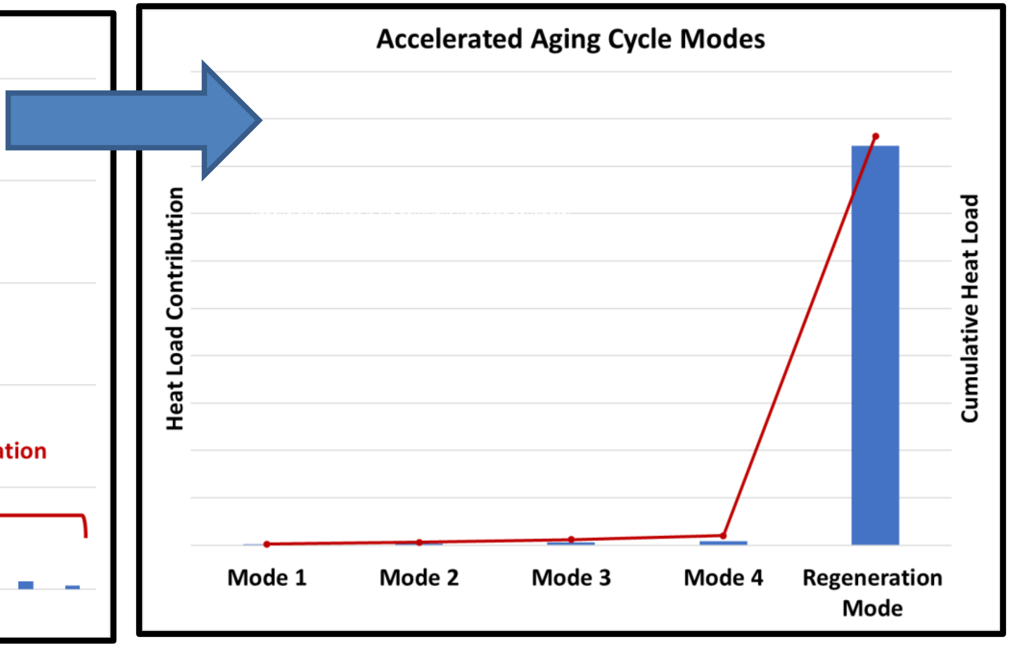
DAAAC Field Data Requirements



Accelerated Aging Cycle Generation

- To generate the cycle modes, a data guided process is followed, which considers non-regeneration and regeneration modes
  - Non-regeneration modes are established primarily as the chemical aging modes
  - A regeneration mode is the dominant heat load contributor for catalysts





Catalyst Heat Load Determination

- Arrhenius equation-based algorithms are utilized to ensure accelerated aging cycle will meet the full useful life heat load targets
  - Regulatory agencies are already utilizing this approach for existing compliance requirements
- Robust activation energy determination experiments have been developed to ensure catalyst aging characteristics are captured

Arrhenius Equation

$$k = Ae^{\frac{-E_a}{RT}}$$

k = rate constant

A = pre-exponential factor

E_a = activation energy (in the same units as R*T)

R = universal gas constant

T = absolute temperature (in Kelvin)

Chemical Aging Exposure

- Chemical aging exposure primarily occurs in the non-regeneration modes
- Oil consumption
  - Available field data is used to quantify expected oil consumption over engine lifetime
  - DAAAC considers in-cylinder oil consumption as the primary consumption pathway
    - Lubricant derived poison exposure should reflect this pathway
- Sulfur exposure
  - Fuel consumption and oil consumption measurements are considered
  - High sulfur fuel or SO_2 gas can be utilized to accelerated sulfur exposure

Accelerated Aging Platform Requirements

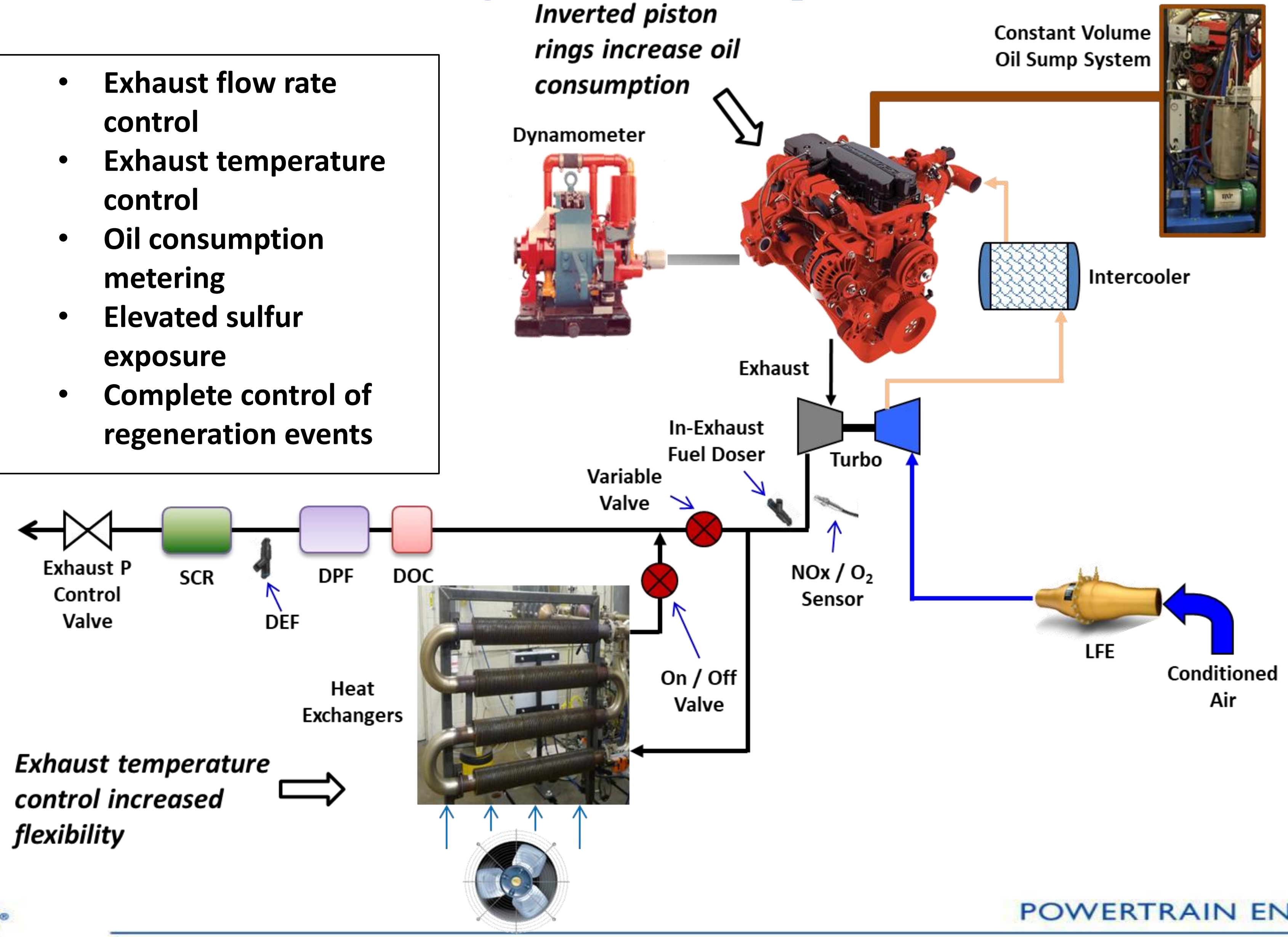
- To operate an accelerated aging cycle, the aging platform should be equipped or modified to allow for the following:
  - Exhaust flow rate control
  - Exhaust temperature control
  - Oil consumption metering
  - Elevated sulfur exposure
  - Complete control of regeneration events

Exposure to deterioration mechanisms need to represent field exposure

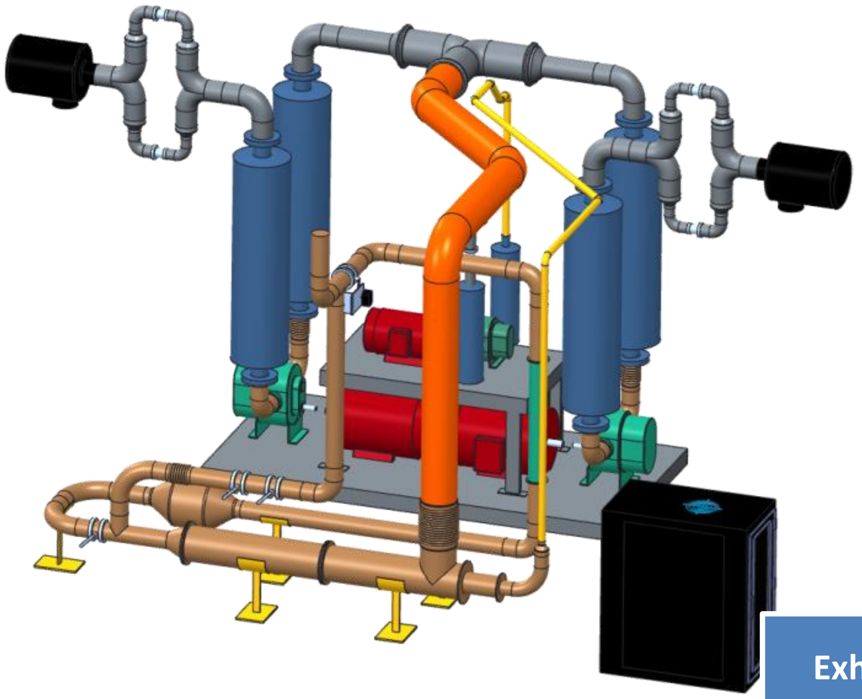
- Known accelerated aging platforms include:
  - **DAAAC modified engine**
  - **Burner based technology**
- Both aging platforms are being considered as part of an accelerated aging cycle validation experiment supported by EPA

DAAAC-Modified Engine Setup

- Exhaust flow rate control
- Exhaust temperature control
- Oil consumption metering
- Elevated sulfur exposure
- Complete control of regeneration events



Exhaust Composition Transient Operation Laboratory™ (ECTO-Lab™) Reactor



- *ECTO-Lab is a computer controlled multi-fueled burner-based reactor system used to replicate stoichiometric and lean exhaust conditions*
- *The system utilizes a modular design, which can be configured to conduct regulatory and specialized testing for aftertreatment emissions components*

Exhaust Components Simulated

- Flow Rate
- Temperature
- NO_X
- HC Species
- O_2
- H_2O
- SO_2
- Lubricant Derived Poisons

Summary

- DAAAC is a protocol utilized to establish accelerated aging cycle conditions
  - Field data is analyzed to generate representative modes and targets for the accelerated aging cycle
  - The following deterioration mechanisms are considered:
    - Hydrothermal aging
    - Lubricant derived poisons
    - Sulfur exposure
  - The protocol can accelerate aging by as much as 10 times compared to conventional service accumulation methods
    - Helps OEMs significantly reduce the aging burden required by the future regulations
  - **DAAAC is being validated for future regulatory use by EPA utilizing engine and burner-based platforms**

Thank You!

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