

# Cummins Tier 4 Clean Power Leader

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# Improving Air Quality Through Clean Power Leadership

- Progress in diesel engine technology & diesel fuel quality are making a major contribution to improve air quality
- By 2030, the EPA estimates a reduction of annual emissions of
  - NOx by 738,000 tons\*
  - PM by 129,000 tons\*
  - Nonmethane hydrocarbons (NMHC)\*
  - Carbon monoxide (CO)\*
  - SOx and air toxins\*
- Engine manufacturers must continue to develop technologies to meet clean air standards while meeting customer requirements



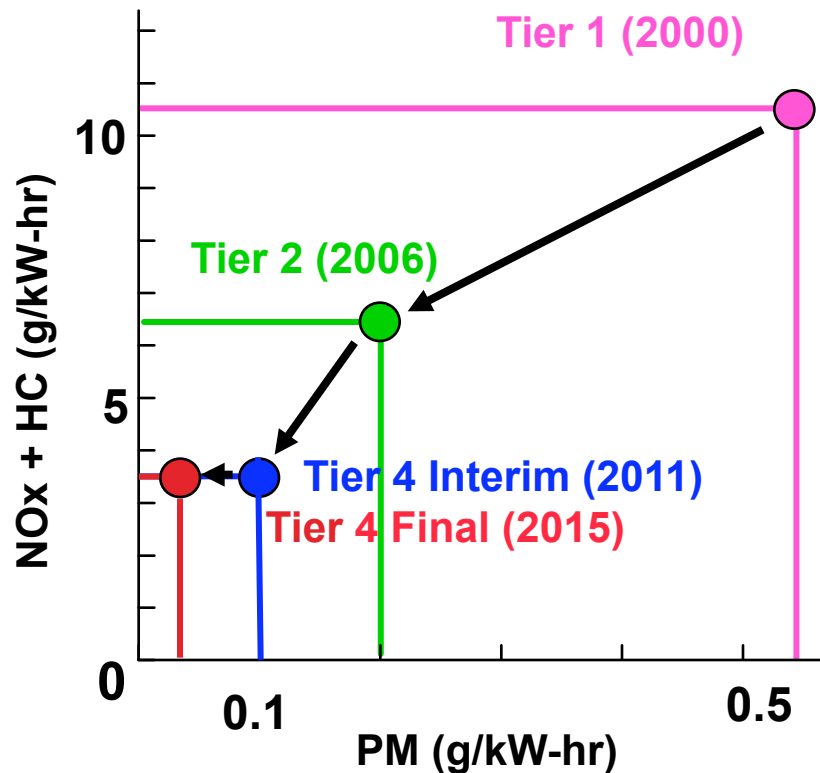
\* Source: <http://www.epa.gov/nonroad-diesel/2004fr/420r04007a.pdf>, pg. 6





# The Tier 4 Emissions Challenge

## EPA MOH Tier 4 > 751 bhp



- Tier4 presents the most significant change in mining engine technology in recent history



# Leading Technology Introduction

SEGMENT	NO <sub>x</sub> / PM LIMITS	FUEL SYSTEM	NO <sub>x</sub> CONTROL	PM CONTROL
<b>Heavy Duty On-Highway</b>	(g/bhp-hr)			
EPA 99	<b>4.0 / 0.1</b>	CELECT - HPI	IN CYLINDER	IN CYLINDER
EPA 04	<b>2.5 / 0.1</b>	CELECT - HPI	CEGR	IN CYLINDER
EPA 07	<b>1.2 / 0.01</b>	CELECT - HPI	CEGR	DPF
EPA 10	<b>0.2 / 0.01</b>	XPI	SCR	DPF
<b>Heavy Duty Off-Highway</b> (225 - 449 hp)	(g/kW-hr)			
Tier 1 (1996)	<b>9.2 / 0.54</b>	MECH	IN CYLINDER	IN CYLINDER
Tier 2 (2001)	<b>(6.4) / 0.2</b>	CELECT - HPI	IN CYLINDER	IN CYLINDER
Tier 3 (2005)	<b>(4.0) / 0.2</b>	CELECT - HPI	IN CYLINDER	IN CYLINDER
Tier 4 I (2011)	<b>2.0 / 0.02</b>	- TBD -	- TBD -	- TBD -
Tier 4 F (2014)	<b>0.4 / 0.02</b>	- TBD -	- TBD -	- TBD -
<b>High Horsepower</b> (> 751 hp)	(g/kW-hr)			
Tier 1 (2000)	<b>9.2 / 0.54</b>	MECH	IN CYLINDER	IN CYLINDER
Tier 2 (2006)	<b>(6.4) / 0.20</b>	MCRS	IN CYLINDER	IN CYLINDER
Tier 4 I (2011)	<b>3.5 / 0.10</b>	- TBD -	- TBD -	- TBD -
Tier 4 F (2015)	<b>3.5 / 0.04</b>	- TBD -	- TBD -	- TBD -



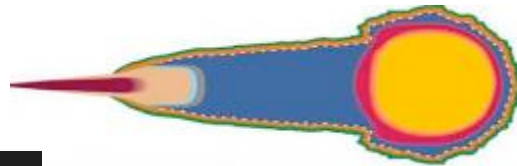
• Engine manufacturer with on-highway experience and technology will have the advantage at Tier4



# Emissions Technology Enablers

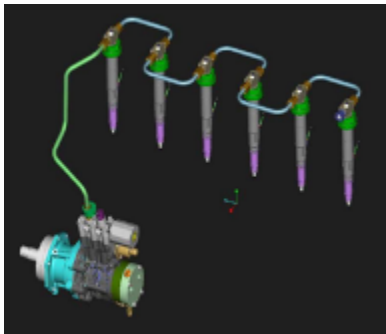
## Combustion

Advanced in-cylinder combustion required for low emissions



## Turbomachinery

Advanced air handling to improve fuel economy



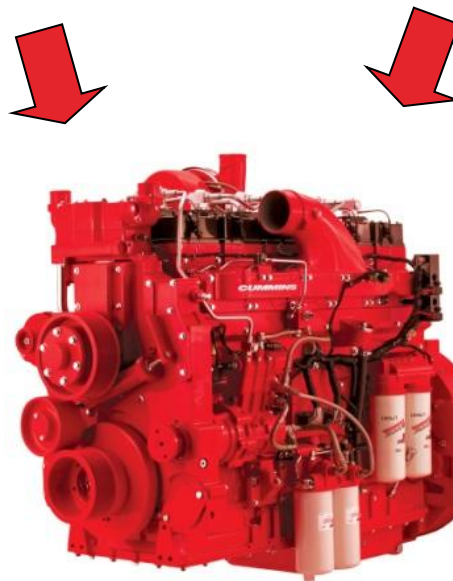
## Fuel System

Modular Common Rail provides higher injection pressure for combustion and power delivery improvements



## Controls

Advanced ECM for fast processing with upgraded sensors

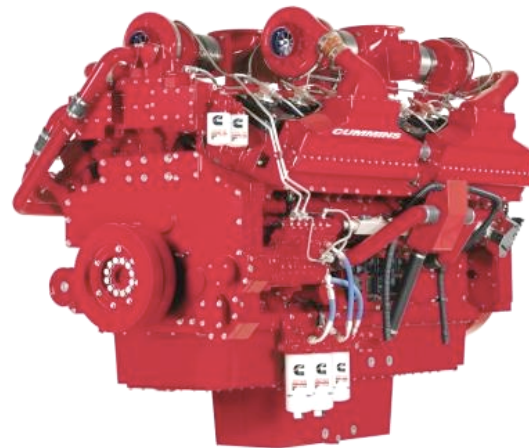




# The Tier 4 Design Challenge

## Operator focused

- Highest durability
- Good power density
- Best fuel efficiency



## OEM focused

- Minimal installation impact
- Worldwide use
- Robust for toughest duty cycles

## Technology focused

- Meet regulated emission levels
- Utilize proven engine platform
- Enhance engine performance

# Cooled Exhaust Gas Recirculation

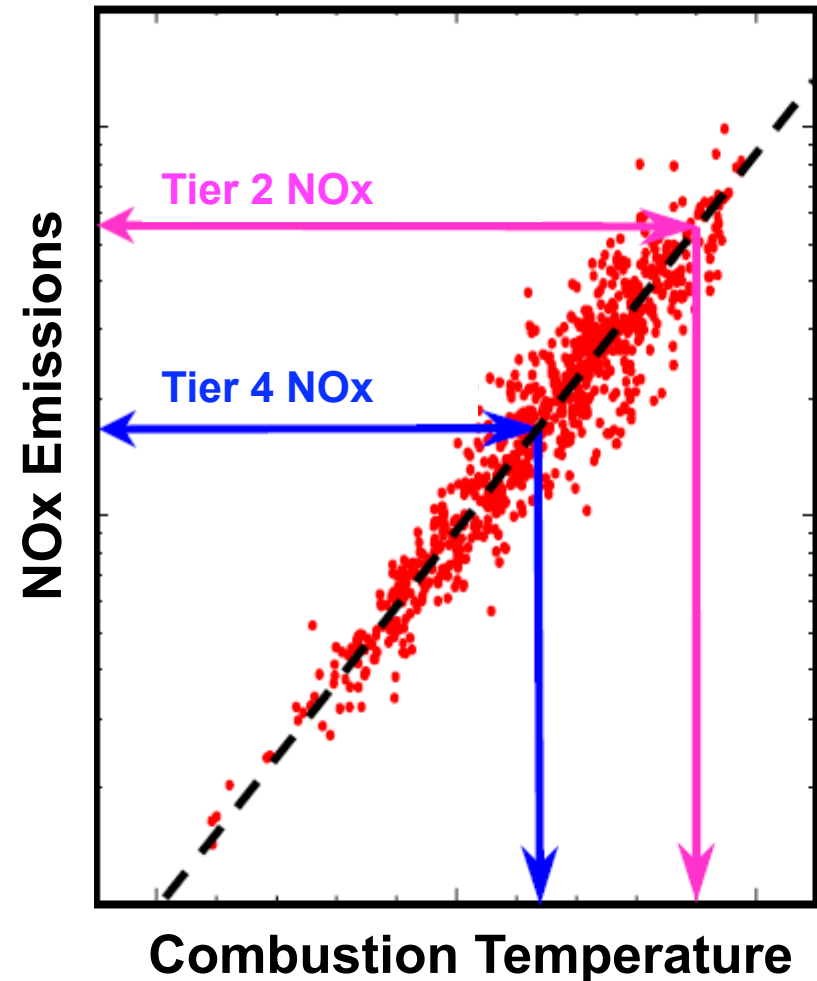
Cooled EGR or CEGR





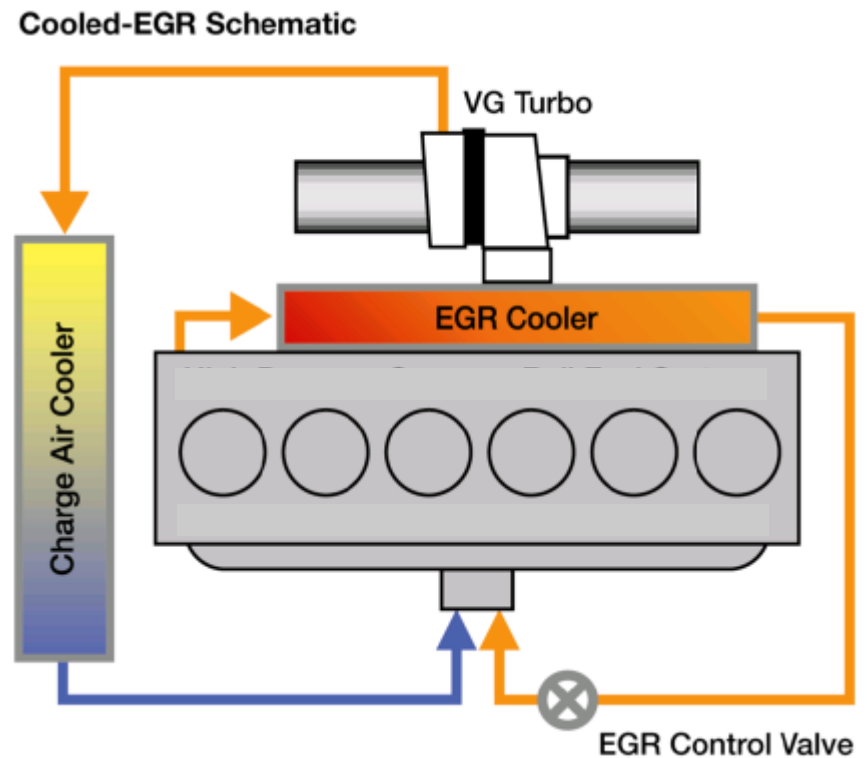
# NOx Reduction Strategy

- Cooled Exhaust Gas Recirculation (CEGR) used to control engine NOx emissions
- Exhaust gas is used to reduce peak combustion temperature
- Lower combustion temperature equals lower NOx output



# Cooled EGR Process

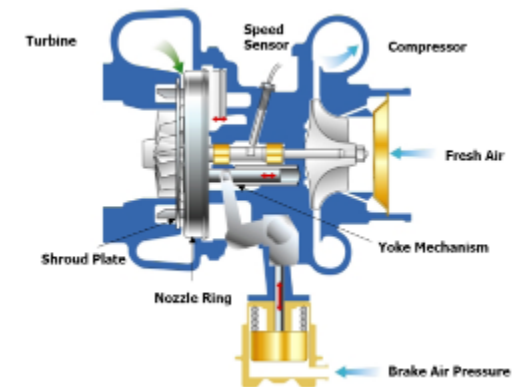
- Exhaust gas is taken from exhaust manifold and is cooled
- Exhaust gas is added to the intake manifold
  - ECM determines volume
  - EGR Valve controls
- Mixture of exhaust gas and fresh air is used in combustion cycle





# Key Components Needed for Cooled EGR

- **Exhaust Gas Cooler**
  - Shell and tube heat exchanger
  - Uses engine coolant to cool exhaust gas
- **Exhaust Gas Valve**
  - Electronically controlled by ECM
  - Hydraulically actuated using high pressure engine oil
- **Exhaust Gas Mixer**
  - Ensures homogeneous mixing of exhaust gas and fresh air
  - Mixing controlled by physical geometry
  - No moving parts or electronic control
- **Variable Geometry Turbocharger (VGT)**
  - Precision control of airflow at all engine speeds and loads
  - Provides necessary pressure differential to drive EGR
  - Electronically controlled by ECM
  - Hydraulically actuated using high pressure engine oil





## Challenges with Cooled EGR

- Over 30% increase in heat rejection due to cooling of exhaust gas
- Scaled EGR cooler and valve
  - Maintain reliability and durability
- Increased complexity of air handling – exhaust throttle, wastegate turbocharger or variable geometry turbocharger
- Increased cylinder pressure
- Increased fuel system injection pressure to maintain low particulate matter
- EGR will require supplemental technologies (e.g., SCR) to meet more aggressive NOx emission regulations

# Miller Cycle Using Variable Valve Actuation

VVA

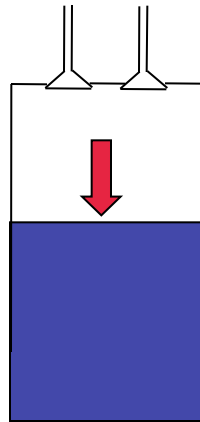




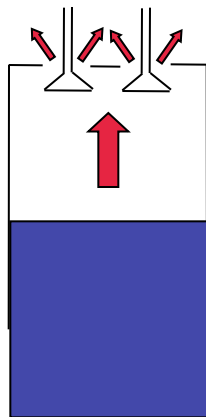
## **“Miller Cycle” Philosophy using Variable Valve Actuation (VVA)**

- Dynamic flexibility is needed to optimize engine performance between standard and late intake valve closing
- Standard Intake Valve Closing
  - Creates higher effective compression ratio and higher compression temperature
  - Good starting and light load hydrocarbon & white smoke control
  - High volumetric efficiency improves transient response
- Late Intake Valve Closing
  - Creates Miller Cycle effect with engine under load
  - Effective compression ratio is reduced for lower compression temperature and therefore lower NOx

# Variable Valve Actuation Process



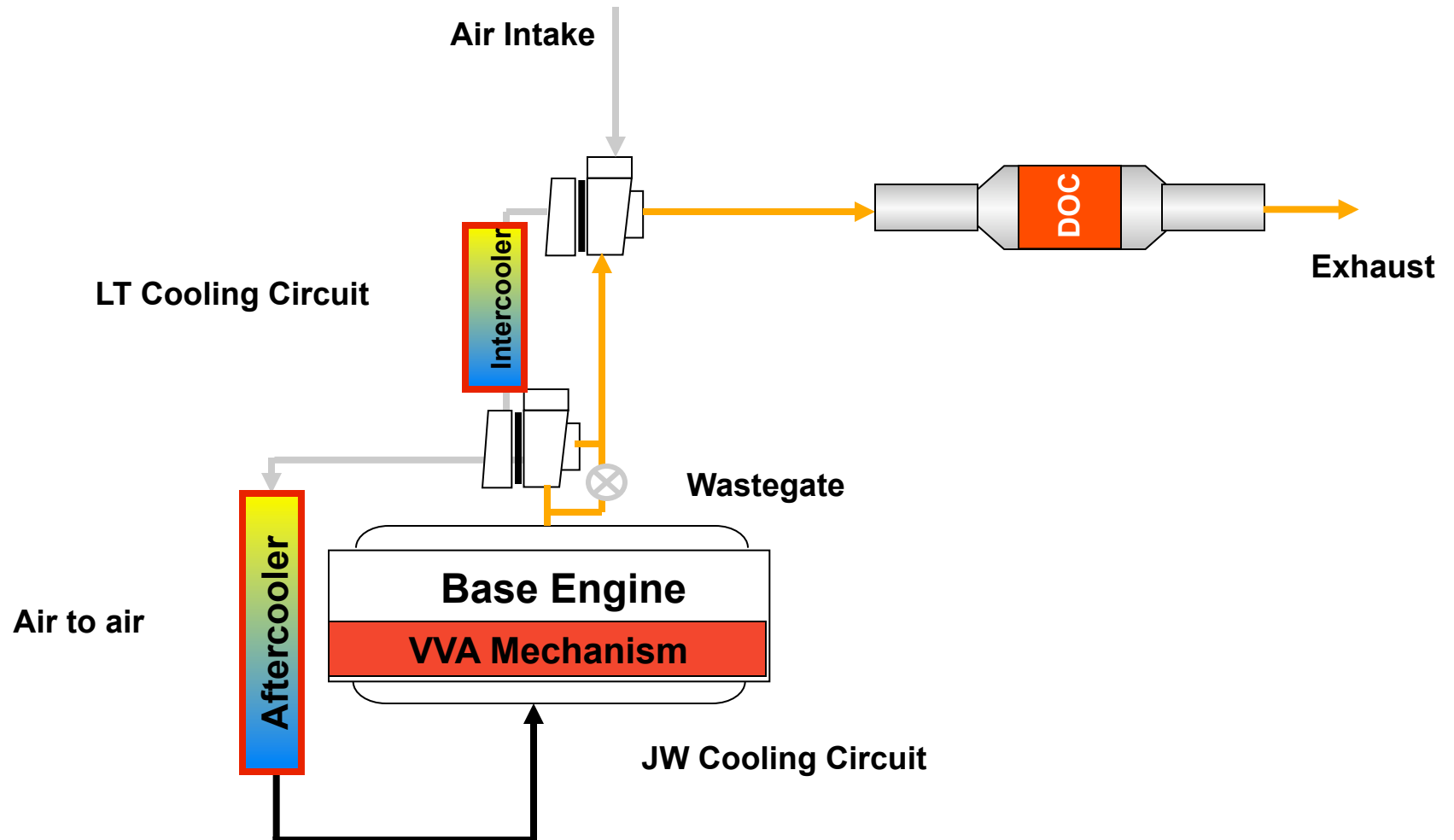
- Standard Intake Valve Closing
  - Valves close near bottom dead center for optimized volumetric efficiency and peak compression temperatures
  - Typical NOx generation occurs



- Late Intake Valve Closing
  - Valves close as much as 50% into the compression stroke allowing some air to be pushed back into the intake manifold
  - High boost pressure maintains necessary air mass in cylinder
  - Reduced effective compression ratio and reduced compression temperature result

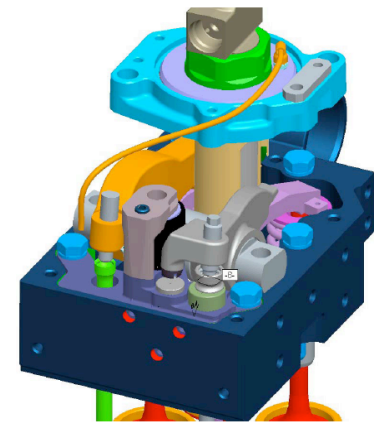


# VVA Schematic for Tier4 Interim



## Key Components Needed for VVA

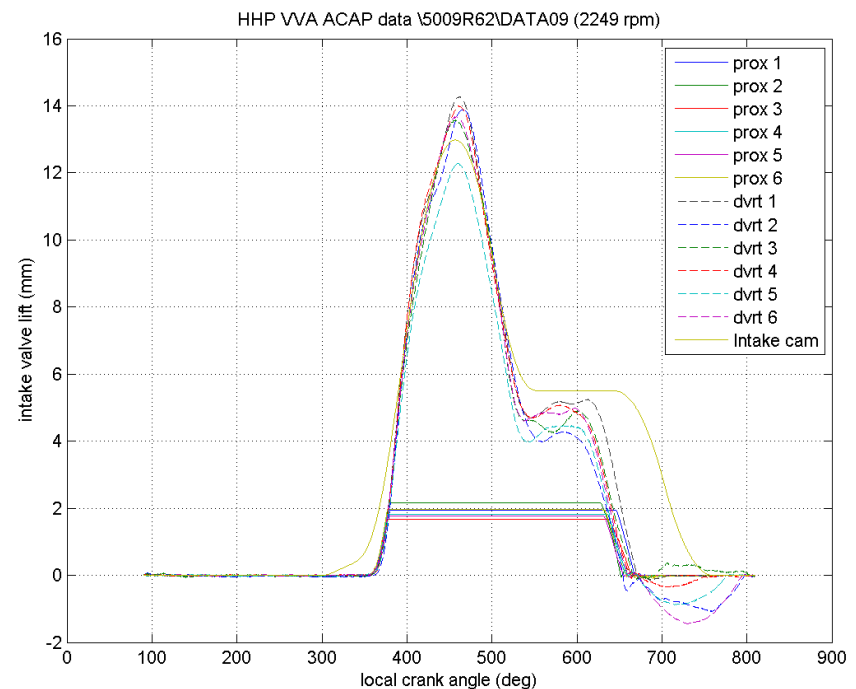
- **Electronic solenoid trigger**
  - To initiate the hydraulic valve actuator
- **Modified tappet and push rod**
  - Allows variation in the valve travel
- **Hydraulic plumbing**
  - To manage engine oil pressure at tappet
- **Modified cylinder head and rocker housing**
  - To contain all components
- **Two-Stage turbocharging**
  - Required to generate sufficient boost for maintaining in-cylinder air mass due to reduced volumetric efficiency
- **2 Pump, 2 Loop cooling along with Air-to-Air aftercooling**
  - To manage a 25% increase in heat rejection over Tier 2
- **Modified ECM logic**





# Miller Cycle Challenges

- Control valve seating velocity for reliability and durability
  - Engine speed dependency
  - Boost pressure dependency
  - Cylinder-to-cylinder variation
- 25% increase in heat rejection over Tier 2
- Additional intercooler – total of 3 cooling circuits
- No margin available for NOx levels lower than MOH Tier 4



# Selective Catalytic Reduction

SCR



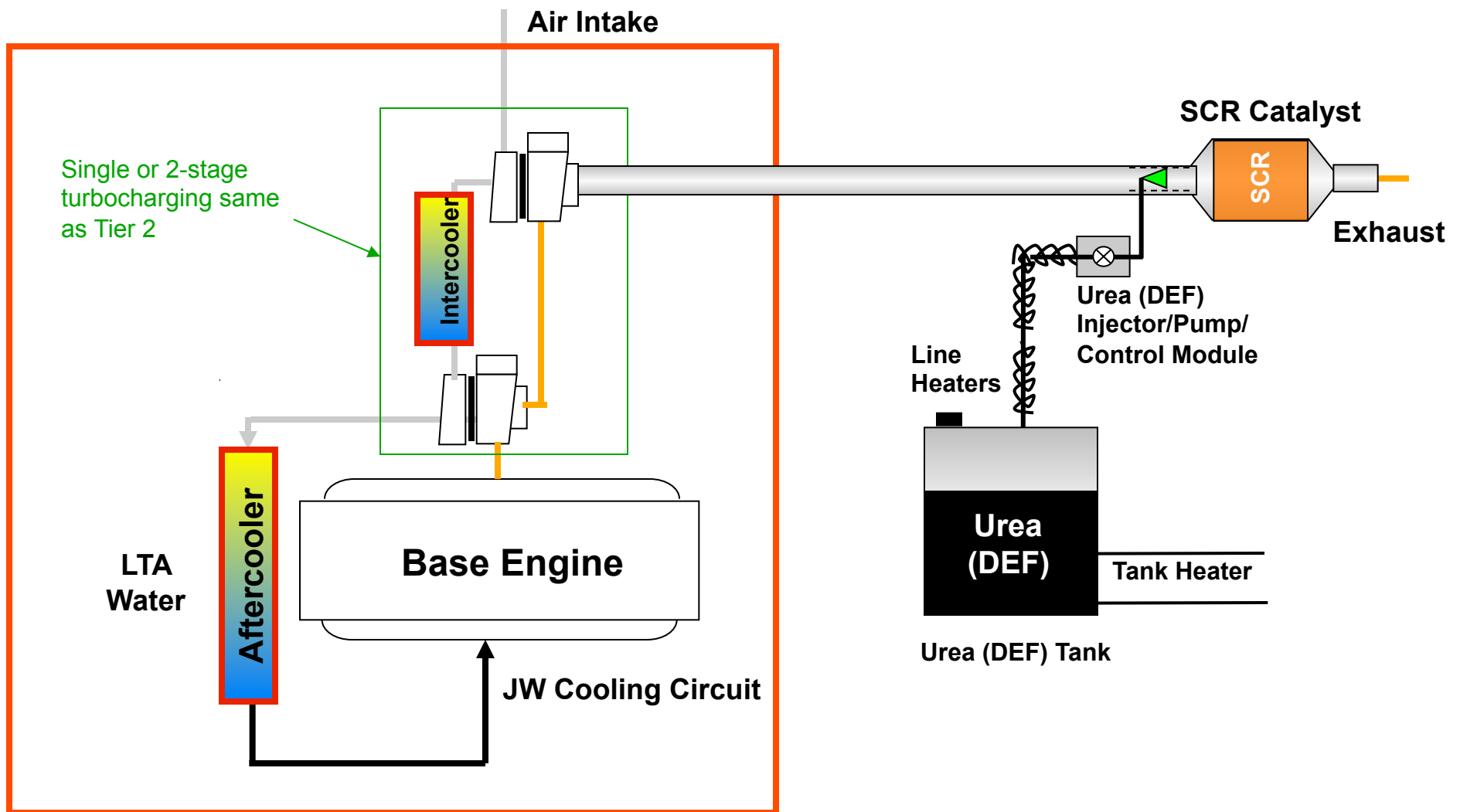


# Selective Catalytic Reduction (SCR) Philosophy

- Ammonia and catalyst to transform  $\text{NO}_x$  in exhaust into nitrogen (N) and water ( $\text{H}_2\text{O}$ )
- A “reductant” is added to exhaust flow to create the reactions in a catalyst chamber
  - Liquefied Urea is best choice  $(\text{NH}_2)_2\text{CO}$
  - Proven in on-highway European applications
  - Safe, clean, effective, and available worldwide



# SCR Schematic for Tier 4 Interim





## Key Components Needed for SCR

- Base engine very similar to current Tier 2
  - Air handling optimized for increase in back pressure
  - Low PM combustion recipe
- Urea handling and injection components
  - Urea tank
  - Urea pump
  - Dosing unit for injection
  - SCR catalyst chamber
  - Temperature and NOx sensors



## Challenges with SCR

- Packaging and installation of aftertreatment
- Urea availability and handling
- Increased back pressure on engine
- SCR catalyst life in Off-Highway applications
- Ammonia slip
- Sulphur tolerance

# Diesel Particulate Filter

DPF

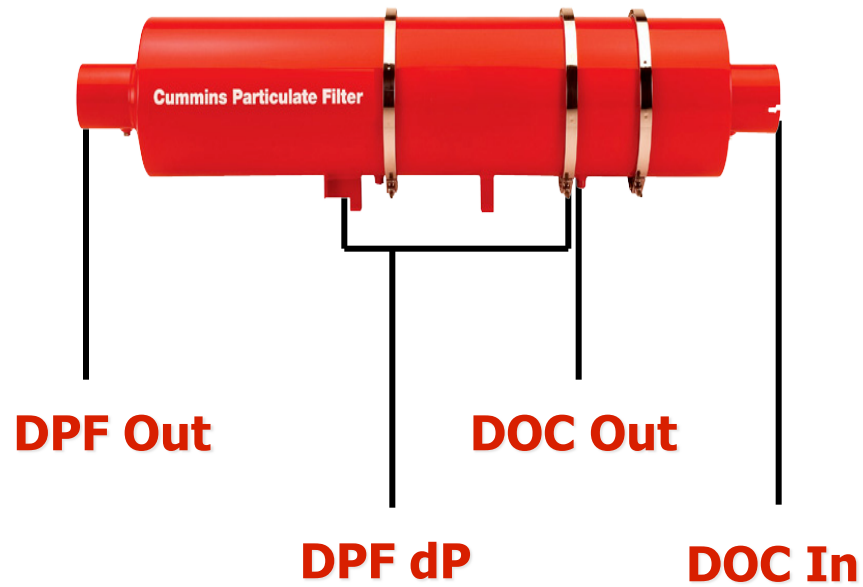




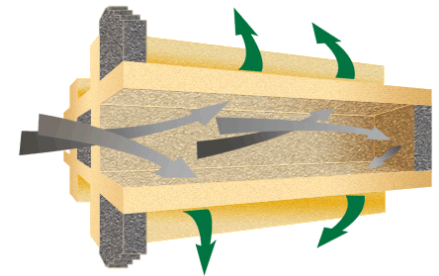
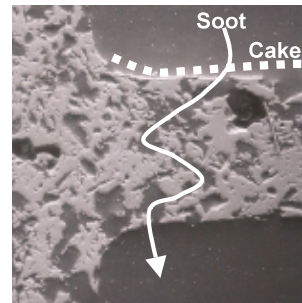
## **Diesel Particulate Filter (DPF)**

- The DPF filters and retains particulate in order to prevent the particulate from entering the atmosphere
- A Diesel Oxidation Catalyst (DOC) is used in sequence with the DPF (DOC – DPF)
- The DOC is used to drive up the exhaust stream temperature in the presence of exhaust-laden hydrocarbons
- The DPF is regenerated (PM burned off) by injecting hydrocarbons into the exhaust stream ahead of the DOC
- A DPF can be used in association with NO<sub>x</sub>-reducing technologies to meet Tier 4 Final emission limits

# DPF Hardware

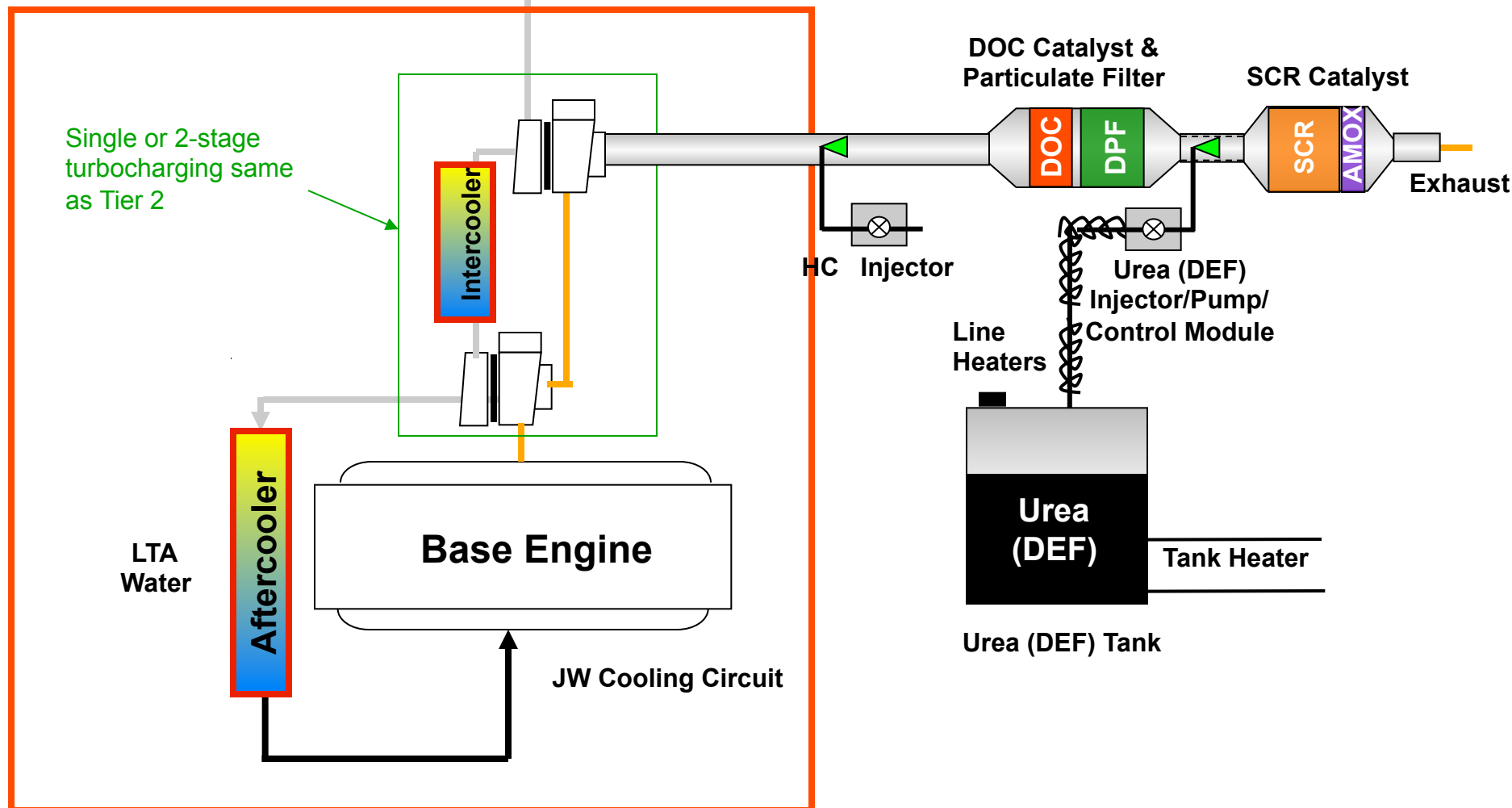


## Wall-flow Filtration





# DPF/DOC Schematic for Tier 4 Final (SCR example shown)





## Challenges with DPF

- Chassis packaging / installation challenges
  - Space claim
  - Surface temperatures
  - Proximity to turbo outlet for thermal management
- Significant and variable engine back pressure as the DPF fills and regenerates
- Requirement for precise, duty cycle-based control of temperatures and dosing frequency for regeneration
- DPF life in Off-Highway applications
- Sulphur tolerance

# Transition Program for Equipment Manufacturers

TPEM





# TPEM Allowance

## Transitional Program for Equipment Manufacturers

- The US EPA created TPEM “to provide original equipment manufacturers (OEMs) with flexibility to comply with new emission regulations”
  - Allows OEMs to continue using Tier 2 engines that comply with Tier 4 emission standards via this flexibility provision
  - TPEM available up to 2017 or until volume limit reached

	1 Family	Multiple Families
Engines per year	200	100
Engines over 7 years	700	350

- Engine manufacturers are working with the OEMs to determine the best introduction plan

# Summary





# Technology Selection Criteria

- Engine manufacturers must consider the right technology for the customer needs
  - Reliability
  - Cost
  - Weight
  - Fuel consumption
  - Serviceability
- The best solution is common components across all applications and markets
- Requires a highly integrated technical supplier to match air handling, combustion, and emission control expertise leveraging on-highway heavy duty experience