Waste Heat Recovery for Heavy Duty Vehicles

Christopher R. Nelson
Cummins Inc.

January 10th, 2008

"This presentation does not contain any proprietary or confidential information"

Goals and Objectives

Concept from final phase of Cummins' HDTE project

Project Goals are:

- **10% Fuel Efficiency Improvement**
- **Reduce or eliminate the need for increased heat rejection capacity for future heavy duty engines in Class 8 Tractors**

A 10% increase in fuel efficiency would:

- **Save a linehaul, Class 8 truck over 1800 gallons of fuel per year**
- **Reduce exhaust emissions due to less fuel use**

Reducing the need for increased heat rejection:

- **Helps maintain the aerodynamic advantages of today's trucks**

January 10th, 2008

Approach

Incorporation of a Rankine Cycle Waste Heat Recovery System with Cummins ISX Engine

Recovered energy is converted to electricity which supplements the engine's output power via a Flywheel Motor Generator

<u>Pathway to Program Efficiency Goal -</u>

EGR Heat Recovery	**6% Improvement**
Selective Exhaust Heat Recovery	**2% Improvement**
'More Electric' Accessories	**2% Improvement**
	10% Achievement

Recovery of Waste Heat will provide additional engine power and mitigate the increased EGR heat load required to meet stringent emission requirements

ISX Technology Roadmap for Efficiency Improvement

Variable Valve Actuation

Fuel System

Advanced Combustion

Variable Intake Swirl

Controls

EGR Loop
- Lower Pressure Drop
- Alternative Cooling

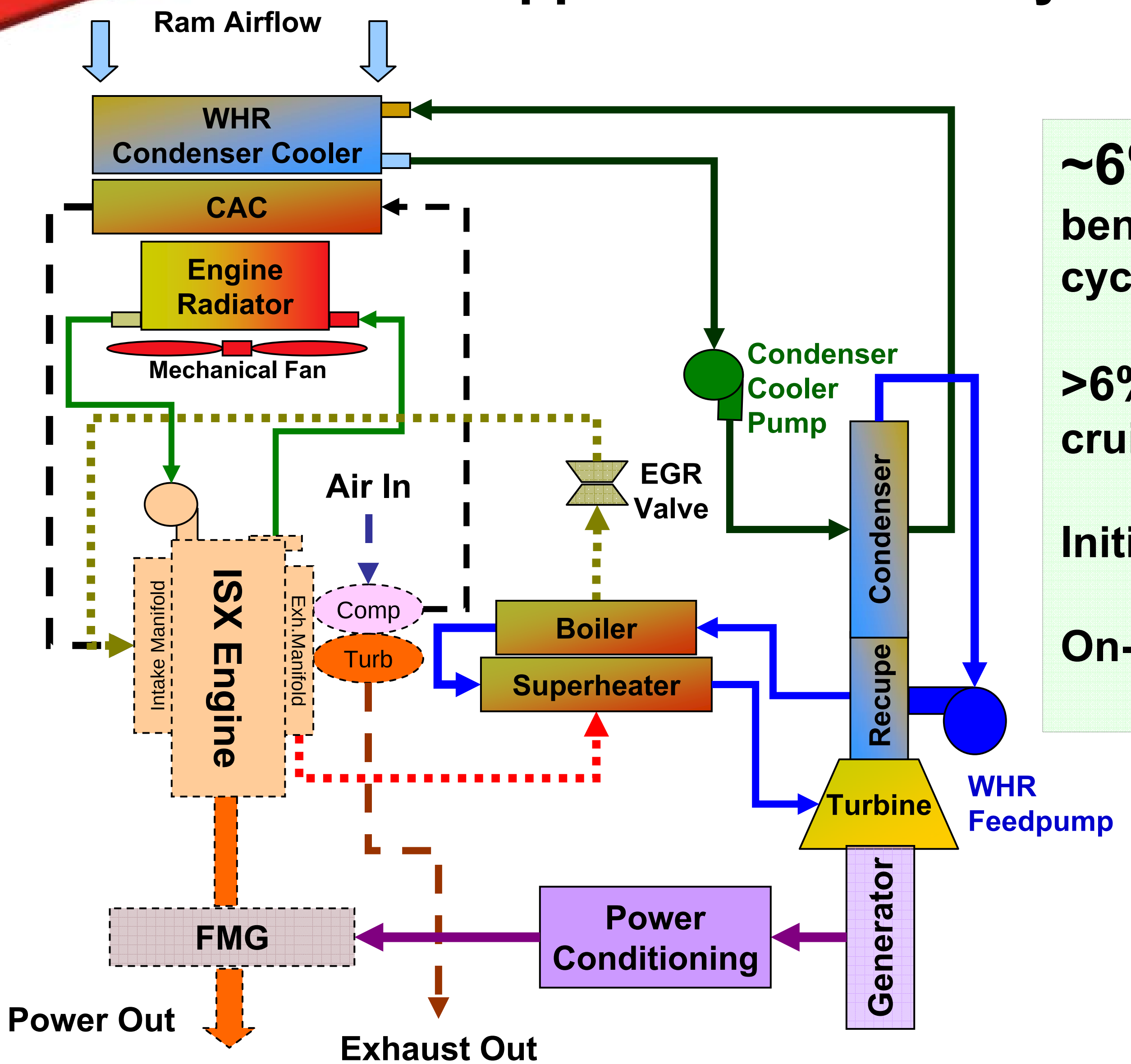
Electrically Driven Components

Turbo and Air Handling

Aftertreatment

Waste Heat Recovery

Approach - EGR Only WHR



~6% efficiency benefit across drive cycle

>6% benefit at level cruise

Initial architecture

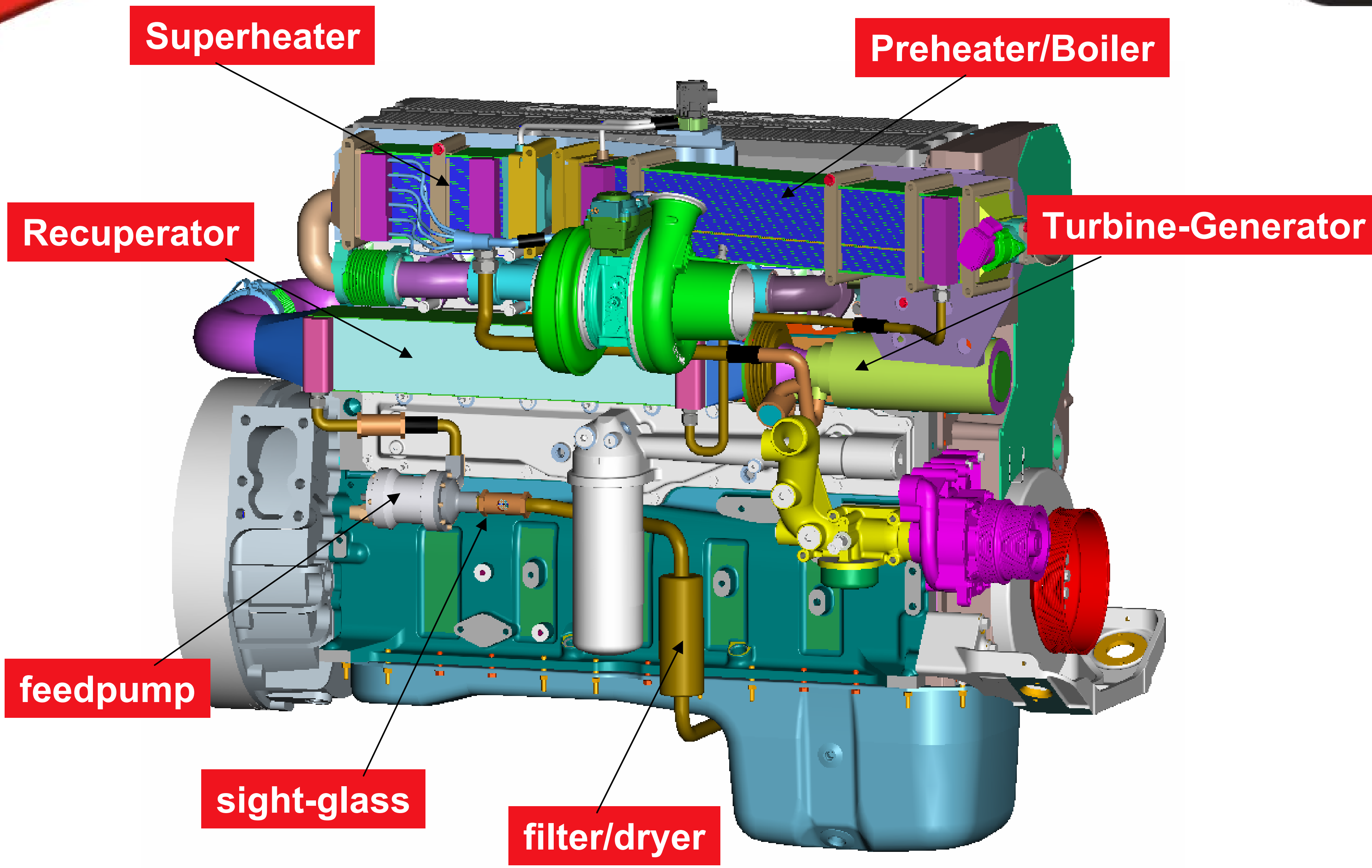
On-engine system

Performance Measures and Accomplishments - Phase I - Applied Research - Heat Input Analysis

- WHR heat input is limited by the capability of the vehicle's cooling package
  - Quantity of heat rejection is reduced with WHR, however…
  - Smaller ΔT to ambient requires increased cooling package size
  - Dictates the use of highest quality (temperature) heat input only

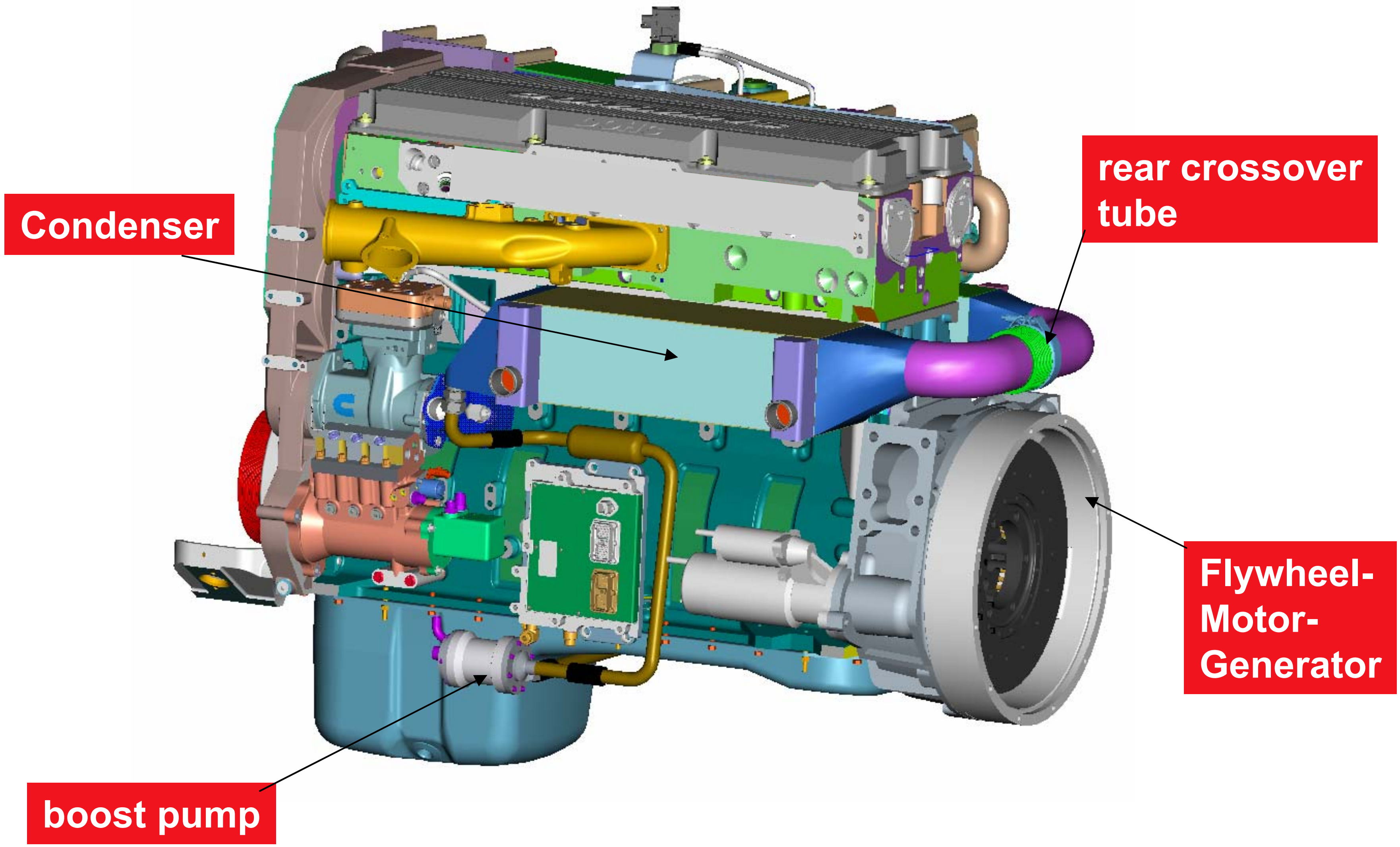
Heat Source	Selection Rationale
~~Jacket Water~~	Fluid temperature is too low to be useful. Offers limited pre-heating potential.
~~Charge Air~~	Vehicle heat rejection limitations prevent efficient utilization. Would also add significant ΔP to CA system.
EGR	Highest temperature source enables higher cycle efficiency with reasonably sized heat exchangers.
Exhaust Gas	High temperature heat source, however, required engine cooling already fully utilizes vehicle's heat rejection capacity.
Recuperator	Allows significant preheating to occur internal to the WHR cycle. Reduces condenser heat rejection load.

Approach - WHR On-Engine



January 10th, 2008

Approach - WHR On-Engine



Working Fluid – R245fa

Main Advantages of R245fa

- Hydrofluorocarbon
  - Not a chlorinated fluorocarbon
- Non Ozone Depleting
- Low Global Warming Potential
- Non-Flammable

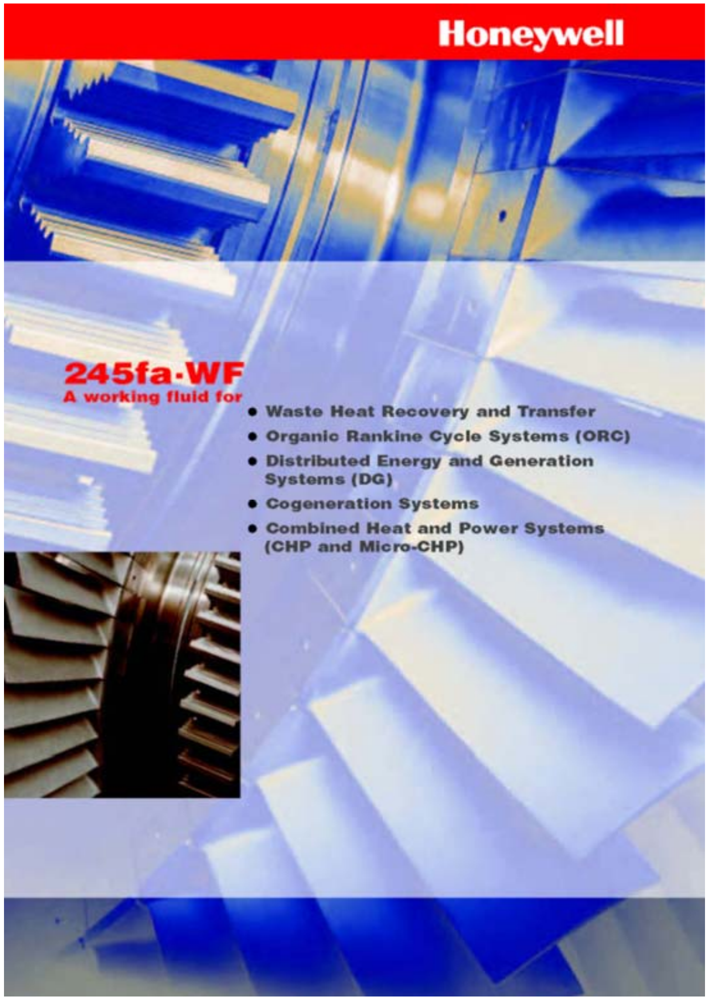
•Also –

- Good heat transfer ability
- Excellent Thermal Stability
- Low viscosity

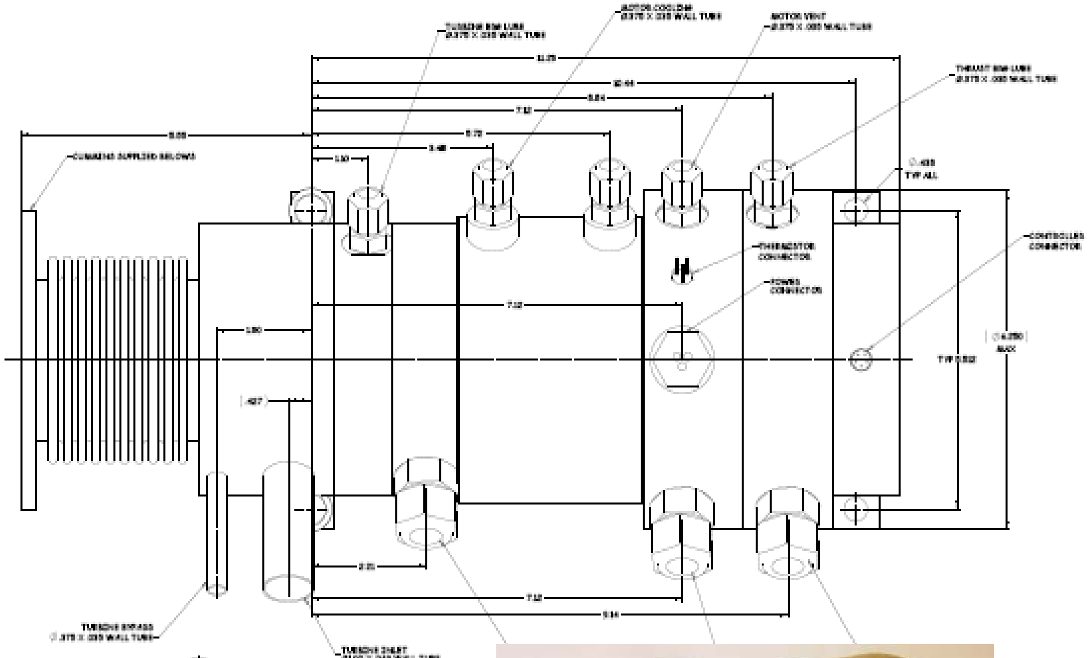
•It can work with the existing AC tool set in service shops

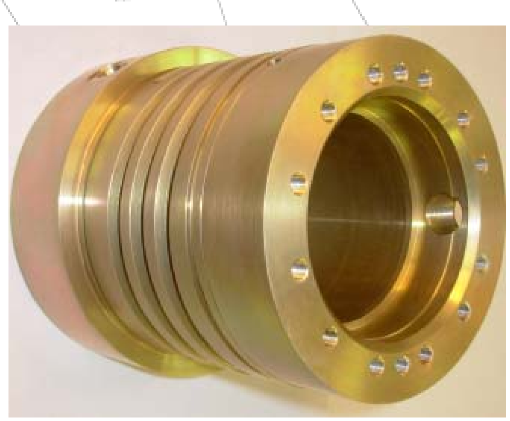
•It runs above atmospheric in its cycle

- Similar in behavior to R134a



Turbine Generator





30 Hp Max. Continuous Power

17”long x 6”dia

84k rpm Operating Speed

340VAC, Permanent Magnet Alternator, 2-pole, 3 Phase

SmCo Magnets

Inconel Retention Sleeve

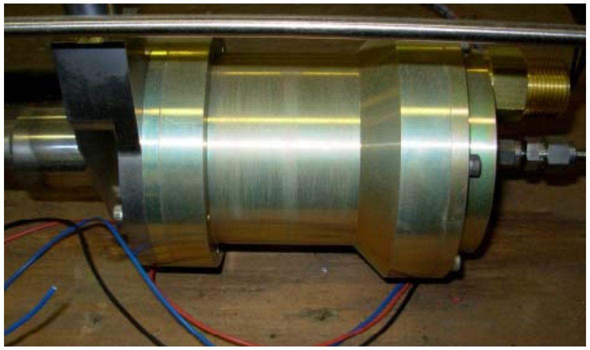
Hybrid-Ceramic Ball Bearings

Barber Nichols

Boost/Feed Pumps

Cummins

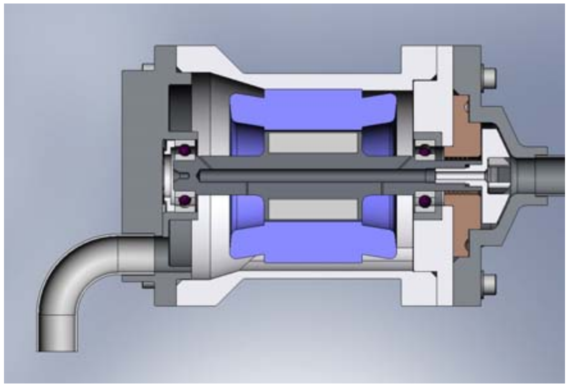
Boost Pump Controller



Boost Pump

Boost Pump –
- 60 psid
- 3-9krpm
- 7.5 lbs
- Hermetically Sealed
- Variable Speed
- CAN Bus Control Interface

Feed Pump Controller



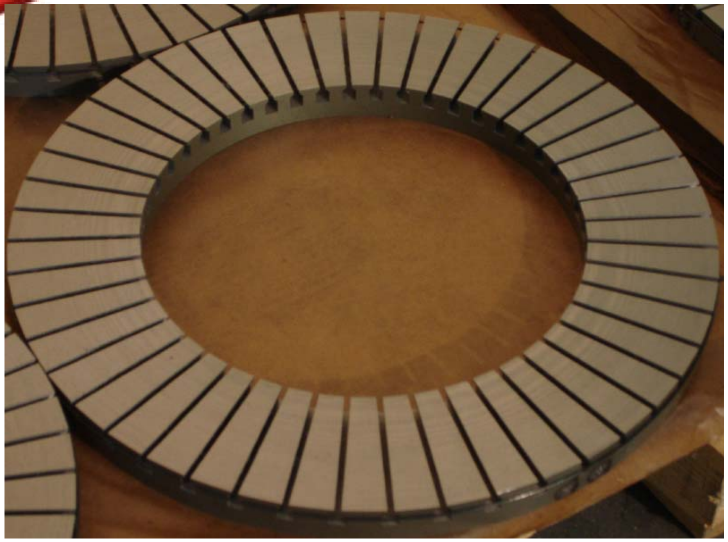
Feed Pump Cross Section

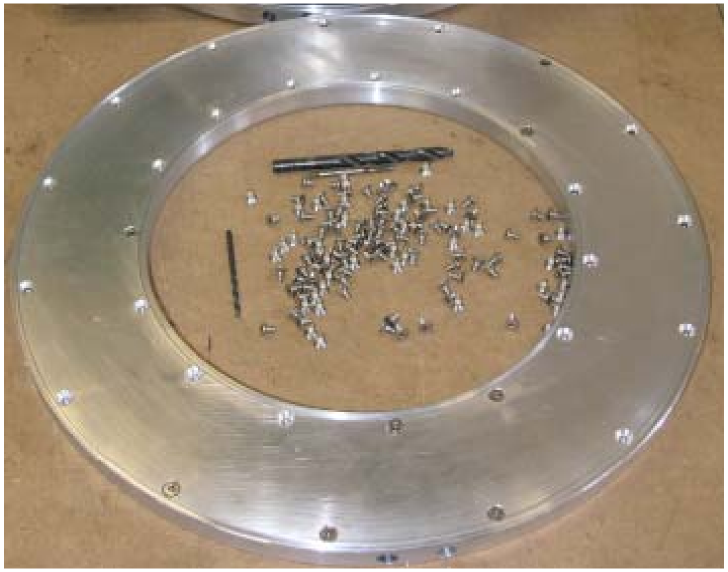
Feed Pump –
- 300 psid
- 0.7-1.7 lbm/sec flow
- 25krpm
- 8 lbs
- Ball Bearing
- Hermetically Sealed
- CAN Bus Control Interface

UQM TECHNOLOGIES

Barber Nichols

Flywheel Motor/Generator



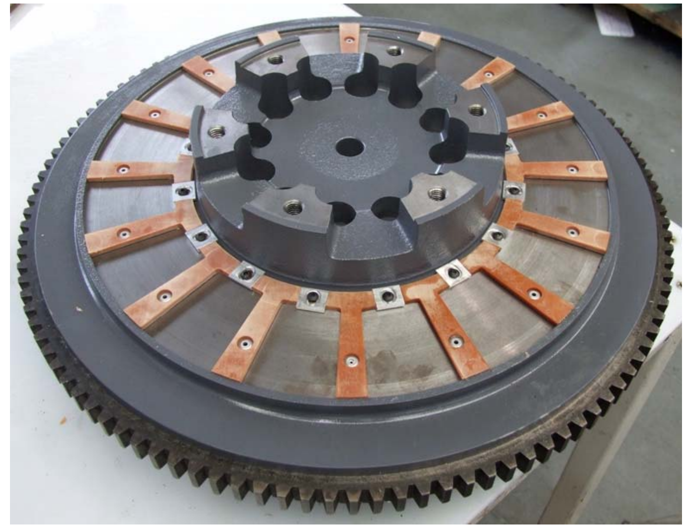


Generator Technologies

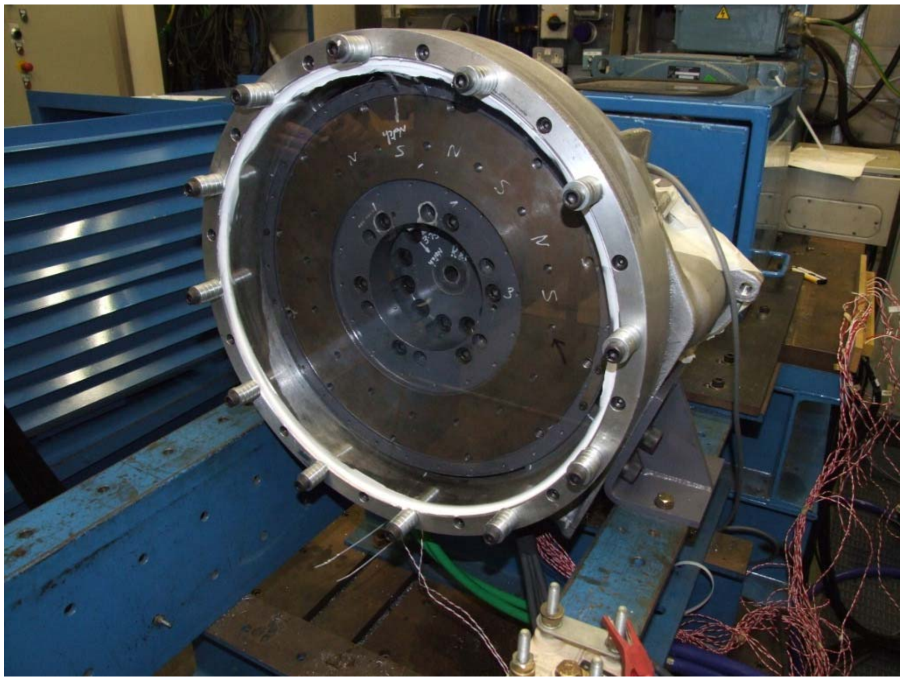
Stators – assembled around water jacket core and installed into Flywheel Housing

January 10th, 2008

Flywheel Motor/Generator

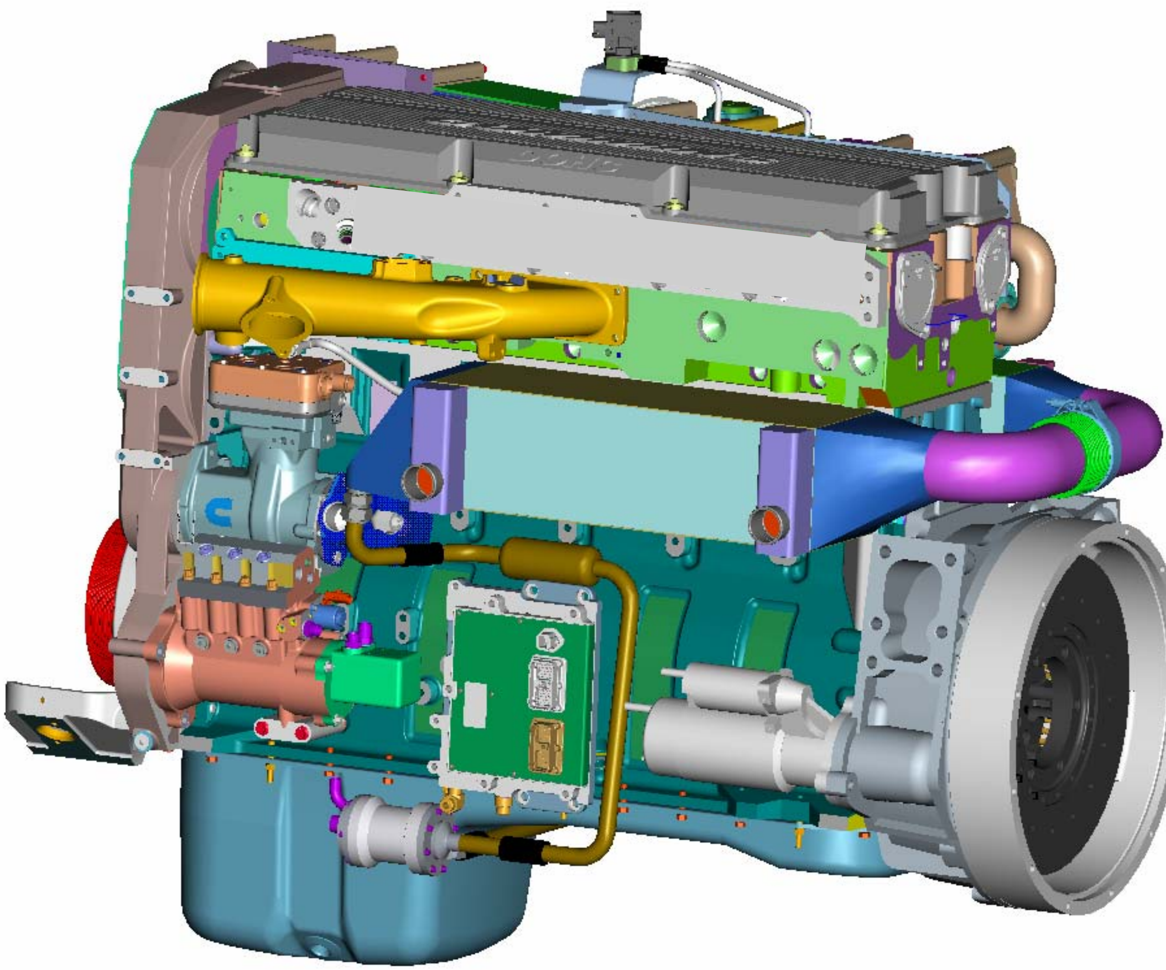


Half of Rotor Assembly showing magnet mounting details



Assembled FMG on test at CGT

Flywheel Motor/Generator

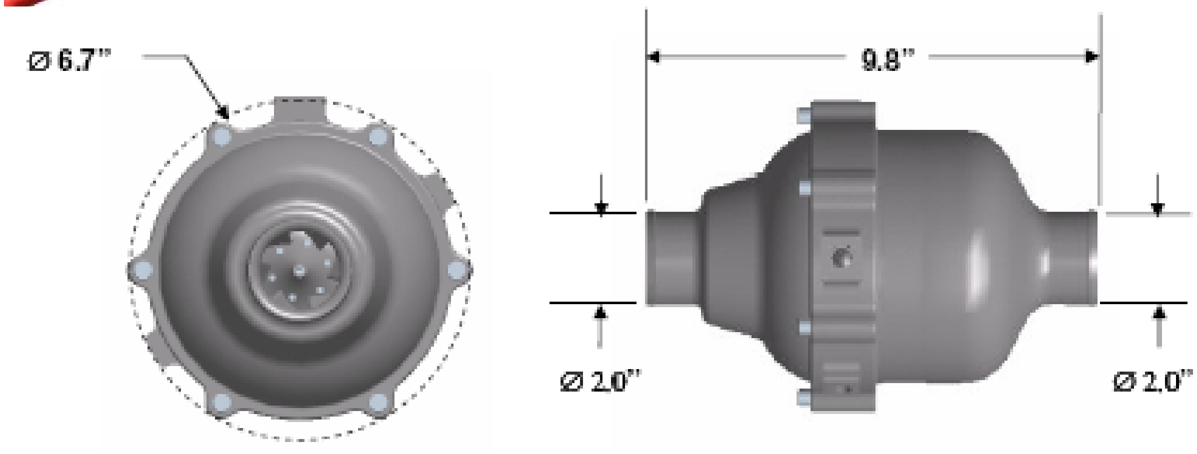


Stator/Cooling Jacket are assembled into Flywheel Housing – extended by 93mm

Standard Ring Gear and Starter are used

January 10th, 2008

Coolant Pump and Controller

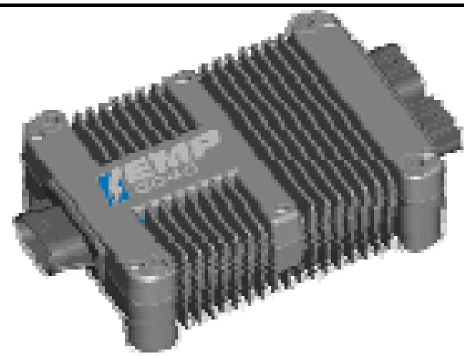


EMP C26 Pump

Low Temperature Cooling Loop pump for Condenser and Electronics

Control Options

- CAN – Variable Speed
  - J1939
  - 250 kBaud
  - 29 Bit Identifier
- SCI – Calibration
- ON / OFF – Set Speed

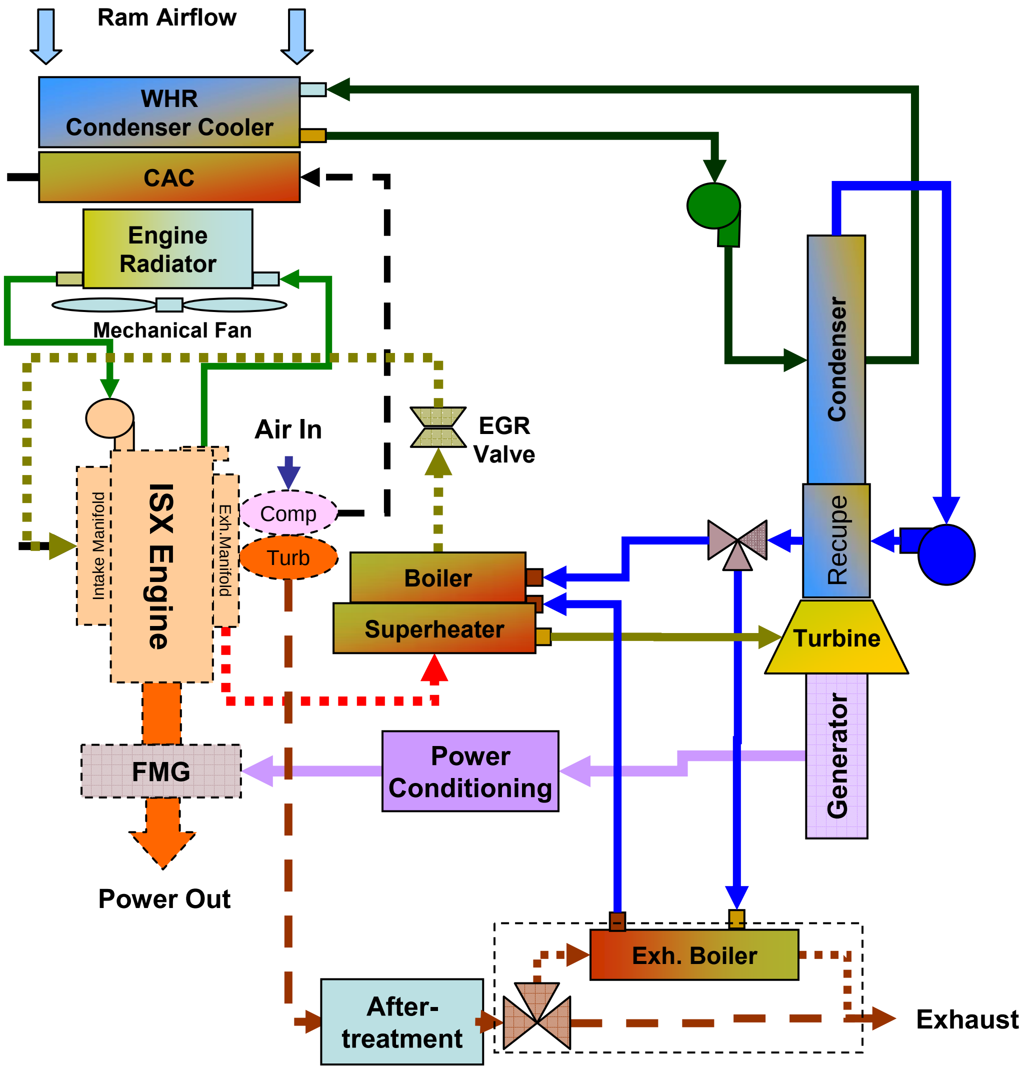


CC40 – Performance limited to 40A output 24V.

Nearly off-the-shelf item from EMP, pre-production prototype at 24VDC

340VDC version available

Performance Measures and Accomplishments - Phase 2 - System Improvements Identified



Extracts Waste EGR Heat primarily -

Takes in Waste Exhaust Heat when off-peak

WHR Loop kept at peak power as much as possible

~8% efficiency benefit across the drive cycle.

>8% improvement at cruise

'More Electric' Accessories will add 2% benefit

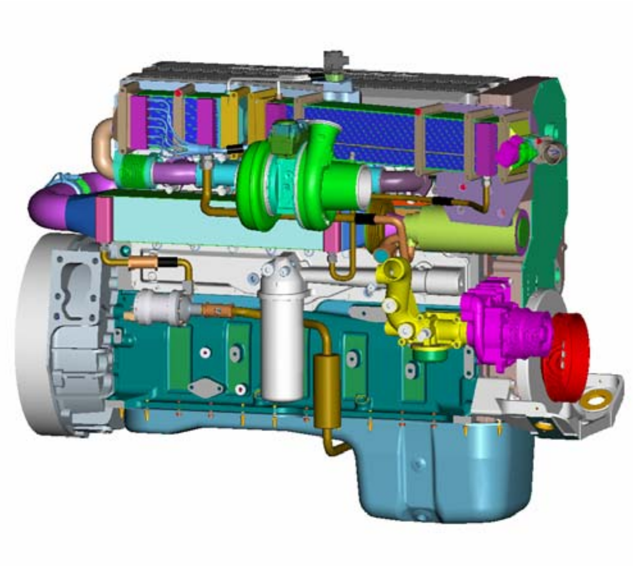
Summary

Cummins Rankine Cycle Waste Heat Recovery –

A clear path to the 10% Efficiency Improvement Goal and mitigates cooling system size increases

Directly aligned with the Goals of:

- **Enhancing energy efficiency**
- **Bringing clean, reliable and affordable energy technology to the marketplace**



Thank You!

January 10th, 2008