Exhaust Energy Recovery

2010 Annual Merit Review

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Research & Technology

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ACE041

Agenda

- Overview
- Program Goals
- Concept Development
  - First Generation Results
  - System Improvements
- Engine System Changes
  - ORC Potential
- Development Progress
  - Technology Development for Supertruck
  - Second Generation Engine System
- Review and Summary

Exhaust Energy Recovery Overview

Timeline

- Project Start – 5/1/05
- Project End – 3/31/10
- Percent Complete 100%

Budget

- Total Project Funding
  - DoE Share – $4.3M
  - Cummins Share – $4.3M
- Funding Received in FY'09
  - $839K

Barriers Addressed

- Engine Efficiency Improvement
- Cost Effectiveness of Exhaust-heat-utilization systems
- System integration/calibration for optimum performance

Partners

- Cummins Turbo Technologies

Exhaust Energy Recovery Program Goals

Exhaust Energy Recovery proposed to achieve:

- 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

Cummins Waste Heat Recovery

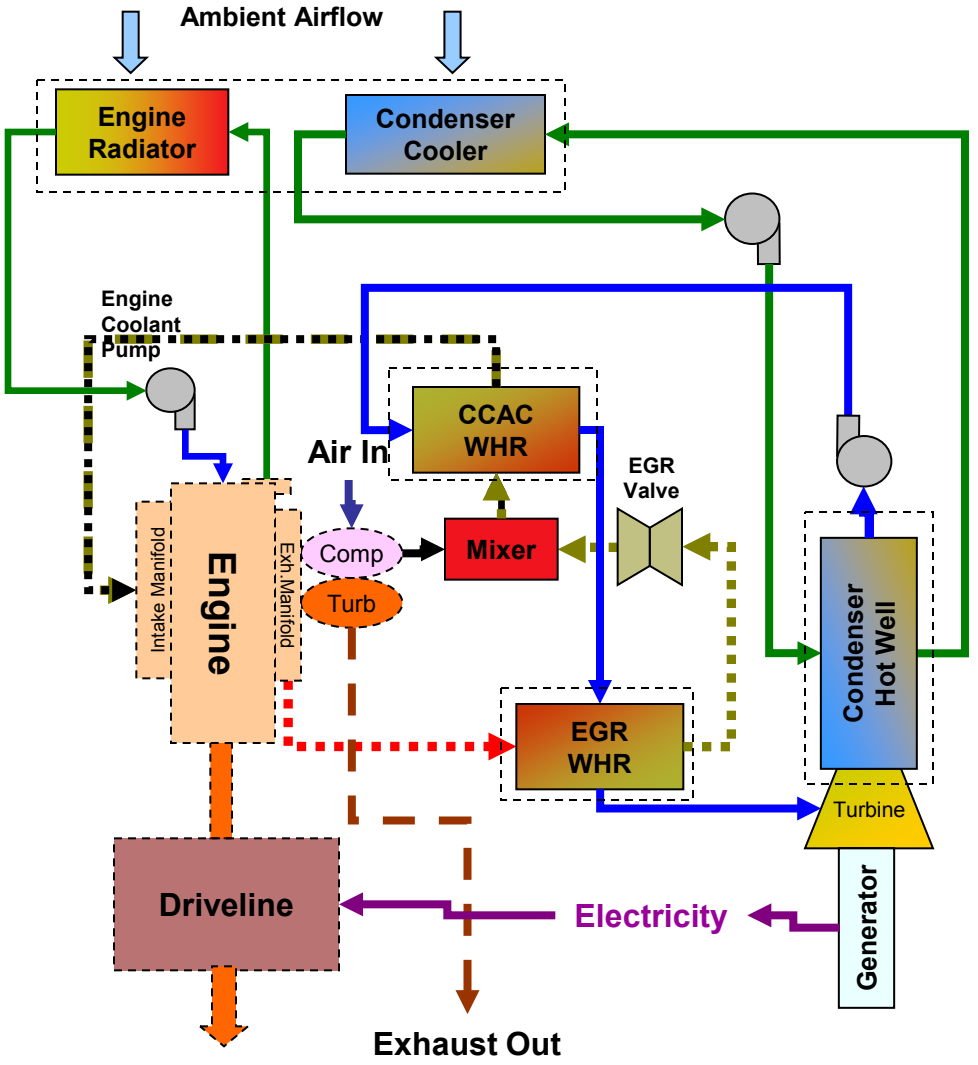
Initial Proposal - Presented at DEER, 2006

Organic Rankine Cycle

Capturing energy from EGR and combined EGR and CAC (CCAC)

Working fluid is proposed as R245fa
Honeywell Genetron

Proposed a 10% BTE Benefit



Early System Investigation and Architecture Changes

Combined Charge Air Cooling -

- Condensation and corrosion within the CCAC was identified as a serious hurdle. Current materials (aluminums) were not capable of lifetime performance

We chose instead to consider exhaust gas energy recovery

Exhaust gas energy could be gathered by the system at 'off design' conditions and offer a significant benefit

A turbine/generator, power conditioning system, and an integrated Flywheel Motor-Generator were designed for the project during this period

Cummins Waste Heat Recovery

1st Generation System - Presented at DEER, 2007

Extracts Waste EGR Heat

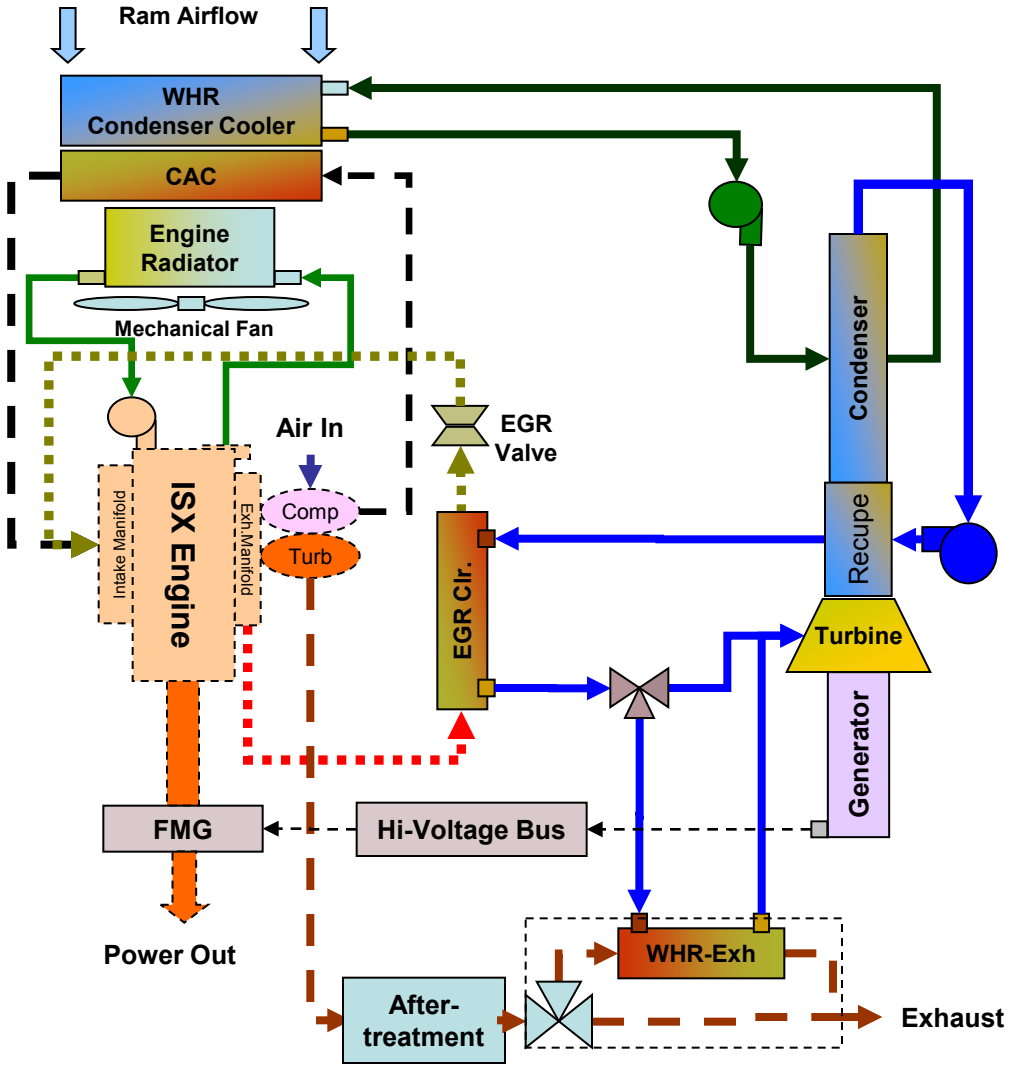
- Takes in Waste Exhaust Heat when off-peak

R245fa working fluid

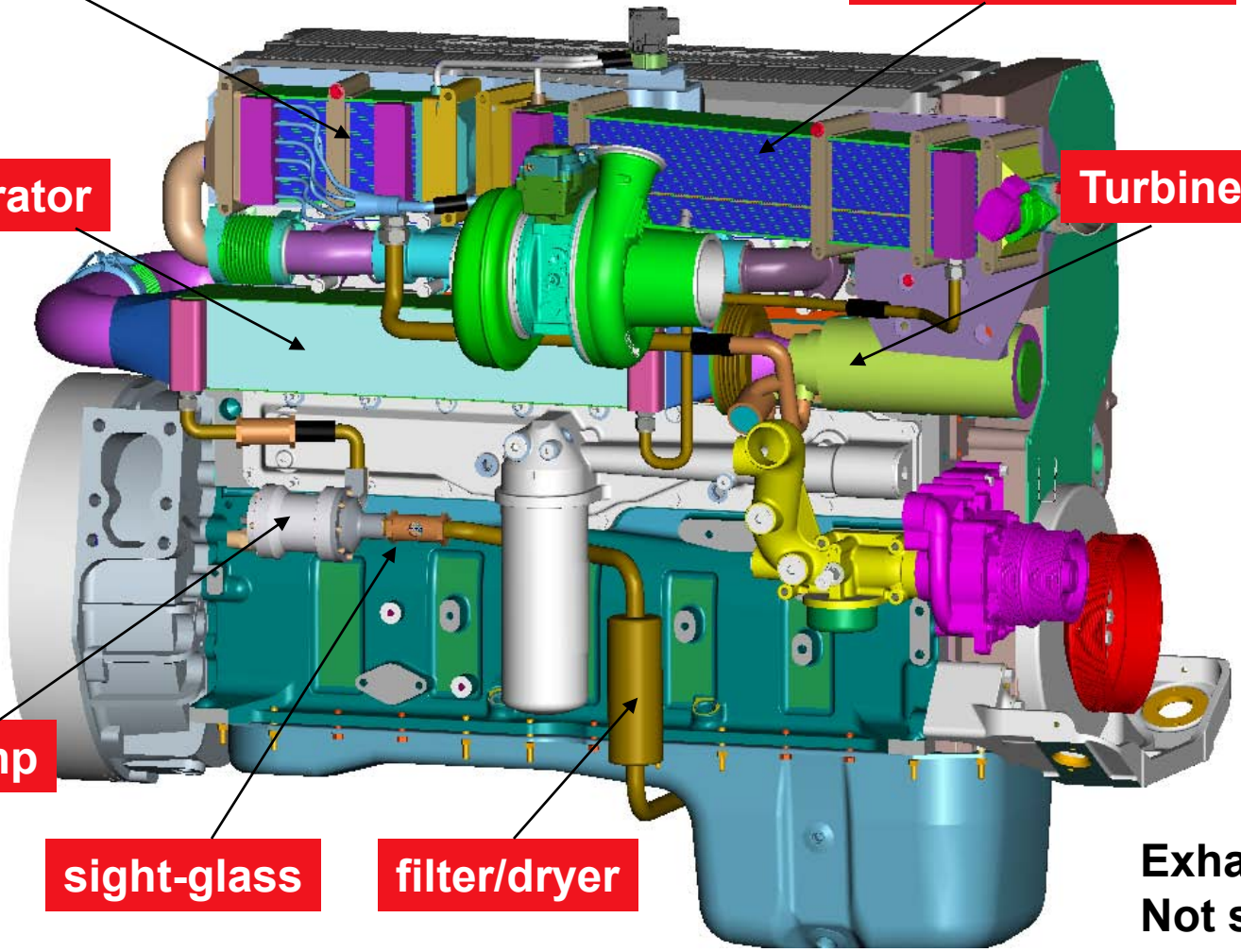
~8% efficiency benefit across the drive cycle.

>8% improvement at cruise

'More Electric' Accessories add 2% benefit

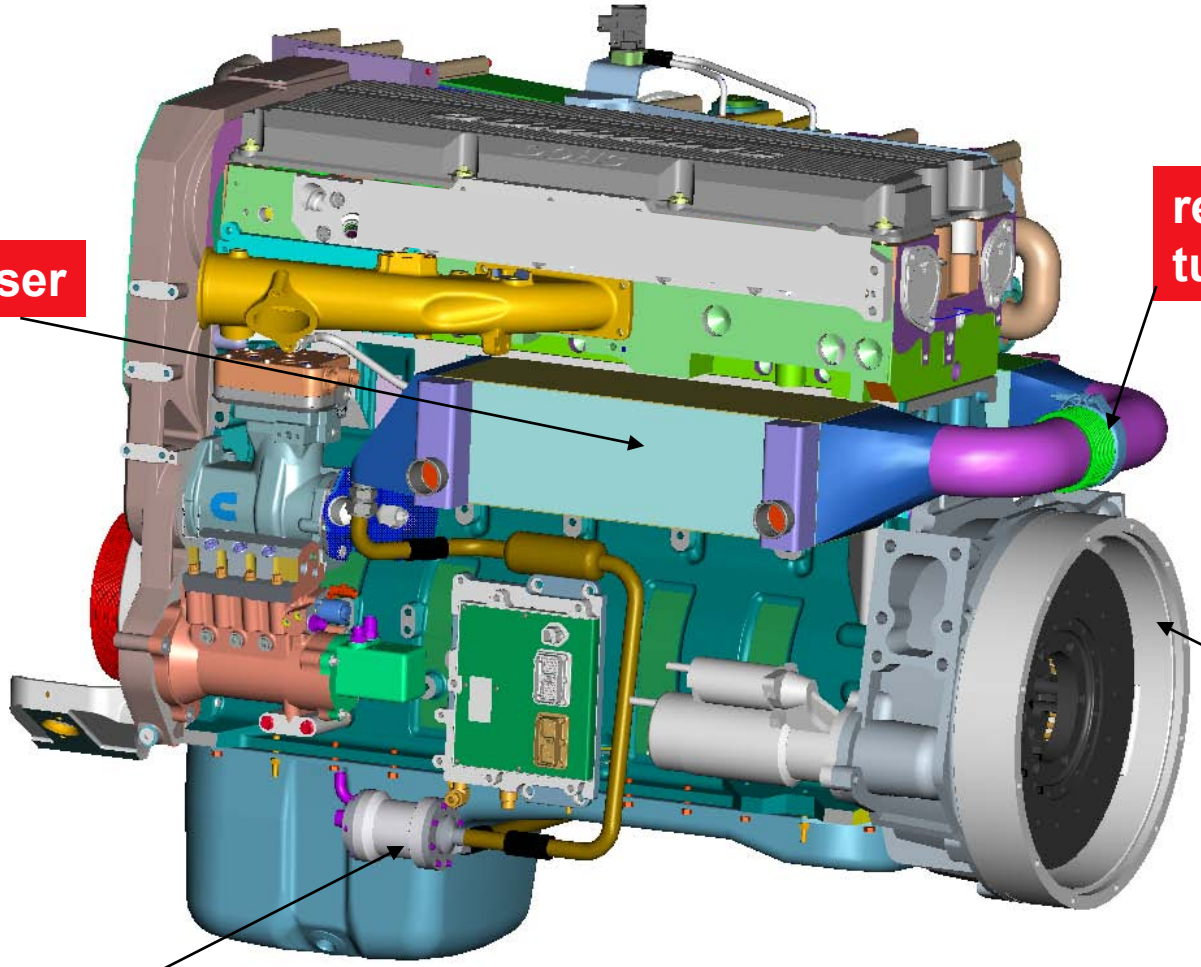


WHR
First Generation Hardware Design



Exhaust Boiler
Not shown

WHR
First Generation Hardware Design



Cummins Waste Heat Recovery
Performance Predicted at DEER, 2008

6% from EGR energy

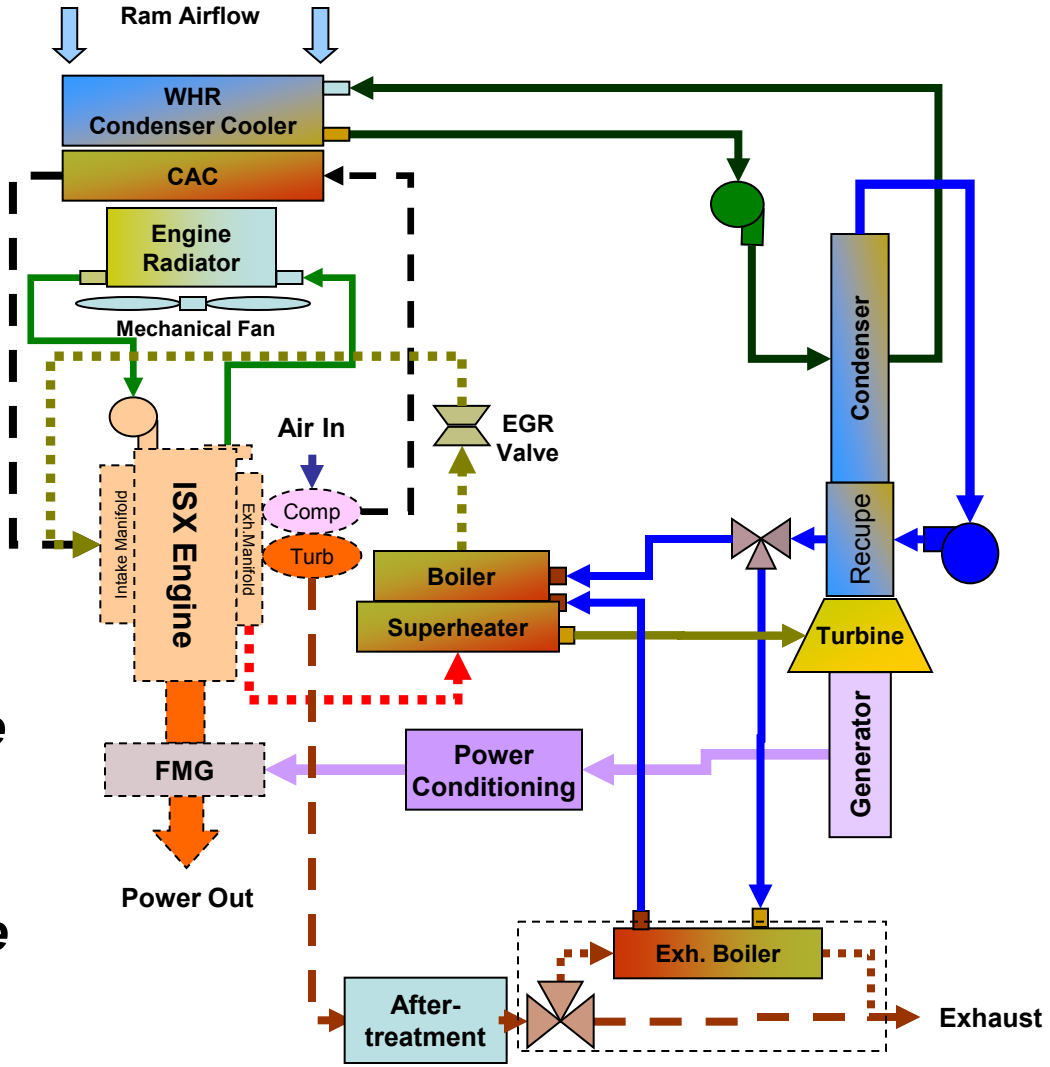
+ 2% from Exhaust

+ 2% from Electric Acc.

10% Improvement

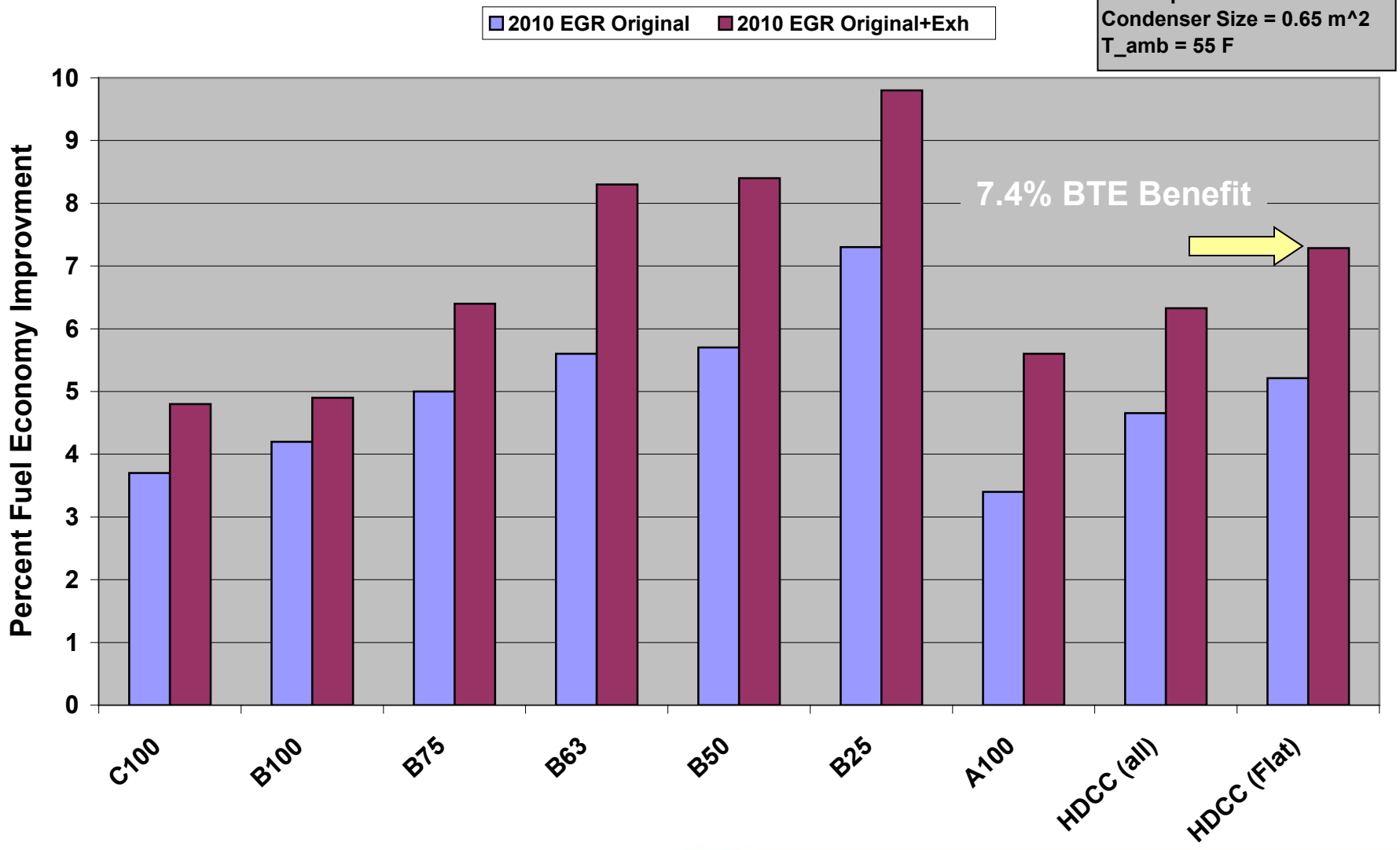
Model-based predictions across Heavy Duty drive cycle

The benefit of electric accessories is included by the presence of high-voltage electricity on-engine.



1st Generation Hardware Test Results

Presented at SMMR, 2009



Cummins Waste Heat Recovery First Generation Results

Presented at SMMR, 2009

5.4% from EGR energy

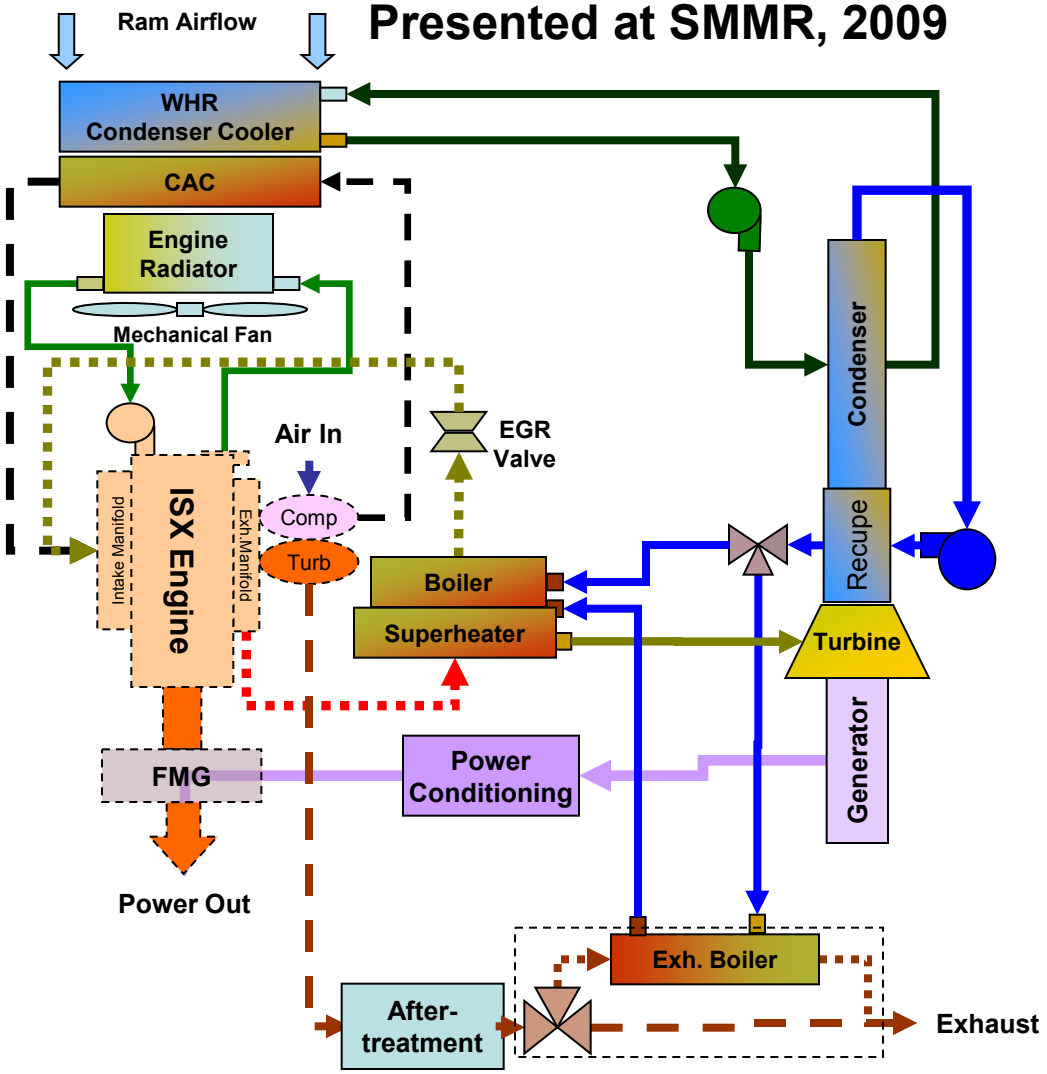
+ 2% from Exhaust

+ 2% from Electric Acc.

9.4% Improvement

Goals were nearly achieved with 1st Gen hardware. Component development would reach the 10% goal

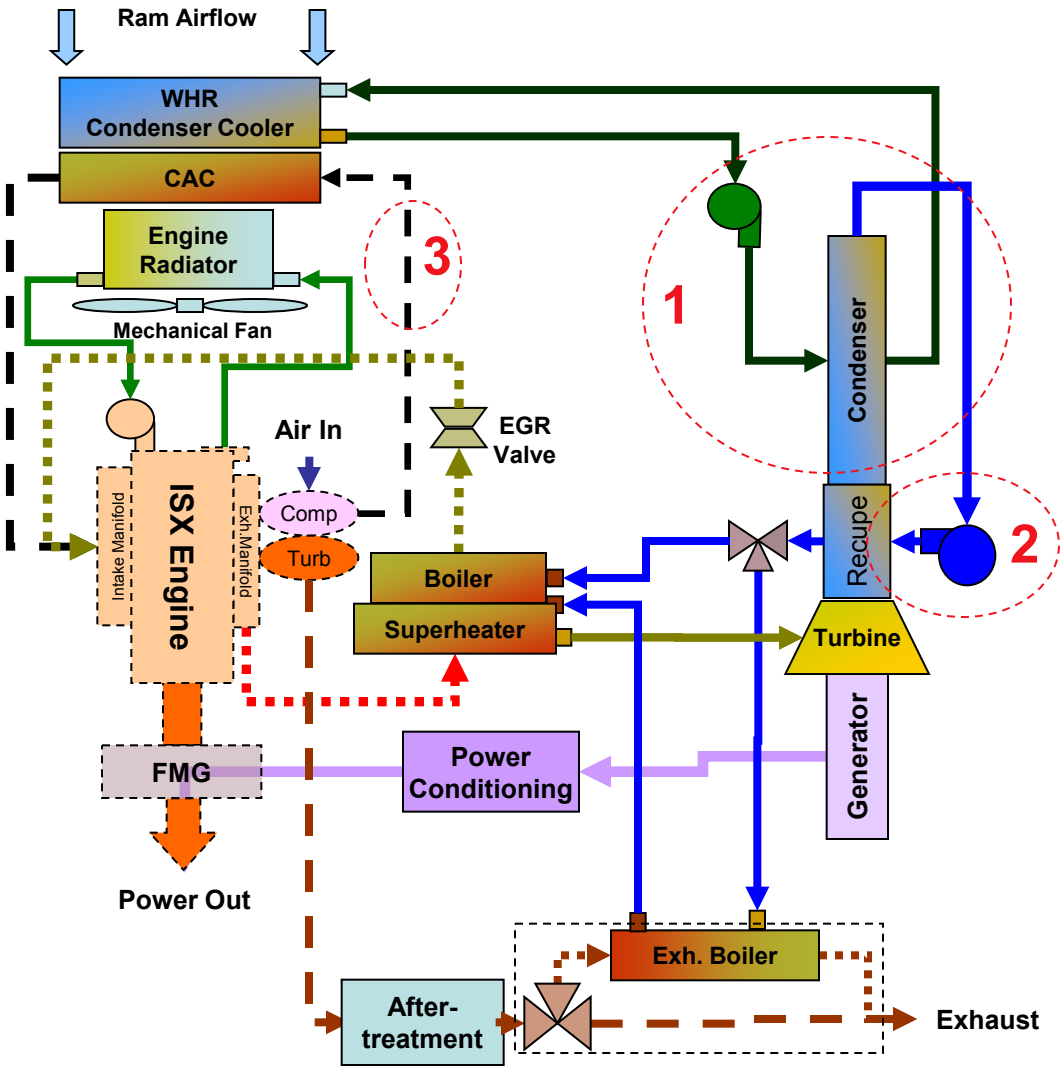
Electric accessories are not being developed under this program



Cummins Waste Heat Recovery System Improvements

First Generation hardware included:

1. Water-cooled, remote condenser/pump
2. Separate boost and feed pumps
3. Did not capture energy from fresh charge air



Cummins Waste Heat Recovery System Improvements

1) Water-cooled condenser and pump
   - We determined that a direct-to-air condenser would provide superior results without the added parasitic pump load
   - Removal of this parasitic added 0.2% BTE Benefit

2) Dual Centrifugal pumps were only ~33% efficient (each)
   - We applied a positive displacement, single-stage feedpump which operates at ~70% efficiency
   - This improvement added 0.6% BTE Benefit

3) Charge Air Heat Recovery
   - Applied to the 1st Generation system would add another 0.6% BTE Benefit

These are additive, drive-cycle based, BTE improvements to the 1st Generation system – 1.4% Additional Benefit

Cummins Waste Heat Recovery
2nd Generation Architecture

5.4% from EGR energy

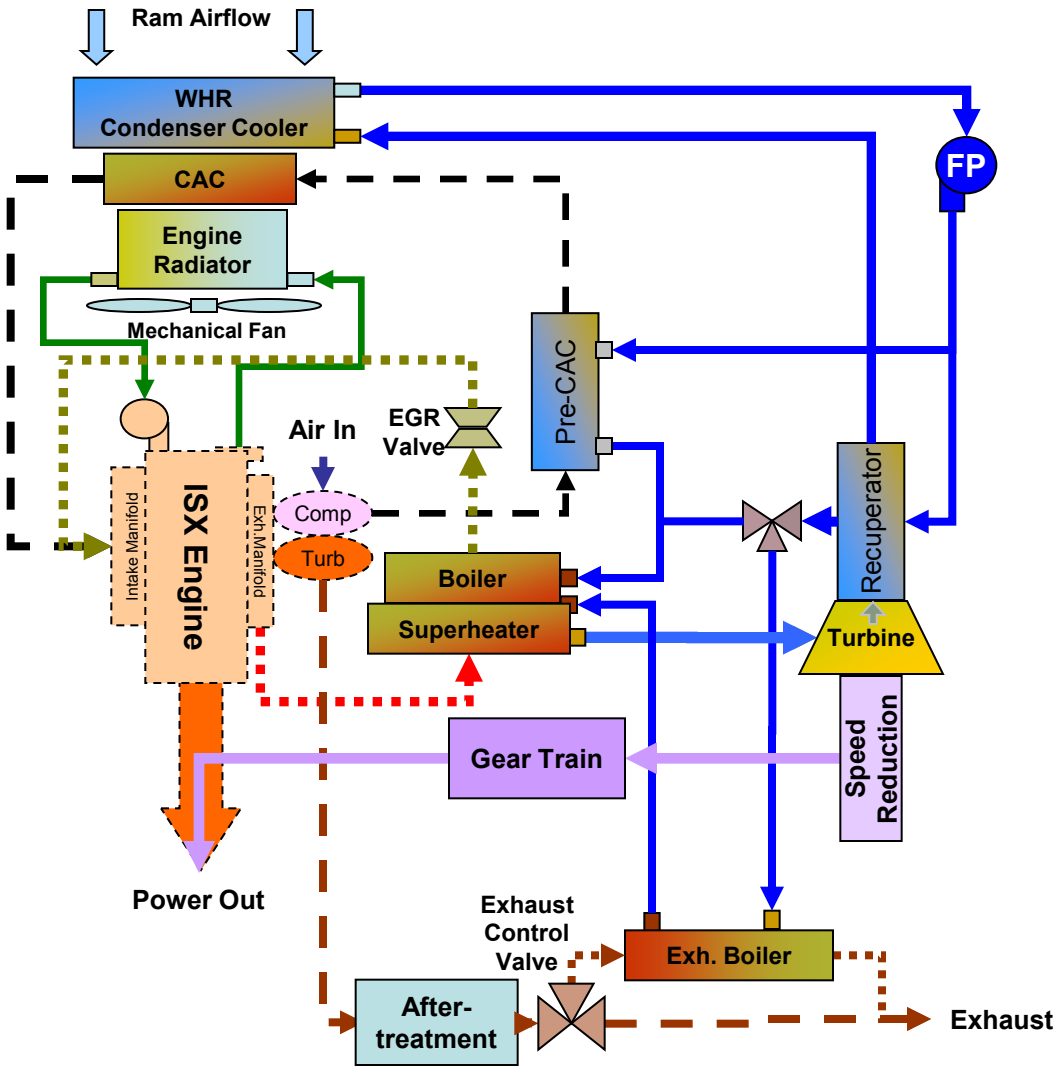
\+ 2% from Exhaust

\+ 1.4% from Improvements

\+ 2% from Electric Acc.

>10% Improvement

Improvements applied to the original engine/system would have exceeded our 10% goal



Engine System Changes

Low engine-out NOx combustion recipe

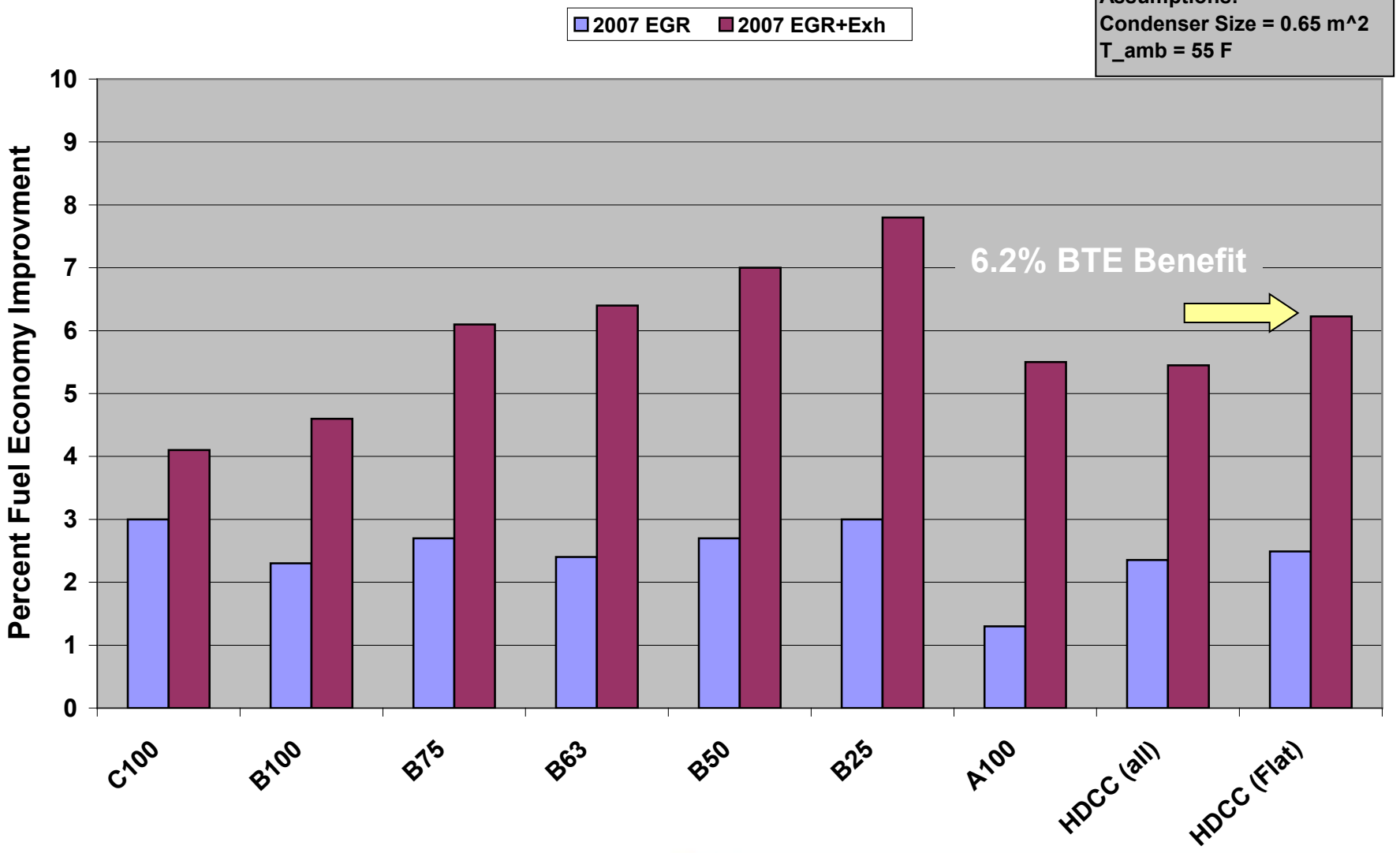
- Engine architecture used for first-generation EER system design targeted 0.2 gm BSNOX **engine-out** emissions
- EGR Charge Mass flow provided a high level of recoverable EGR energy

SCR-based aftertreatment on Cummins 2010 heavy-duty engines significantly reduced the amount of EGR flow required to meet engine-out NOx emissions and improved base engine fuel economy.

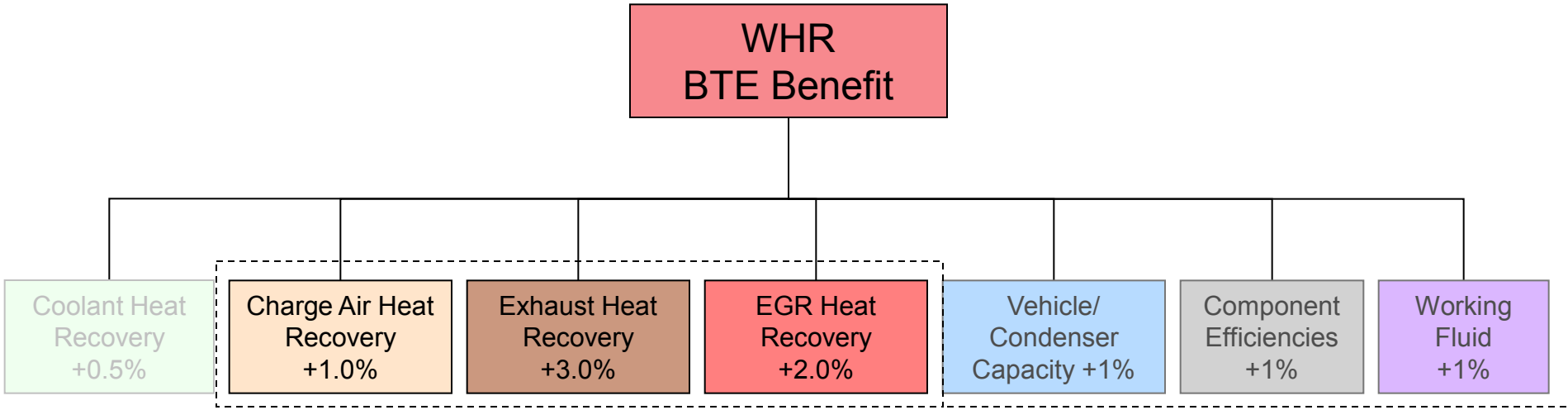
This drove re-evaluation of our system with a greater emphasis on exhaust heat recovery

1st Generation Hardware Test Results from ISX'07

Presented at SMMR, 2009



ORC Energy Recovery for 2nd Generation Development



- Post-2010 engines will have less EGR than 2007
- Exhaust gas energy can only be recovered up to the limit of the cooling module but development of maximum condenser capacity will be pursued
- Charge Air recovery will continue to be a part of our go-forward recipe
- Improvements in component efficiencies are being developed and pursued
- System Cost will be a key focus

Milestones for 2009 presented at March'09 SMMR

2nd Generation WHR System Development -

Mechanical Gear Train Design	Underway
Condenser/Subcooler/Reservoir Testing	May '09
Pump Assessment and Testing	August '09
Gear Train Component Testing (Start)	September '09
2nd Generation Turbine Testing	Q4 '09
2nd Generation Engine Builds	Q1 2010

Progress 2009 – Q1, 2010

2nd Generation WHR System Development -

Mechanical Gear Train Design	Completed
Condenser/Subcooler/Reservoir Testing	Completed
Pump Assessment and Testing	Completed
Gear Train Component Testing (Start)	Begun Q4'09
2nd Generation Turbine Bench Testing	Completed Q1'10
2nd Generation Engine Build/Test Start	Completed Q4'09 (sans Turbine)

Progress 2009 – Q1, 2010

Further Progress -

Subcooling Control Development	Completed
System control for vapor quality	Completed
2nd Gen Heat Exchanger Design	Completed
2nd Gen Heat Exchanger Performance	Evaluated
2nd Generation Feedpump Design	Completed
Exhaust Bypass Valve Designed/Tested	Completed
System in-vehicle concepts/layouts	Underway

We plan to continue this work under the Supertruck program

Areas of Continuing Development:

- System Architecture and Controls
- Turbine Expander
- Expander to Engine Geartrain
- Heat Exchangers – on and off engine
- Feedpump and instrumentation
- Fluid Development (low GWP alternatives)
- Vehicle Packaging

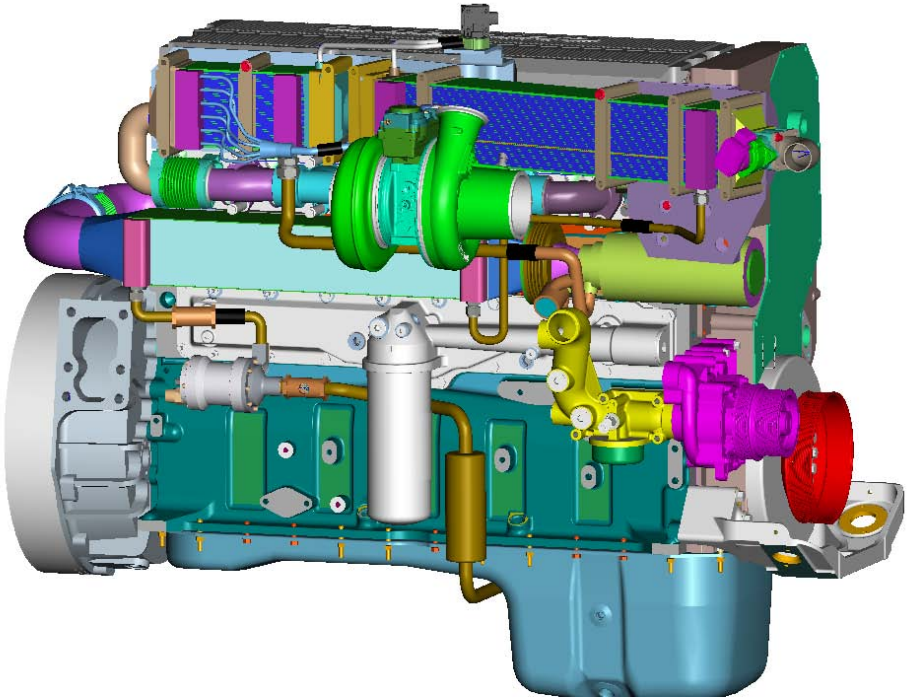
Review and Summary

The Exhaust Energy Recovery program at Cummins has made considerable progress

- Demonstrated the significant potential of ORC-based Waste Heat Recovery
- Designed, built, and tested 2 generations of system hardware and developed supporting technology
- Successfully met the program's 10% improvement goal
- Identified a path forward to further improve system performance and benefit in future programs

Cummins Waste Heat Recovery

Cummins Inc. appreciates the partnership with the U.S. Department of Energy in this highly innovative and unique program



Thank You!