Exhaust Energy Recovery

2009 Annual Merit Review

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Research & Technology

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Cummins

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Exhaust Energy Recovery Overview

Timeline -

- Project Start – 5/1/05
- Project End – 3/31/10
- Percent Complete ~80%

Barriers Addressed -

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

Budget -

- Total Project Funding
  - - DoE Share – $3.2M
  - - Cummins Share – $3.2M

    (as of 3/1/09)
- Funding Received in FY'08 –
  - $1.3M
- Funding Received in FY'09 –
  - $0

Partners -

- Cummins Turbo Technologies
- Cummins Power Generation
- Cummins Generating Technologies

Agenda

- Program Goals
  - Exhaust Energy Recovery System Architecture
- Program Accomplishments
  - First Generation Hardware Results
- Engine Architecture Changes
  - SCR Aftertreatment Effect on Performance
- System Development
  - Path to target
- 2009 Plans and Milestones
  - Component development and next generation hardware
- Review and Summary

Program Goals

Exhaust Energy Recovery seeks 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:

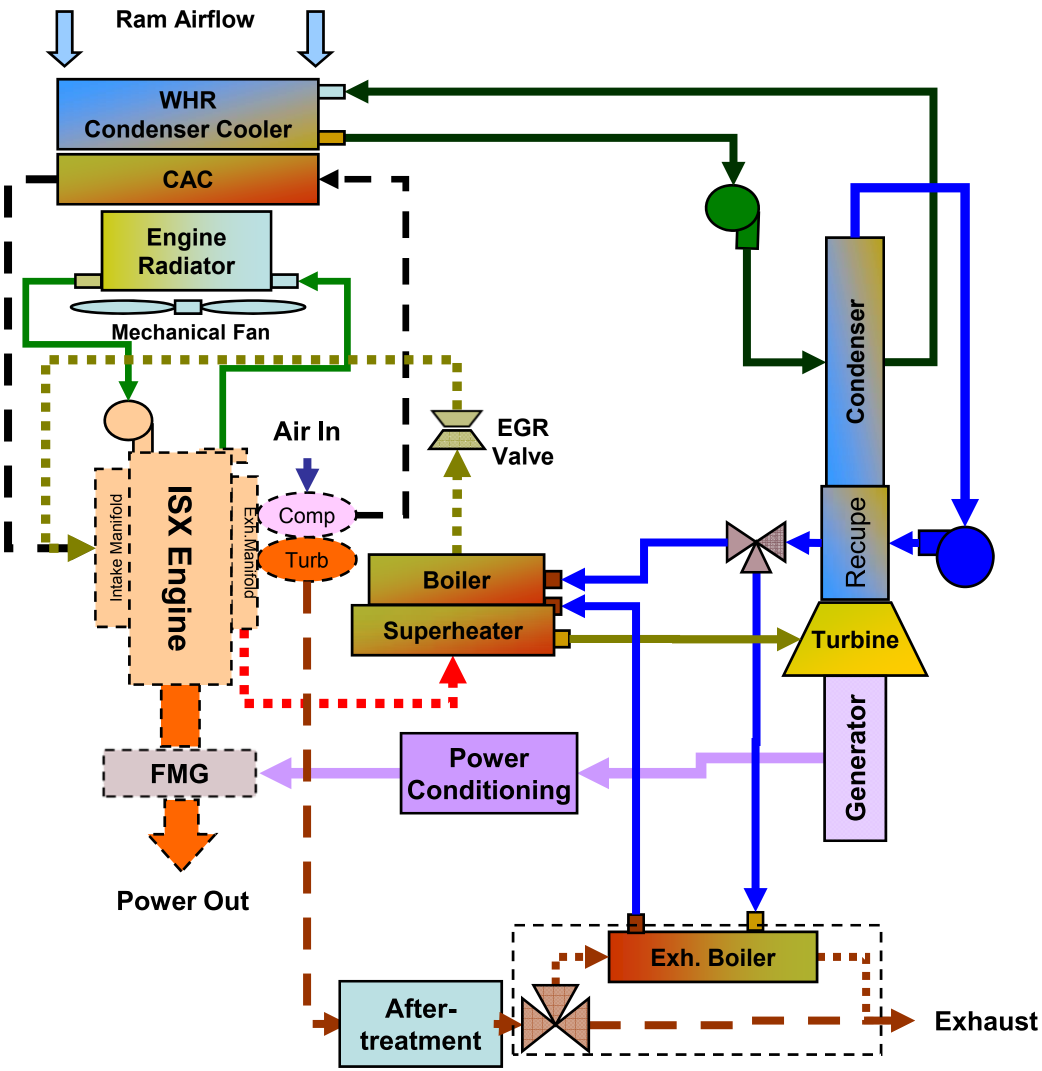
- Helps maintain the aerodynamic advantages of today's trucks

Exhaust Energy Recovery Concept

Organic Rankine Cycle

Converts otherwise wasted thermal energy from the EGR and main exhaust gas streams

Works best for high-EGR flow engine recipes for low-NOx combustion



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Recipe for 10% Efficiency Improvement

6% from **EGR energy**

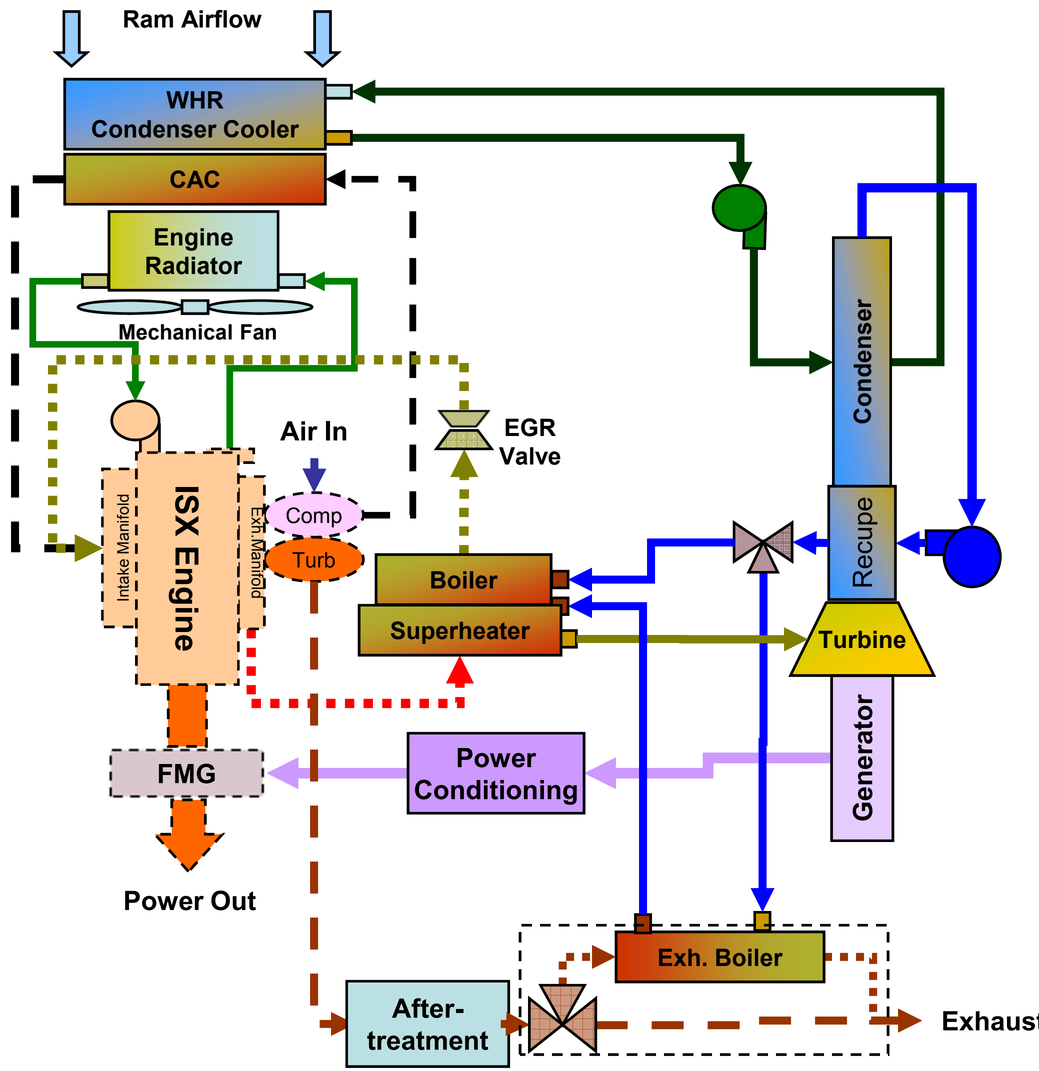
+ 2% from **Exhaust**

+ 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.

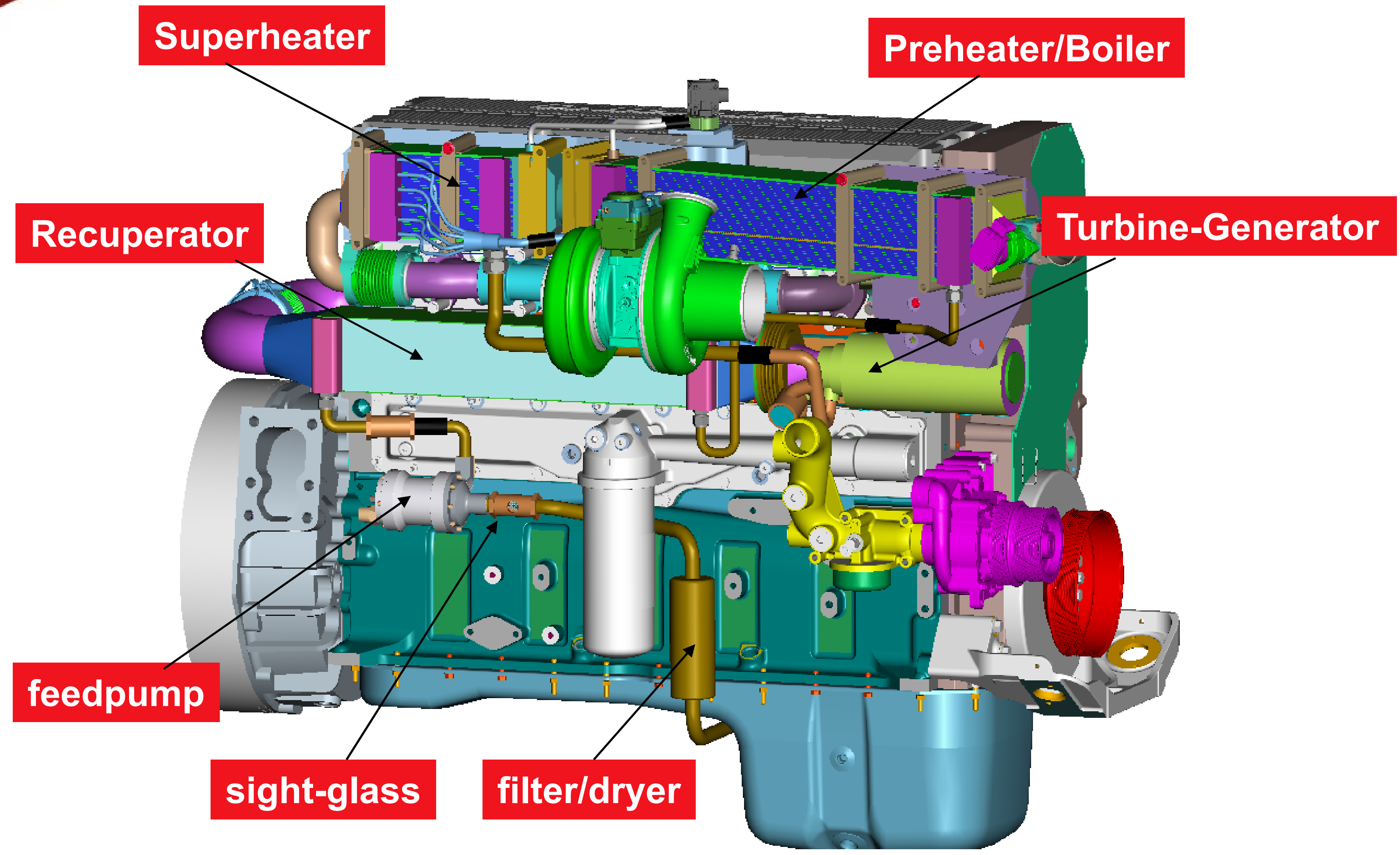


Original System Architecture Plans and Assumptions

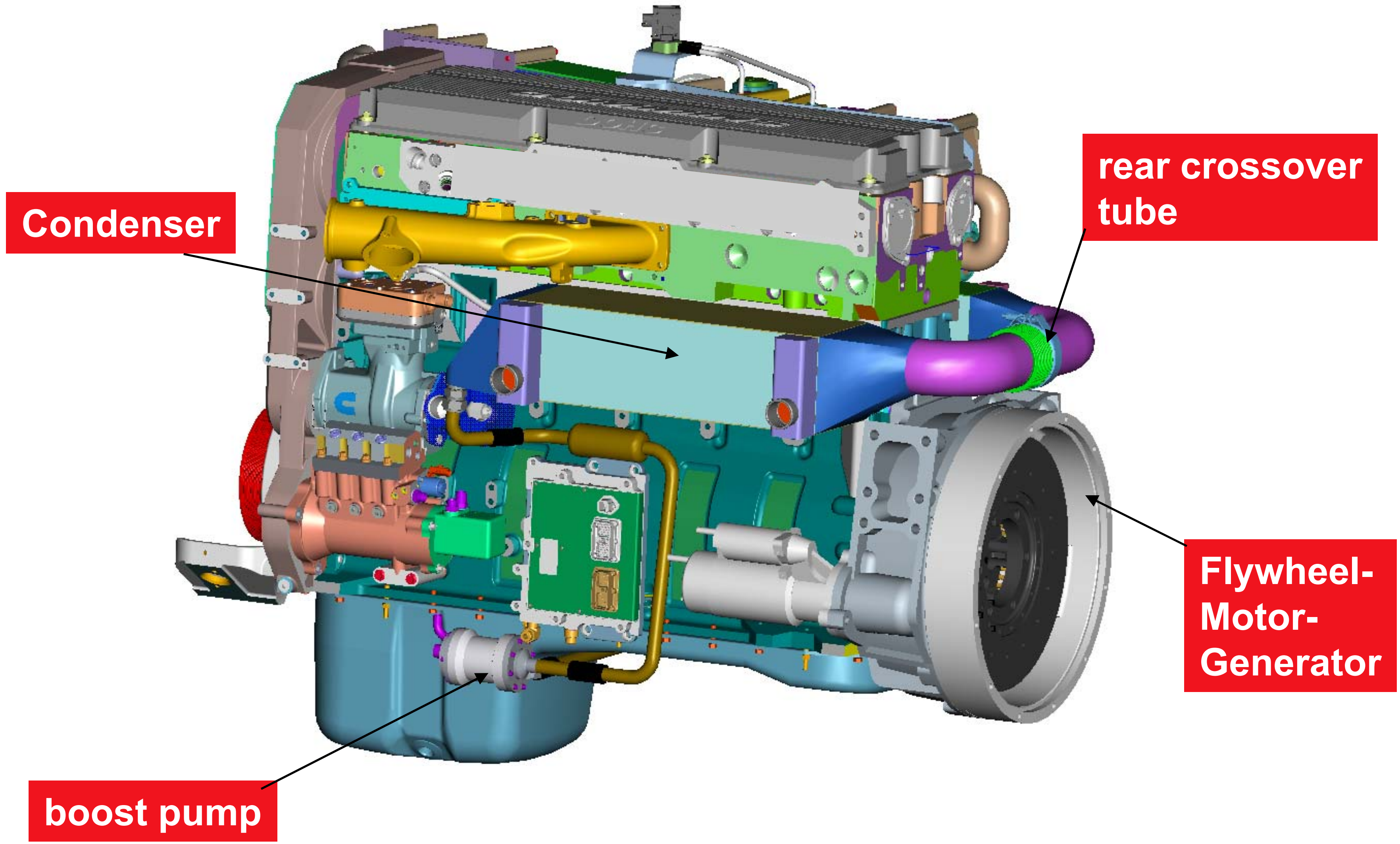
Low engine-out NOx combustion recipe

- 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
- Additional energy was recovered from the engine's main exhaust gas stream to keep the system at its full potential
- EER System performance was limited to the heat rejection capacity of a MY2007 Class 8 tractor

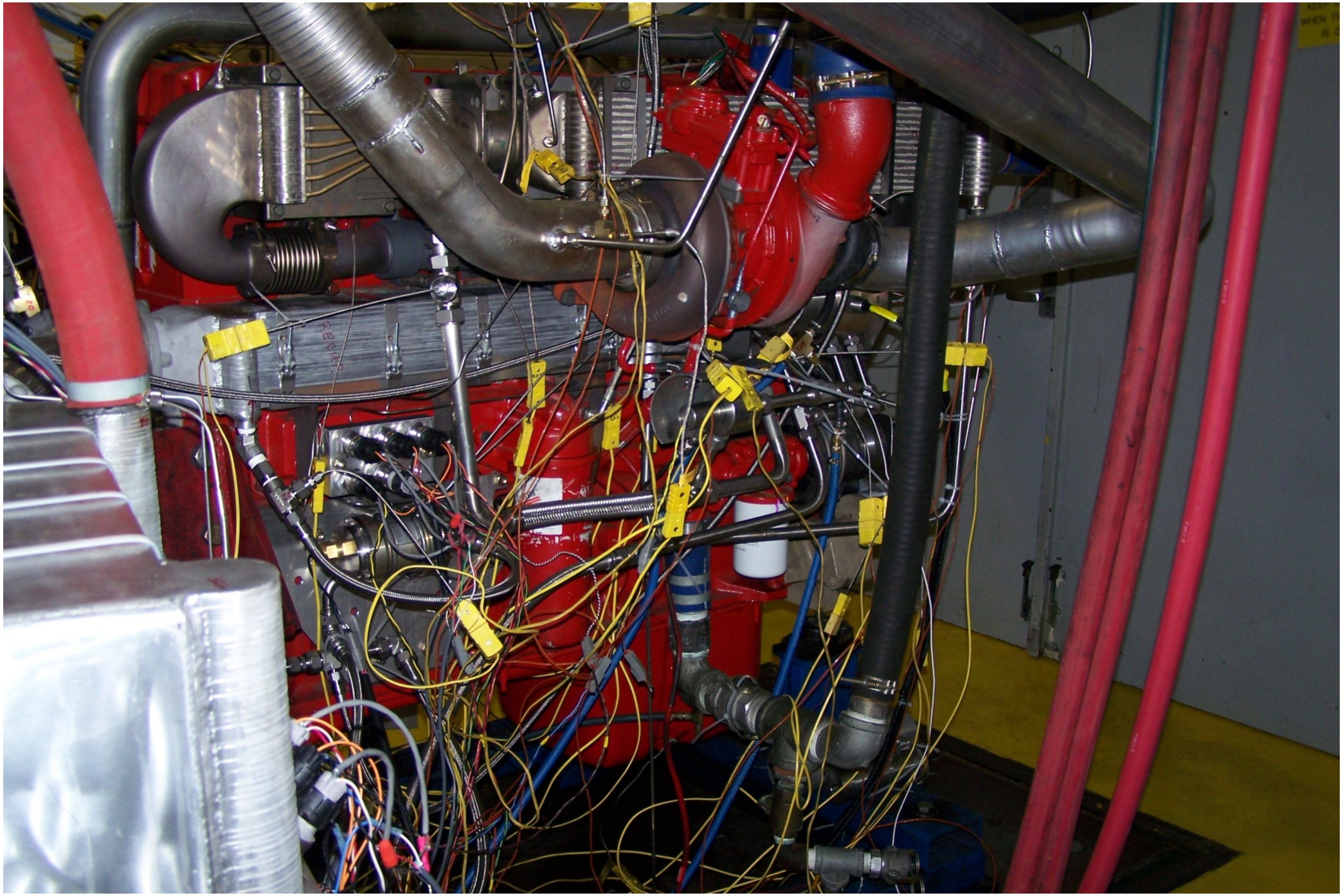
WHR
First Generation Hardware Design



WHR
First Generation Hardware Design



ISX with WHR System in Test Cell



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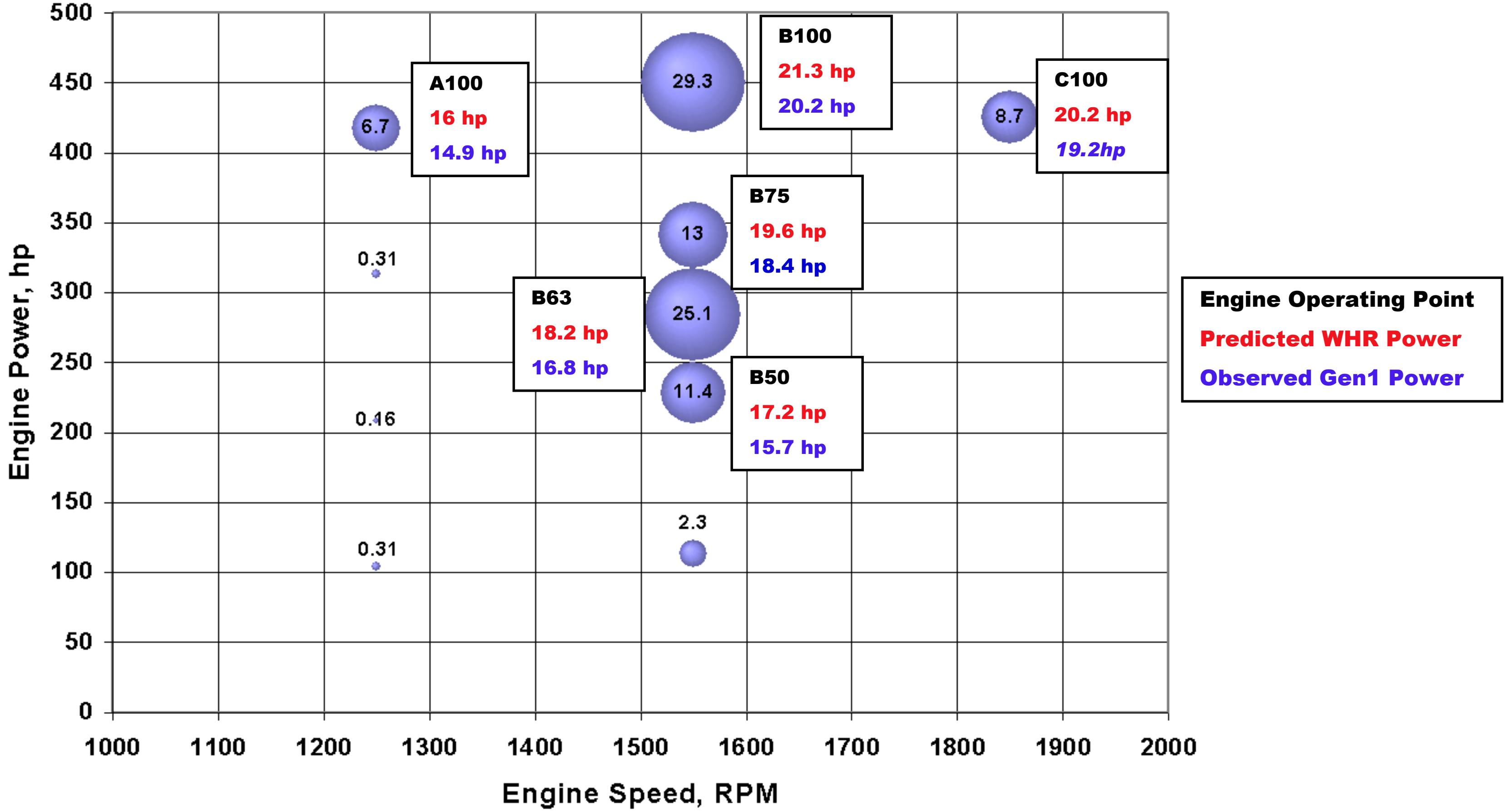
Innovation You Can Depend On

1st Generation Hardware Fuel Efficiency Improvement Results

Class 8 Tractor modeled on Heavy Duty, 500 mile route



EGR-Only WHR Net benefit on HDCC cycle = 6% Predicted

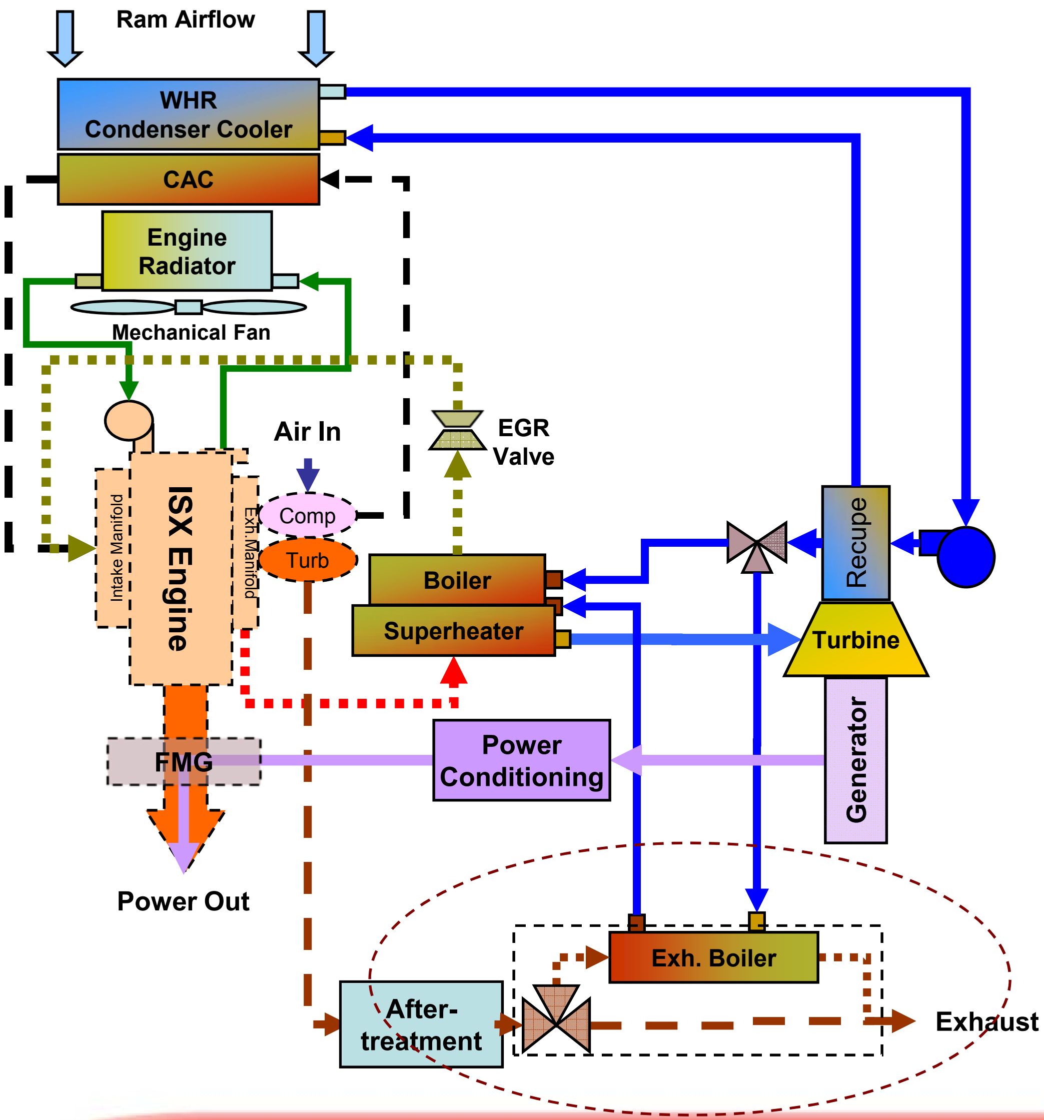
5.4% Observed from EGR Only with 1st Generation Hardware

Cummins Waste Heat Recovery

Exhaust Energy Recovery

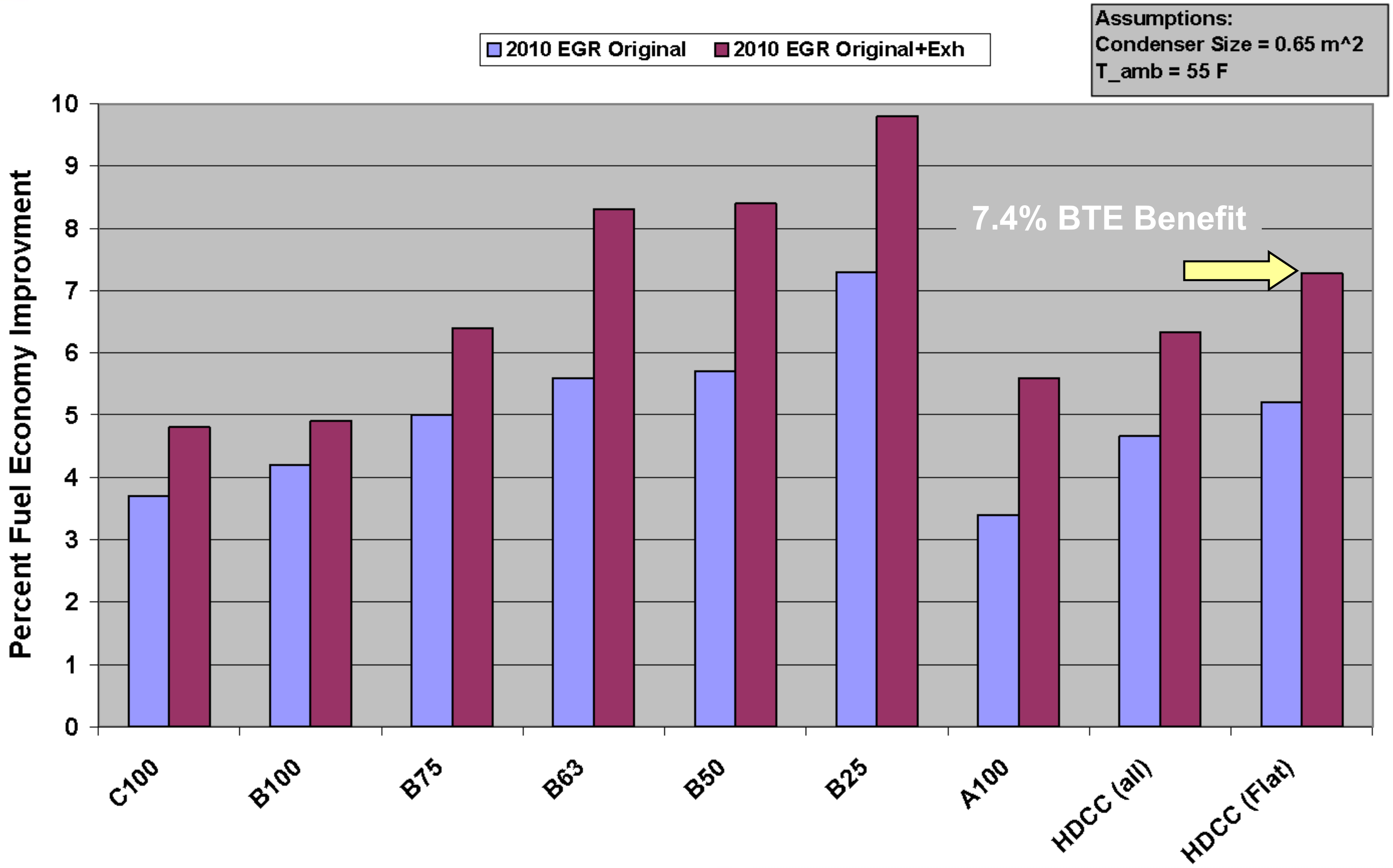
At off-peak operation, heat rejection capacity exists in the Recuperator and Condenser and Rad. Pack

Taking in additional heat energy from the main exhaust stream maximizes the power supplied by the ORC



1st Generation Hardware Test Results

Fuel Economy Rollup



Recipe for 10% Efficiency Improvement

5.4% from EGR energy

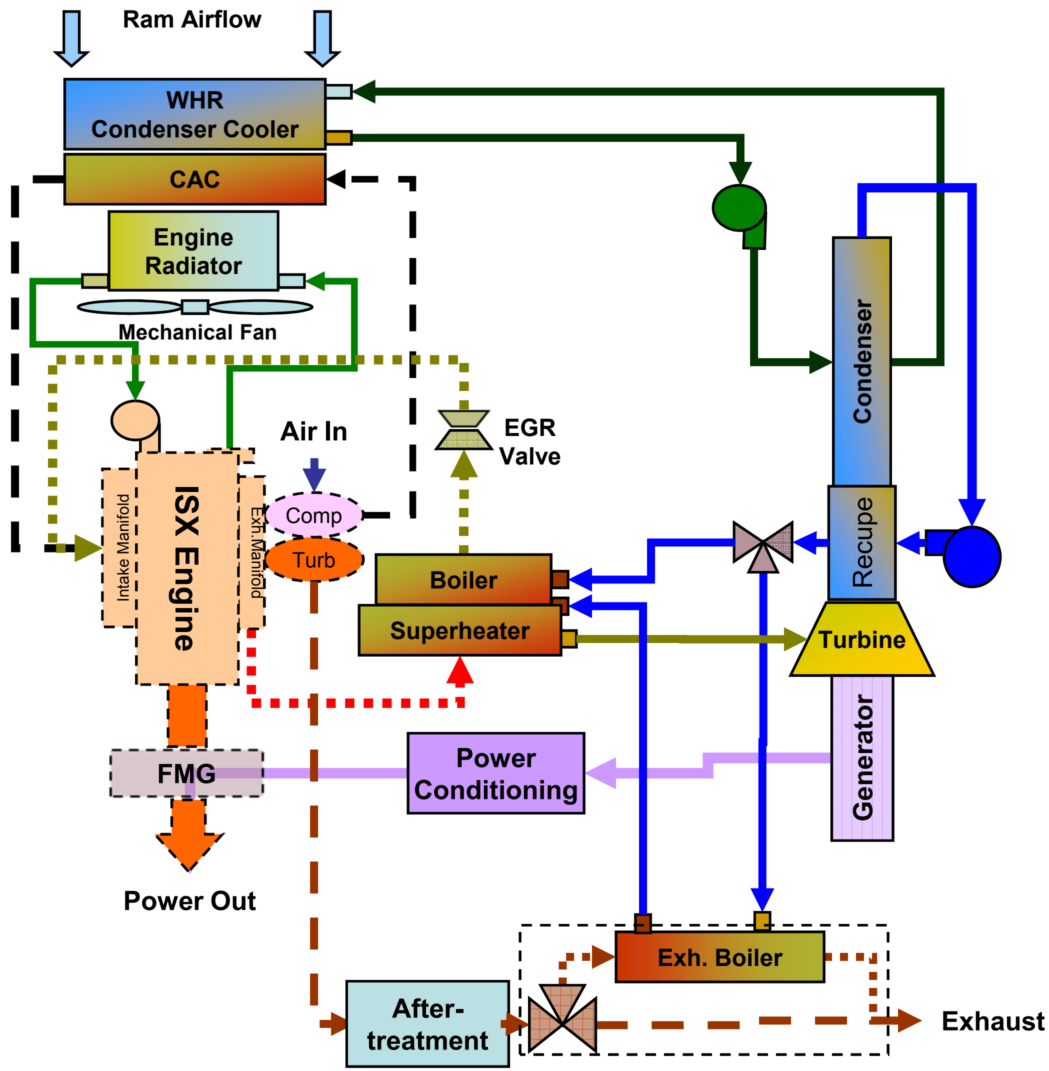
+ 2% from Exhaust

+ 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



Engine Architecture Changes

- **Affect of SCR Aftertreatment**

Cummins announced during August of 2008 that it would use SCR-based aftertreatment on its 2010 heavy-duty engines

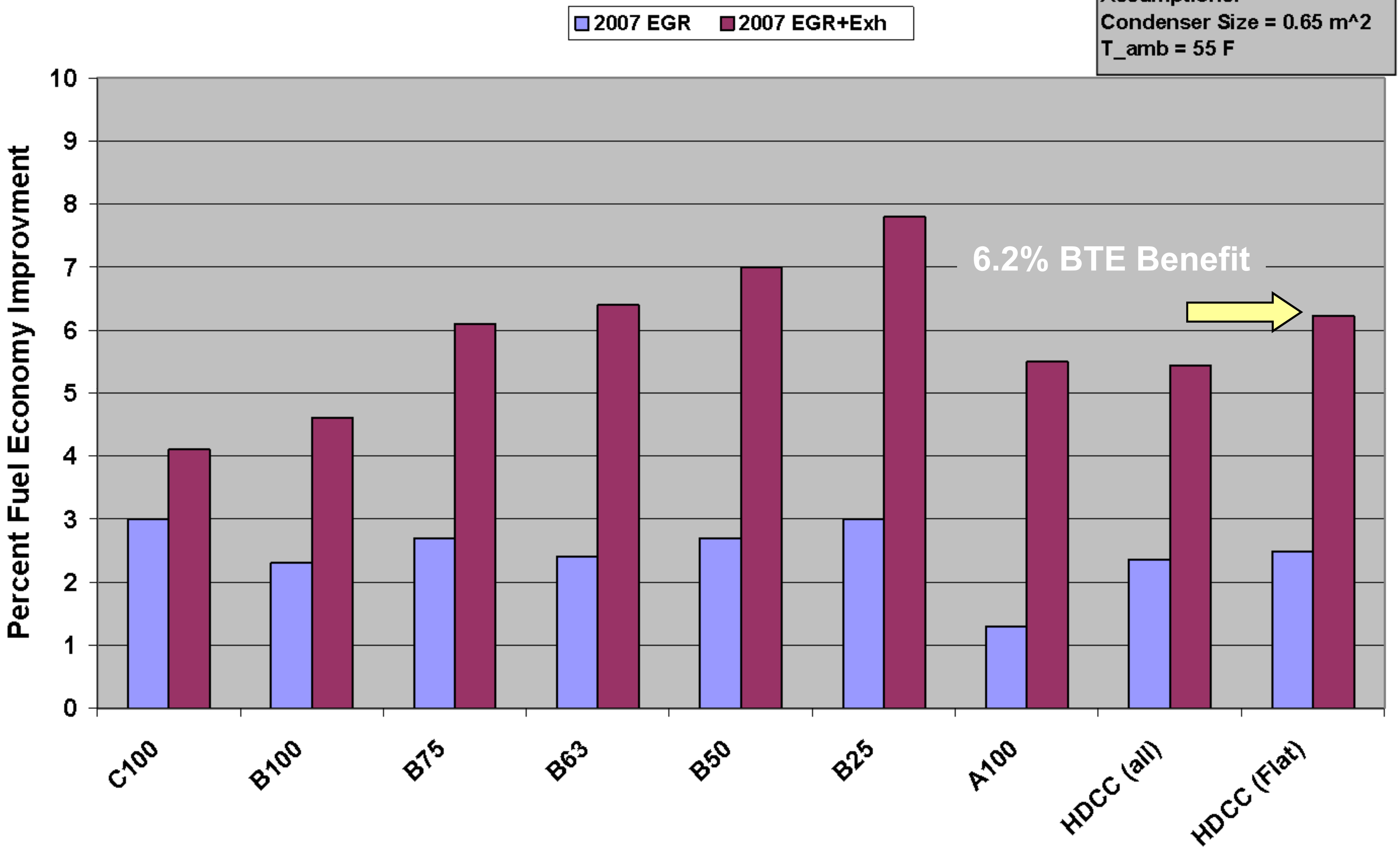
This significantly reduced the amount of EGR flow required to meet engine-out NOx emissions and improved base engine fuel economy. However, it reduced the potential benefit of Exhaust Energy Recovery

Our recipe to maximize the recovery of EGR and Exhaust Gas heat within the limit of the vehicle's cooling module ability still offers significant fuel economy savings

1st Generation Hardware Test Results from ISX'07

Fuel Economy Rollup

Assumptions:
Condenser Size = 0.65 m^2
T_amb = 55 F



Engine Architecture Changes

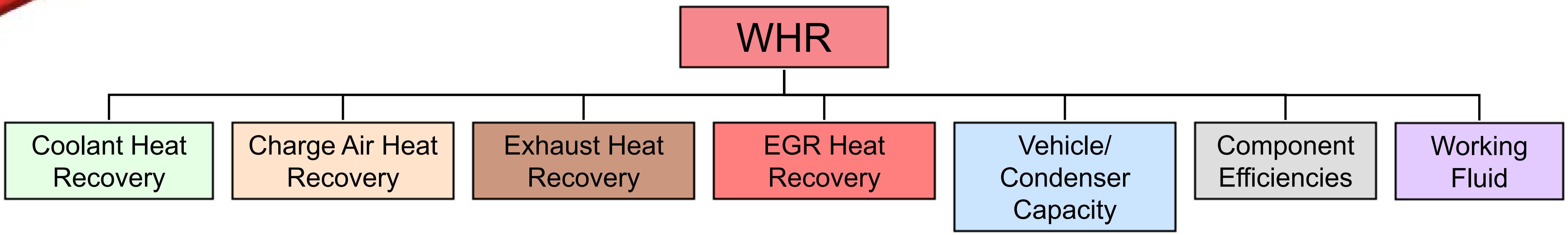
- **Affect of SCR Aftertreatment**

  Cummins has not established its 2010 and beyond engine recipes but significant waste heat will still remain for recovery in the EGR and Exhaust gas streams

  The potential benefit from ORC-based Exhaust Energy Recovery remains very significant and merits further development

  We are therefore identifying our path to the 10% target -

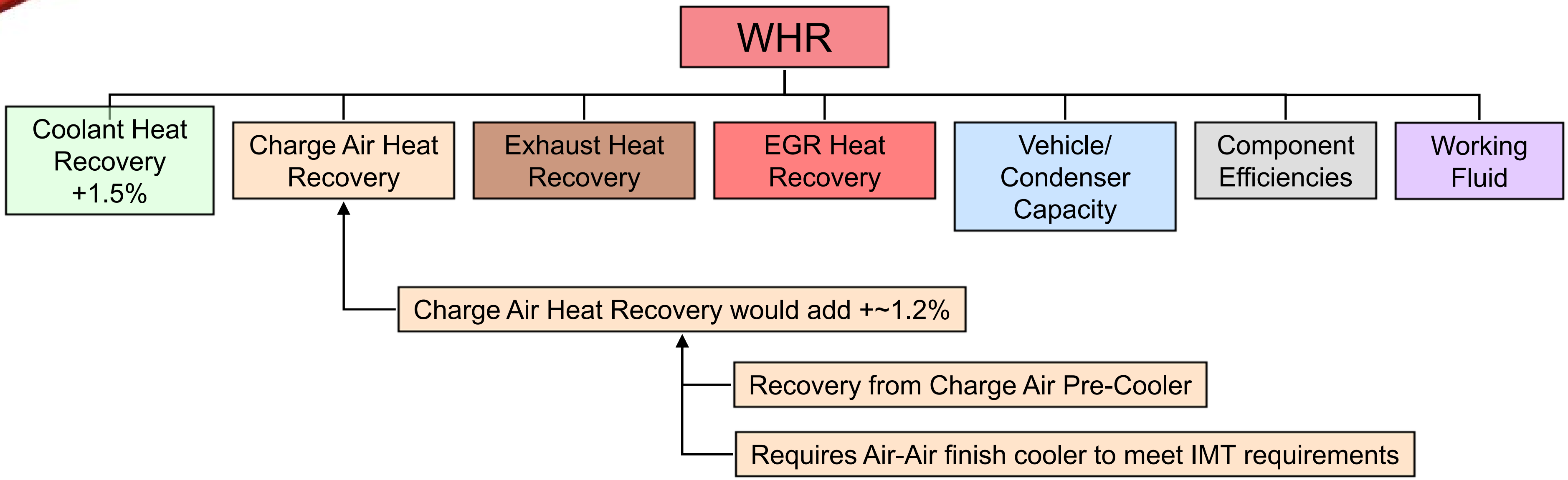
System Development – Path to Target



System Development – Path to Target

- WHR
  - Coolant Heat Recovery
    - From bulk coolant at 200F
      Potential for + ~1.5% improvement
      - Utilize existing engine design/hardware, AEG, water pump,
      - Recovery from AEG to working fluid heat exchanger
      - Eliminate radiator, system cooling with WHR condenser only
  - Charge Air Heat Recovery
  - Exhaust Heat Recovery
  - EGR Heat Recovery
  - Vehicle/ Condenser Capacity
  - Component Efficiencies
  - Working Fluid

System Development – Path to Target

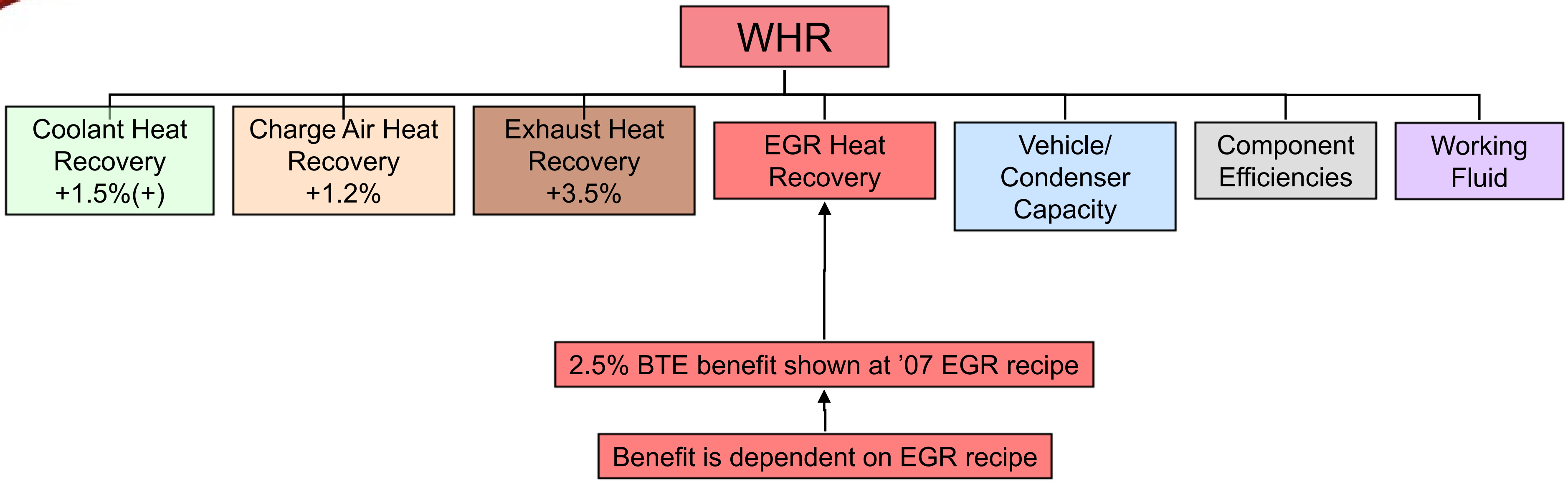


System Development – Path to Target

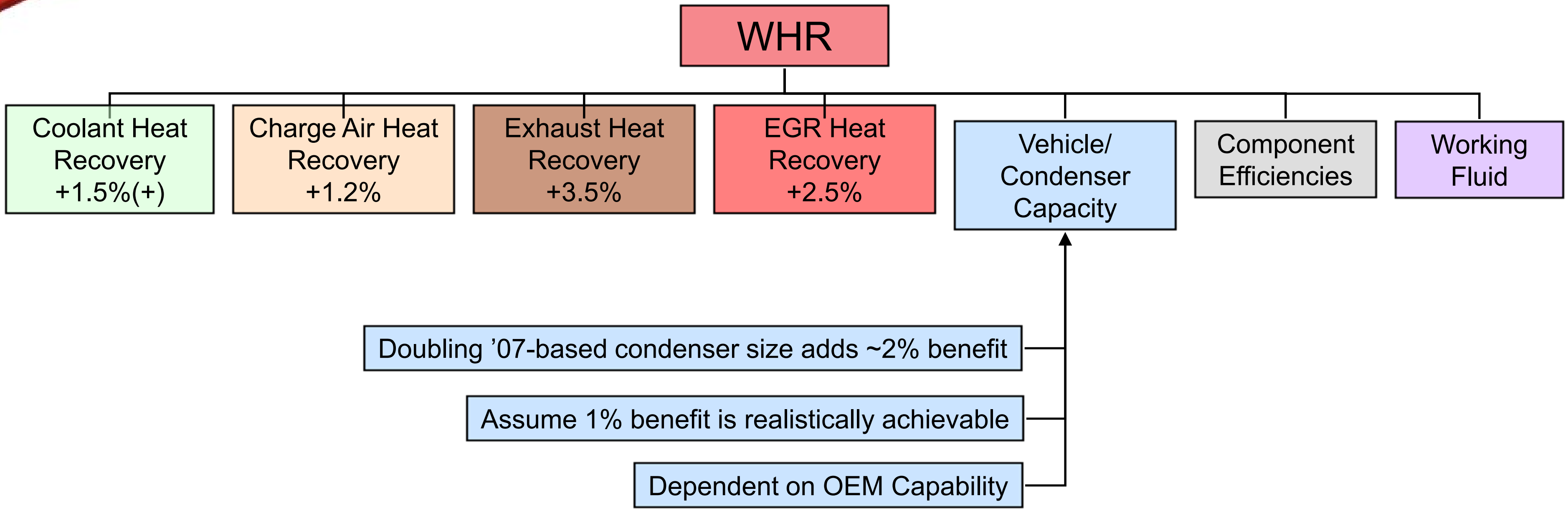
WHR

- Coolant Heat Recovery +1.5% (+)
- Charge Air Heat Recovery +1.2%
- Exhaust Heat Recovery
  - Exhaust recovery performed to maximize use of heat rejection capacity
  - Amount of benefit depends on EGR recipe and cooling system capacity
  - ~3.5% BTE benefit shown at ’07 EGR recipe
- EGR Heat Recovery
- Vehicle/ Condenser Capacity
- Component Efficiencies
- Working Fluid

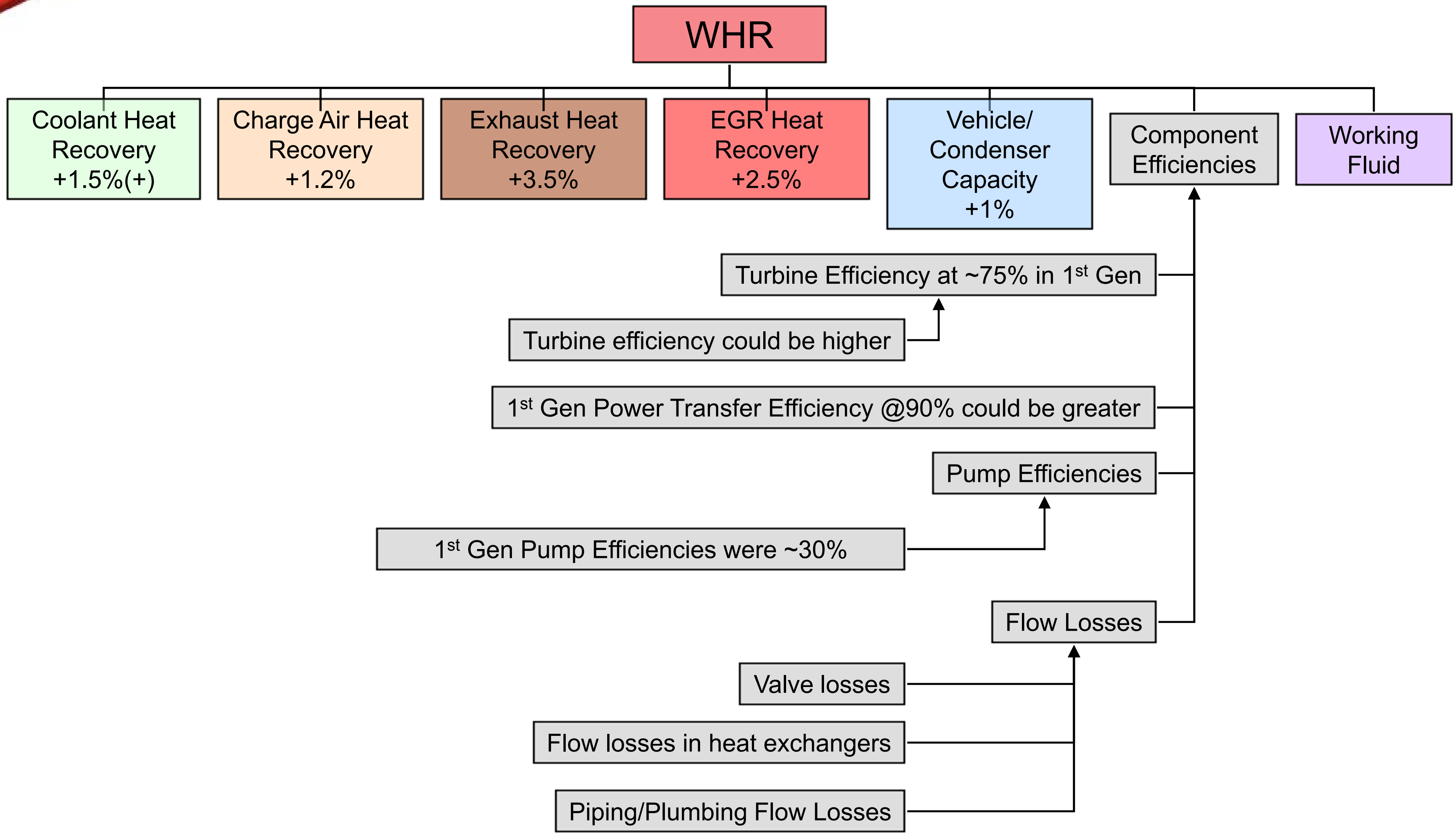
System Development – Path to Target



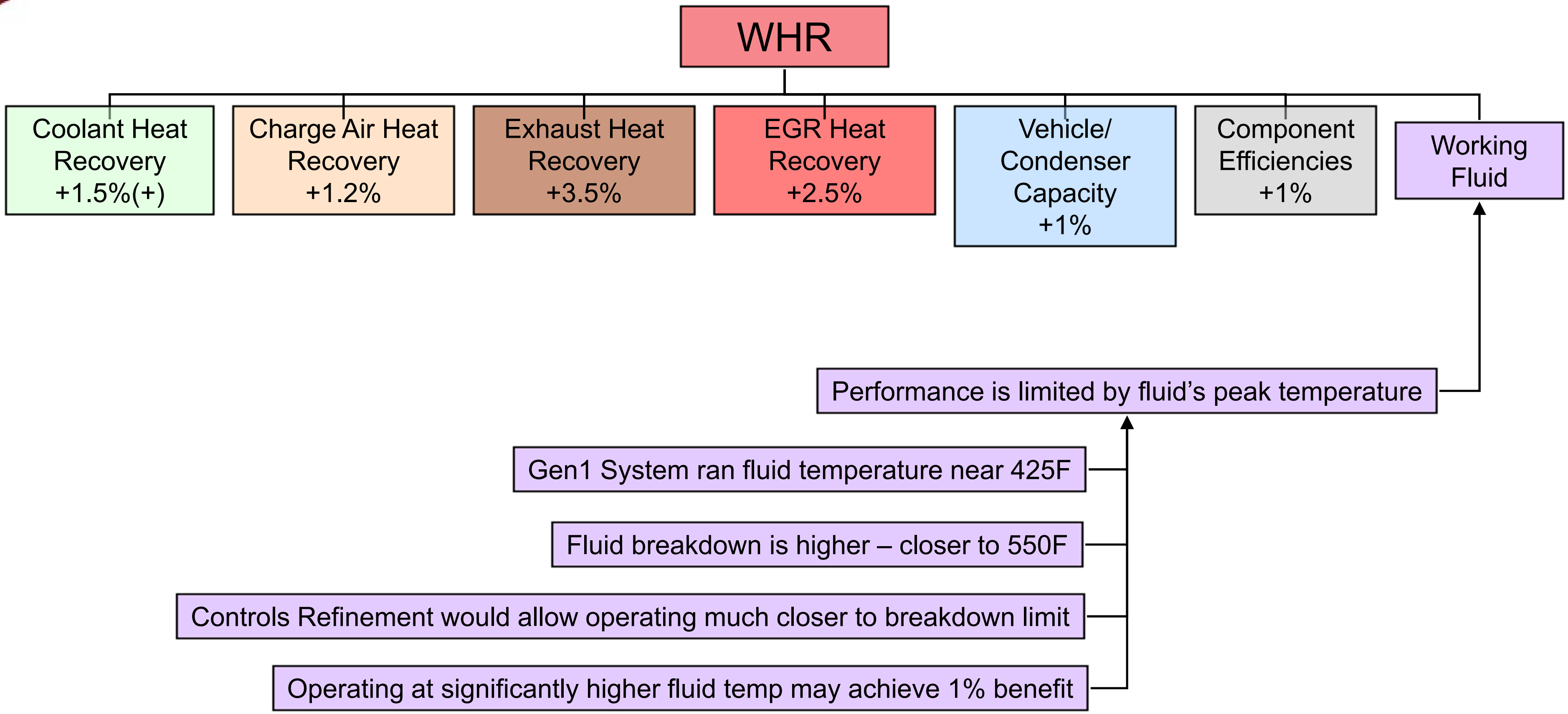
System Development – Path to Target



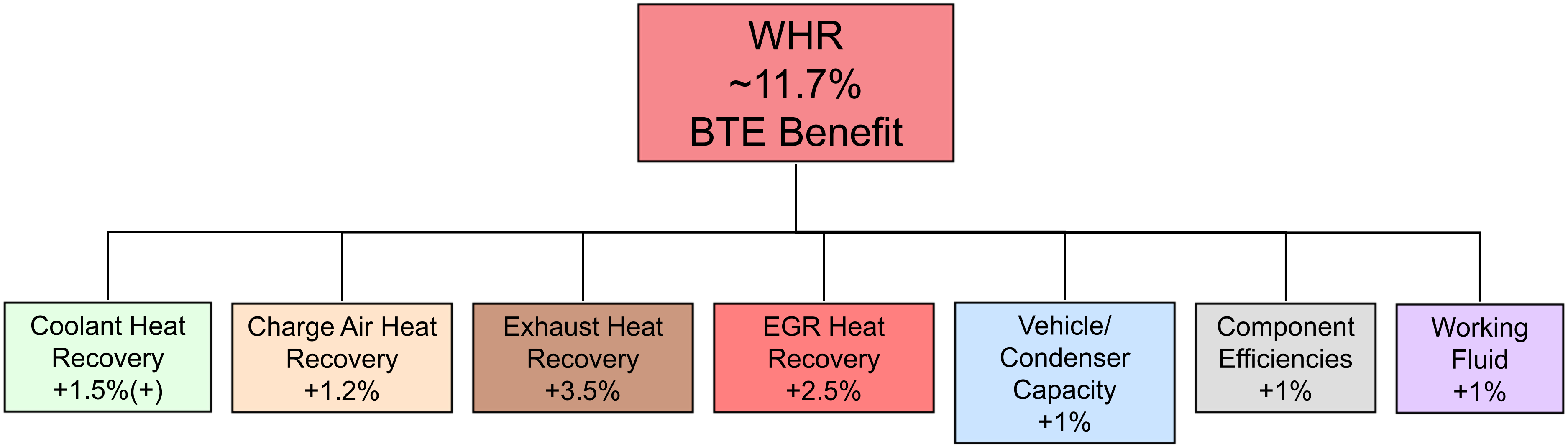
System Development – Path to Target



System Development – Path to Target



System Development – Path to Target



The addition of Coolant and Charge Air heat is done within the existing cooling system capacity

Refinements to system components and controls offer an avenue toward significantly greater benefit from ORC Energy Recovery

ORC-based energy recovery offers the greatest engine efficiency improvement potential

2009 Plan and Milestones

2nd Generation Component Development –

- **Turbine and Power Transfer**
  - Mechanical gear train coupling of Turbine to Engine
    - Should decrease losses over electrically-based system
    - Should improve system robustness and overall cost
  - Slower speed turbine
    - Should improve turbine efficiency
- **Heat Exchanger Design and Development**
  - 2nd Generation EGR Boiler/Superheater – more production-like design
  - Exhaust Boiler, Recuperator, CAC Pre-Cooler, and Coolant Heat Exchangers
    - Addition of CAC Pre-Cooler and Coolant heat should improve system performance
  - Condenser/Subcooler/Receiver Integration
- **Pumps and Plumbing Development**
  - Positive Displacement Pumps (1st Gen were centrifugal)
    - Improved pump efficiency should decrease losses/improve system performance

Milestones for 2009

2nd Generation 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

Review and Summary

The Exhaust Energy Recovery program at Cummins has made considerable progress –

- **Successfully demonstrated ORC-based energy recovery from EGR and Exhaust gas**
- **Delivered results against our model-based predictions for system performance**
- **Identified areas for system improvements**
- **Identified avenues for development towards the 10% Goal**

Cummins Inc. Appreciates the Partnership Support of the U.S. Department of Energy in this highly innovative and unique program –

Thank You!