Exhaust Energy Recovery

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Chris Nelson

Research & Technology

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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:

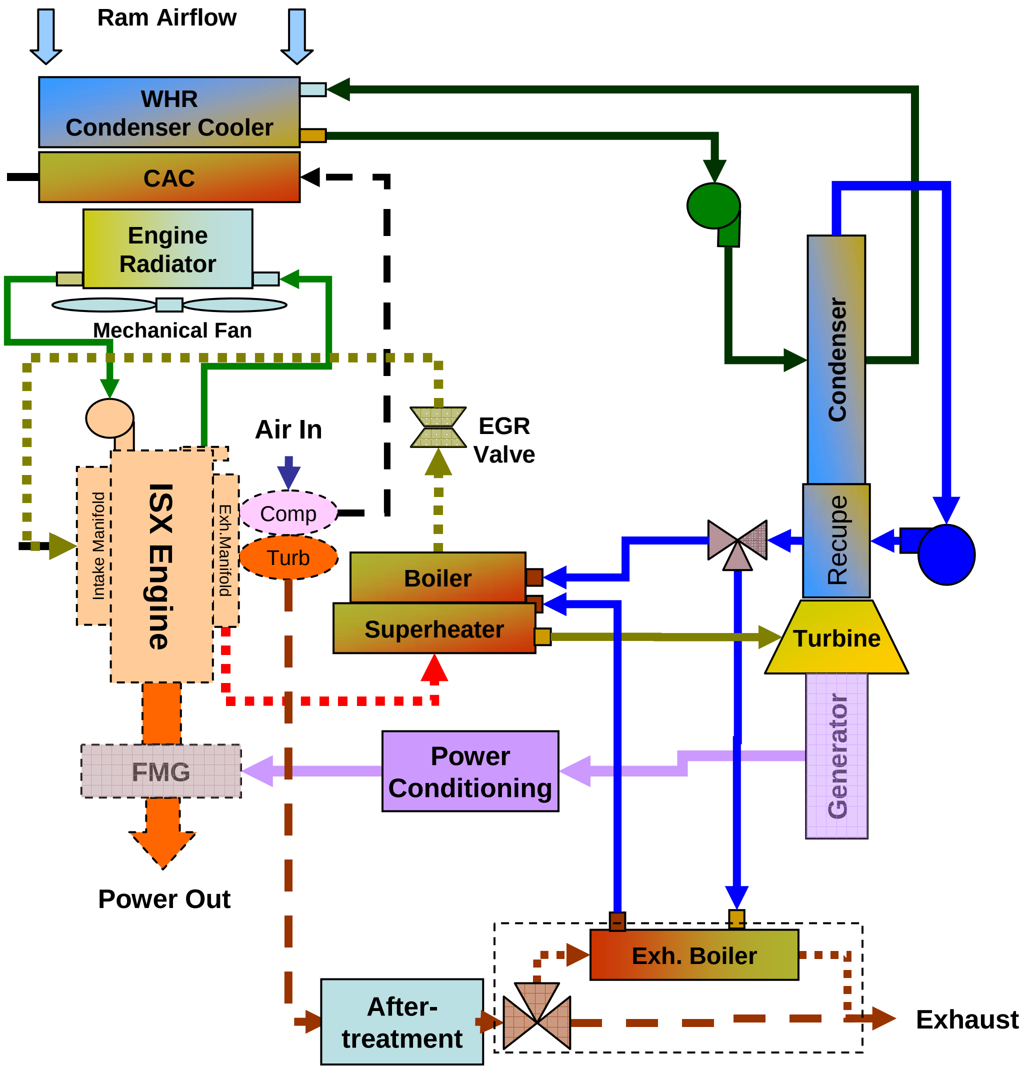
- Helps maintain the aerodynamic advantages of today's trucks

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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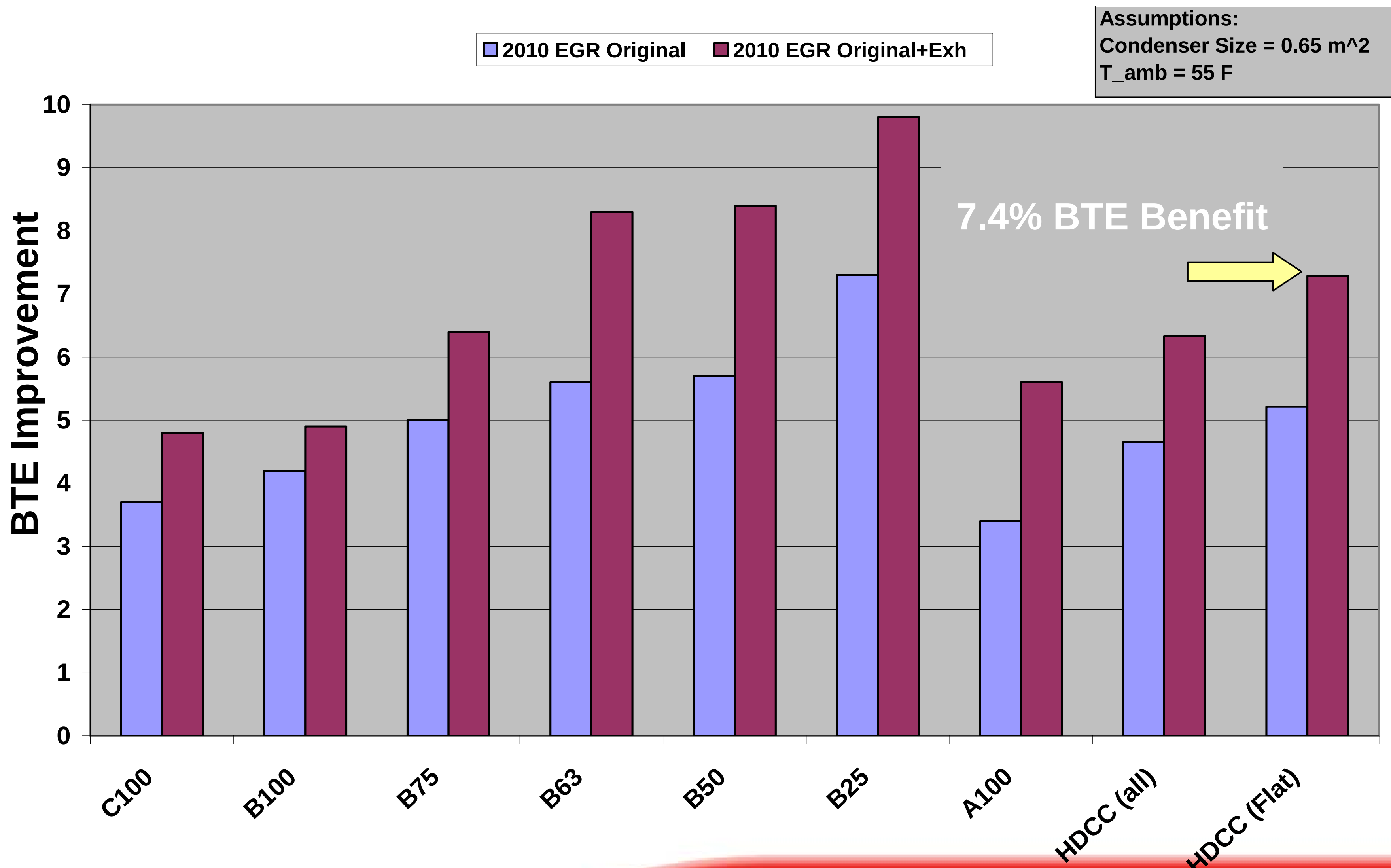
Program Accomplishments
Fuel Efficiency Improvement Results



Recipe for 10% Efficiency Improvement

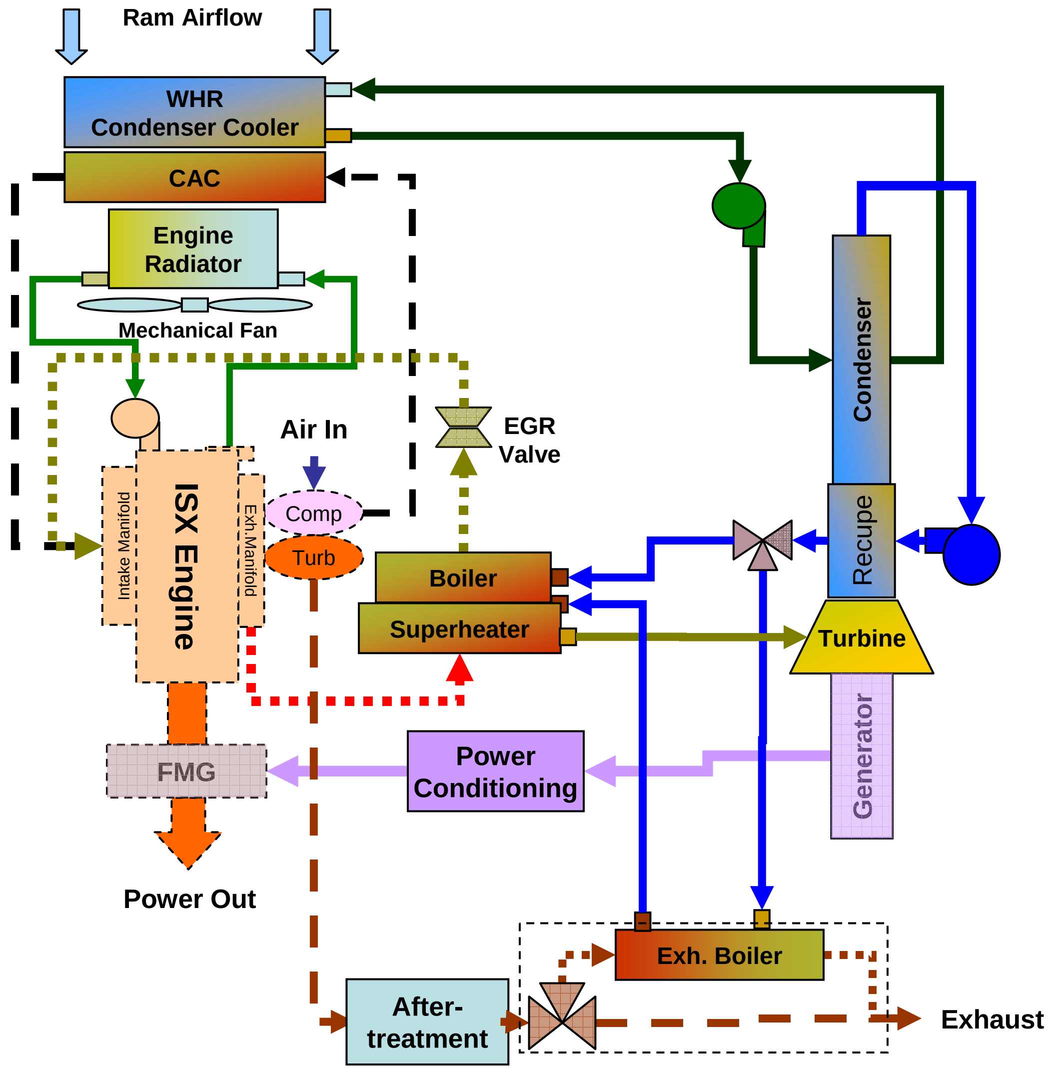
6% from EGR energy

+ 2% from Exhaust

+ 2% from Electric Acc.

10% Improvement

Our hardware results showed that our predictions were valid and realistic



Original System Architecture Plans and Assumptions

A low engine-out NOx combustion recipe was a key ingredient of the original proposal

- 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 – 6% recovered from EGR along with first prototype hardware
- Additional energy was recovered from the engine's main exhaust gas stream to keep the system at its full potential – we hit our predicted 2% additional benefit target
- System performance was limited to the heat rejection capacity of a MY2007 Class 8 tractor

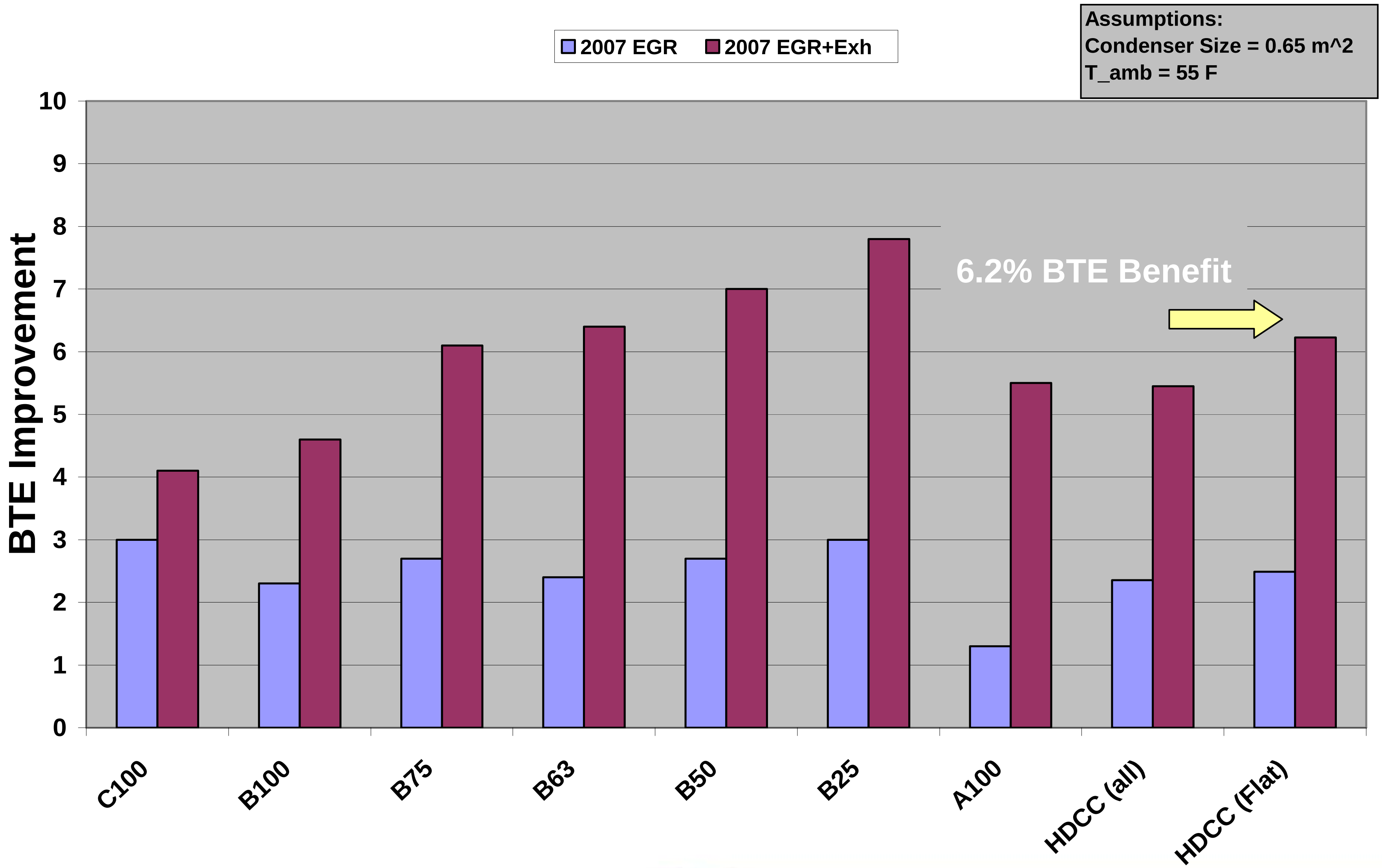
Engine Architecture Changes

▪ Affect of SCR Aftertreatment

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

Our recipe to maximize the recovery of EGR and Exhaust Gas heat within the limit of the vehicle's cooling module capacity was therefore tuned for performance with lower EGR flow:

Test Results from ISX'07



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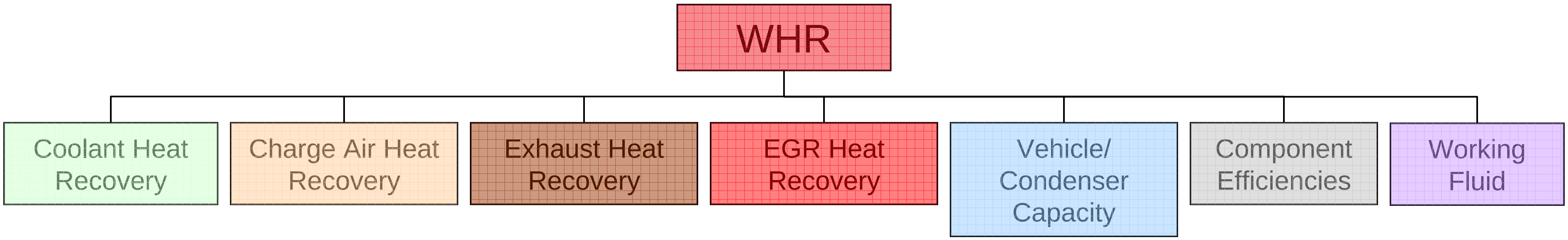
Engine Architecture Changes

Optimization of SCR aftertreatment will further erode the benefit of EGR-based energy recovery

- Engine-out NOx levels will rise with SCR conversion efficiency improvement, however a significant level of EGR will remain
- We have demonstrated how we can tune an engine-integrated ORC system to recover energy and provide a benefit within the confines of the existing heat rejection space on-vehicle

We therefore investigated to determine the realistic potential of ORC energy recovery –

ORC Energy Recovery Potential



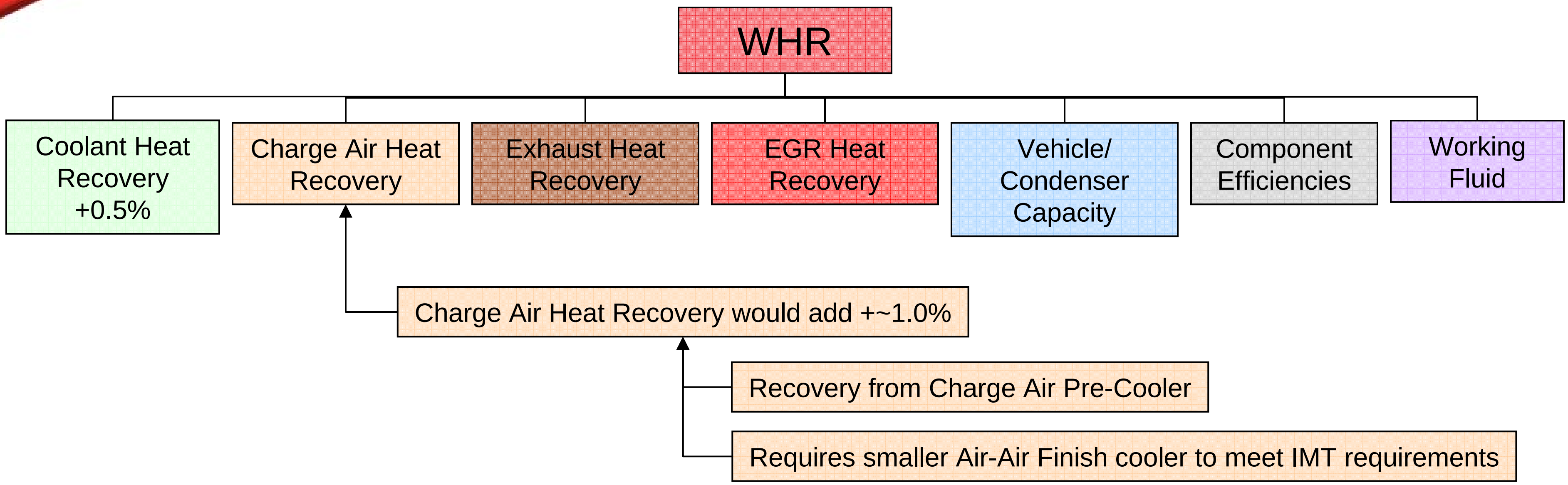
ORC Energy Recovery Potential

- WHR
  - Coolant Heat Recovery
    - From bulk coolant at 200F
      Potential for + ~0.5% 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
      - Very low potential benefit for extra system cost/complexity
  - Charge Air Heat Recovery
  - Exhaust Heat Recovery
  - EGR Heat Recovery
  - Vehicle/ Condenser Capacity
  - Component Efficiencies
  - Working Fluid

The potential recovery benefit from bulk coolant flow represents only what may be accomplished with existing architecture (AEG or non-boiling, water-based cooling).

Data updated from SMMR material

ORC Energy Recovery Potential



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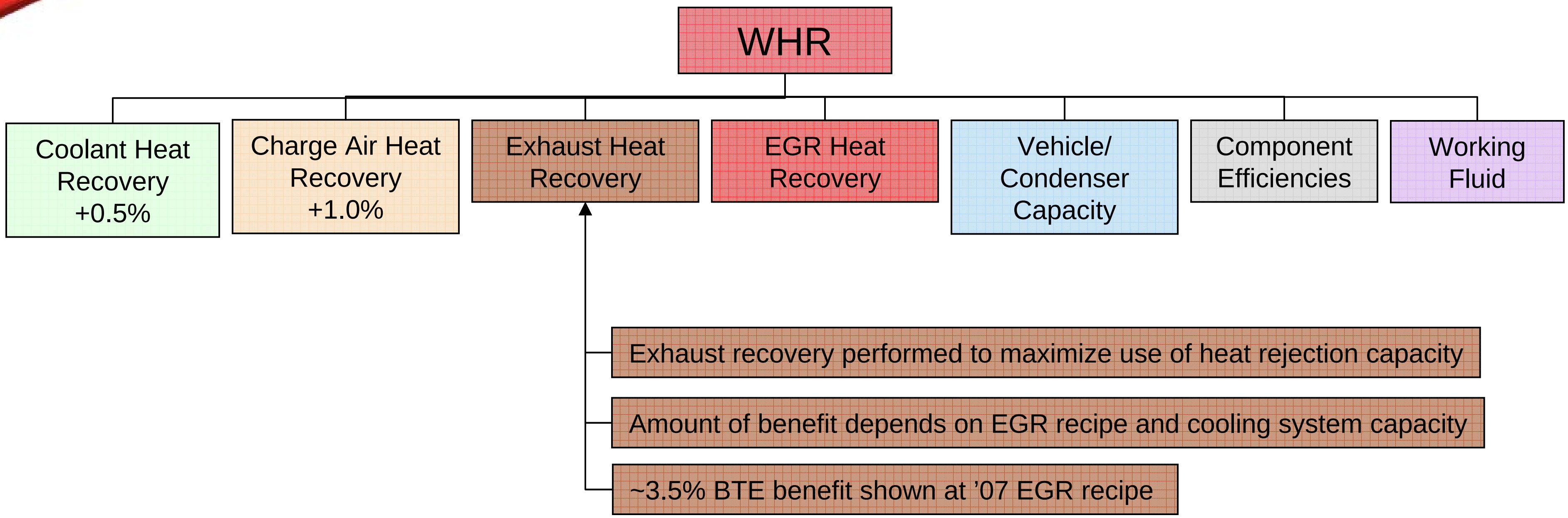
ORC Energy Recovery Potential



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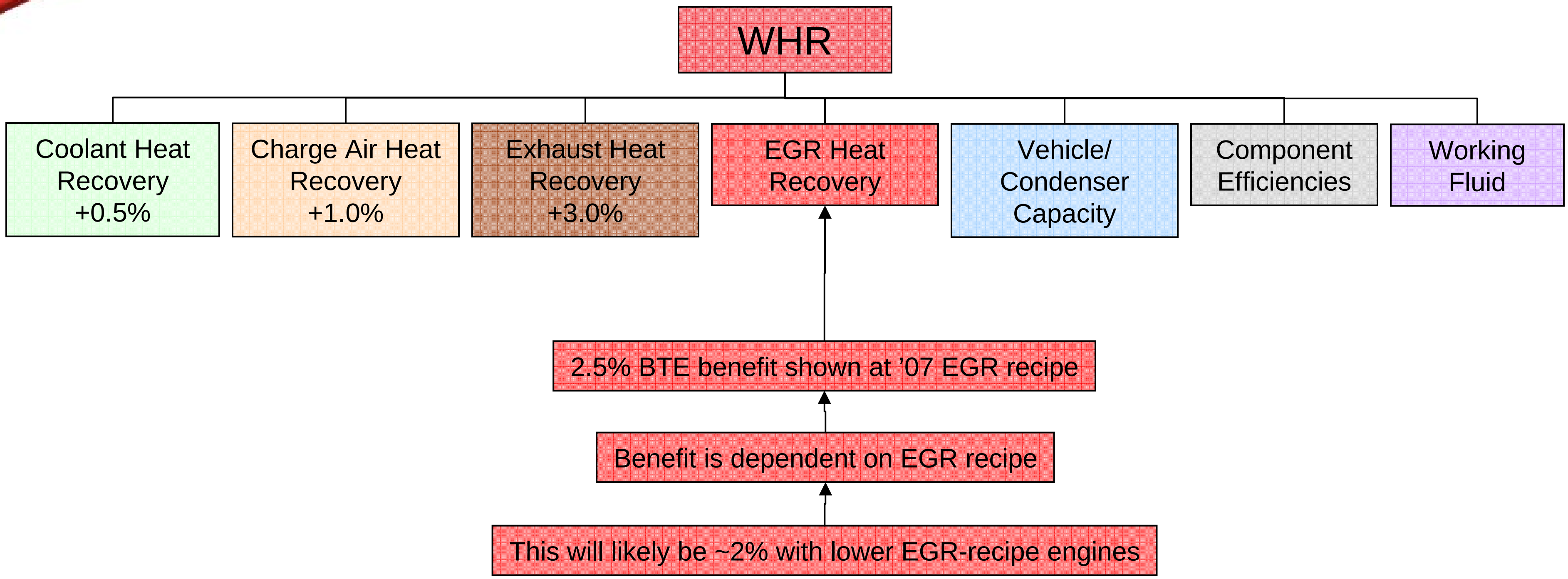
ORC Energy Recovery Potential



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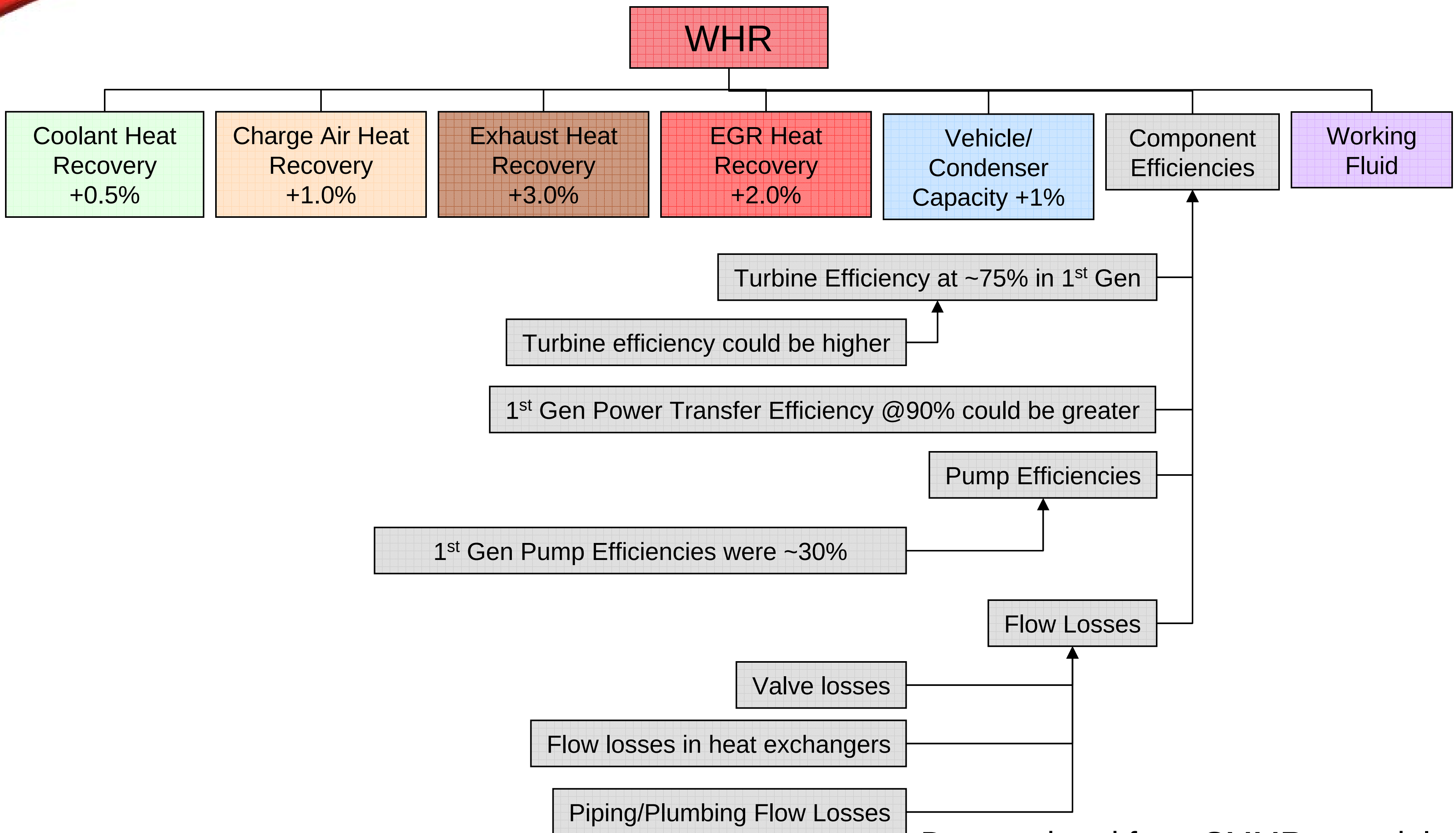
ORC Energy Recovery Potential

WHR

- Coolant Heat Recovery +0.5%
- Charge Air Heat Recovery +1.0%
- Exhaust Heat Recovery +3.0%
- EGR Heat Recovery +2.0%
- Vehicle/ Condenser Capacity
  - Doubling '07-based condenser size adds ~2% benefit
  - Assume 1% benefit is realistically achievable
  - Dependent on OEM Capability
- Component Efficiencies
- Working Fluid

Data updated from SMMR material

ORC Energy Recovery Potential



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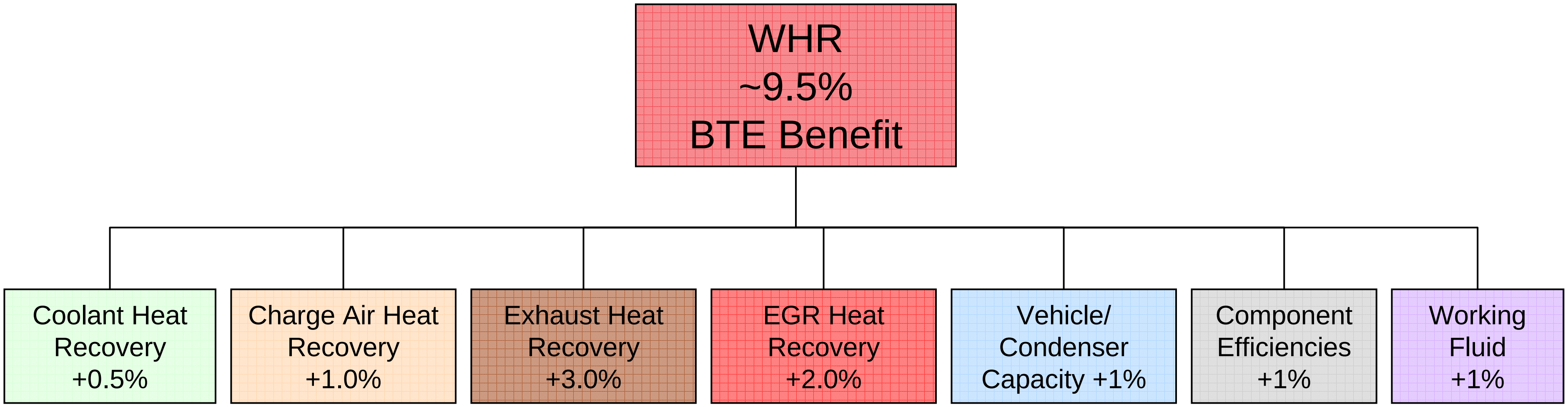
ORC Energy Recovery Potential

- WHR
  - Coolant Heat Recovery +0.5%
  - Charge Air Heat Recovery +1.0%
  - Exhaust Heat Recovery +3.0%
  - EGR Heat Recovery +2.0
  - Vehicle/ Condenser Capacity +1%
  - Component Efficiencies +1%
  - Working Fluid
    - Performance is limited by fluid's peak temperature
      - Controls Refinement would allow operating much closer to breakdown limit
      - Operating at significantly higher fluid temp may achieve 1% benefit
      - <u>Higher temperature robustness must be demonstrated long-term</u>

Data updated from SMMR material

ORC Energy Recovery Potential



Nearly a 10% performance improvement is possible – though with high additional cost and system complexity

Future development must focus on the most promising and realistic potentials energy recovery sources -

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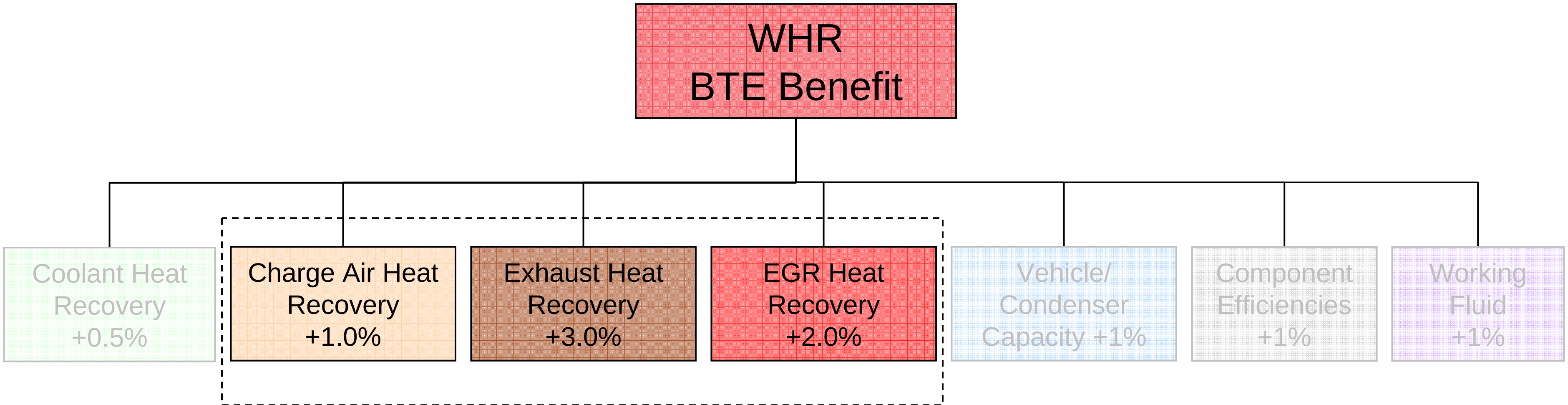
ORC Energy Recovery for 2nd Generation Development



Next generation development will target the highest-return recovery opportunities – EGR, Exhaust and Charge Air – the hottest waste heat streams on the engine

- Vehicle Condenser Capacity benefit is dependent on vehicle installation
- Component and fluid improvements remain to be demonstrated

Cost will remain a key focus

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
- Successfully delivered our original model-based predictions for system performance
- Identified areas for system improvements/optimization
- Identified avenues for development towards the 10% Goal
- We continue to work towards a practical implementation of ORC-based WHR to complement future engine development programs

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

Thank You!