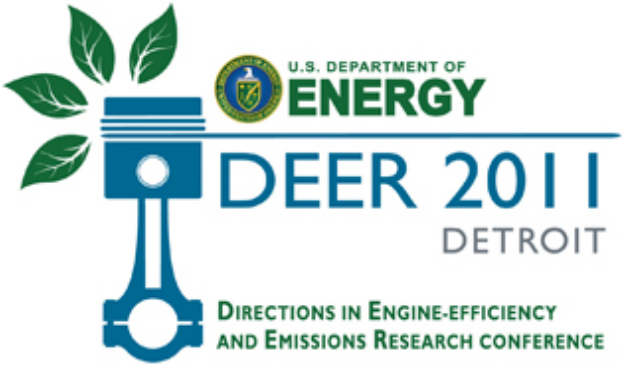
DAIMLER

DETROIT DIESEL

Exhaust Heat Driven Rankine Cycle for a Heavy Duty Diesel Engine



October 5, 2011

Rakesh Aneja, Sandeep Singh, Kevin Sisken

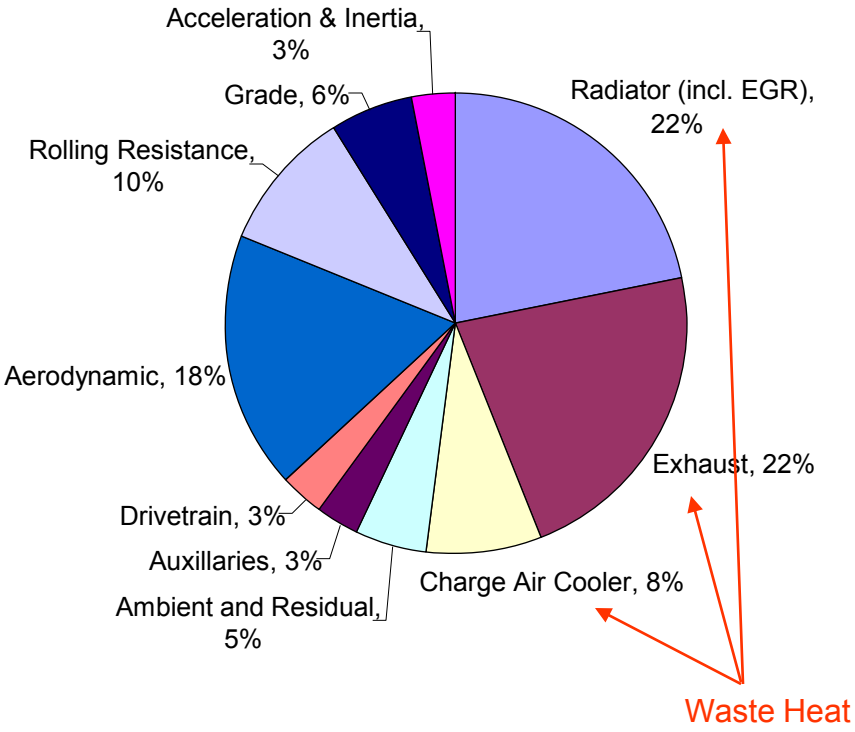
Detroit Diesel Corporation

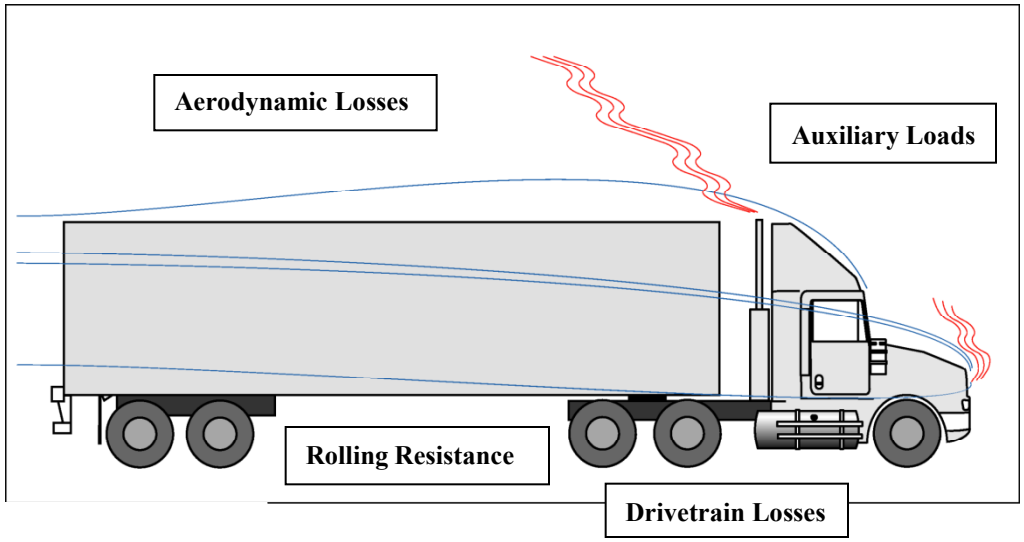
Roland Dold, Heijo Oelschlegel

Daimler AG

Waste Heat Recovery (WHR) Fuel Economy Targets

- Improve fuel economy 5%on a commercial heavy duty truck
- Improve engine brake thermal efficiency (BTE) by 3%points; contributing to overall goal of 50%engine BTE

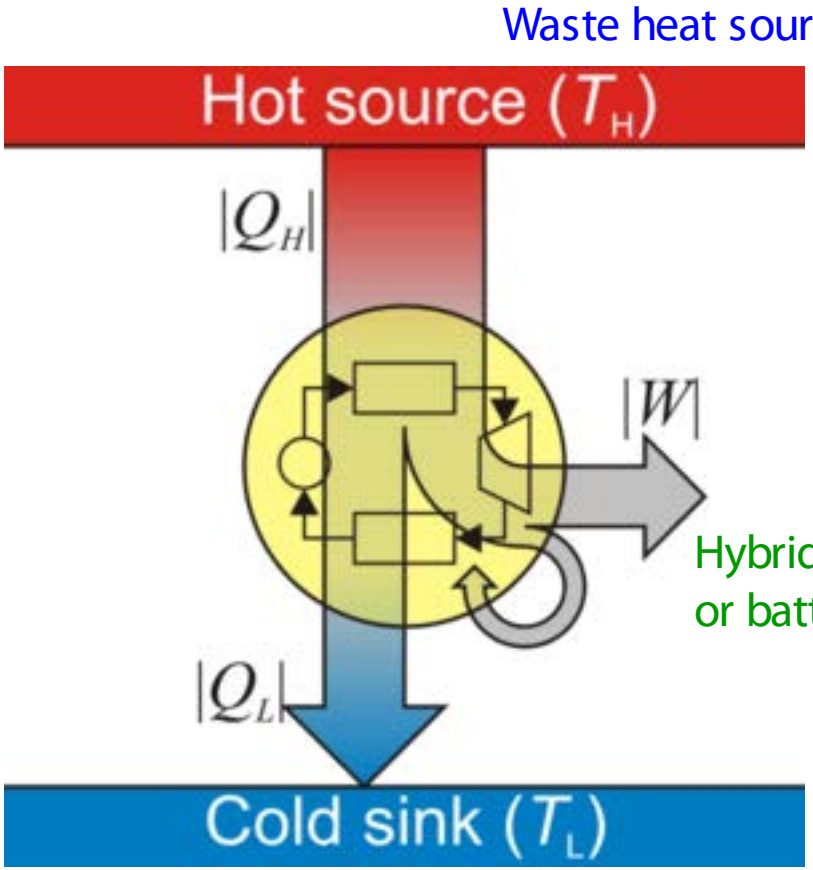




WHR Relevance and Motivation

- Daimler's Super Truck project to demonstrate technologies for 50% improvement in freight efficiency by 2015
- Daimler's goal to continuously improve fuel efficiency of its production vehicles
- EPA/ NHTSA legislation to reduce GHG emissions and improve fuel efficiency of on-road heavy duty vehicles
- Nation's energy independence

WHR Strategy – Heat Engine

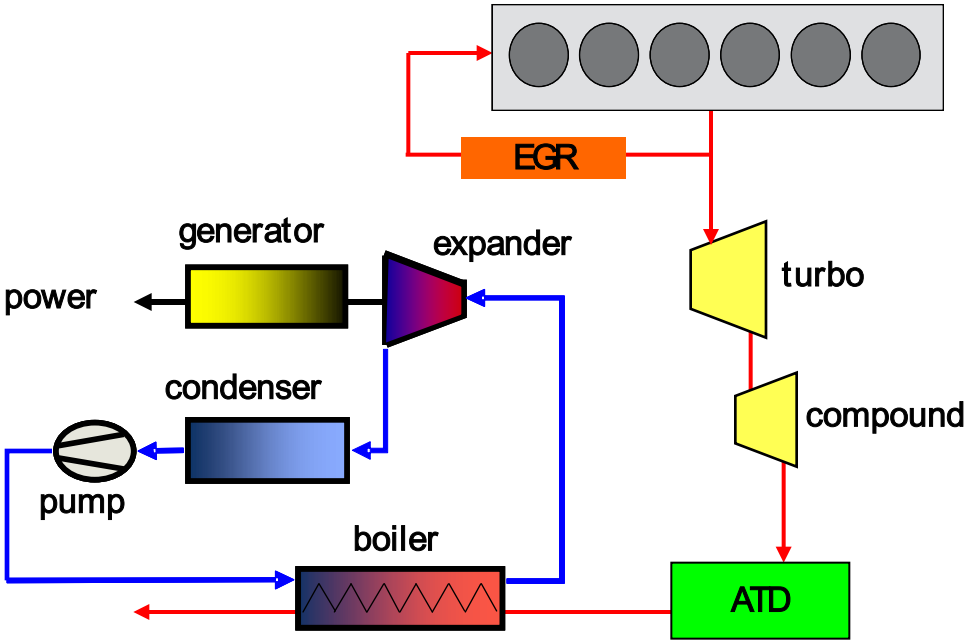


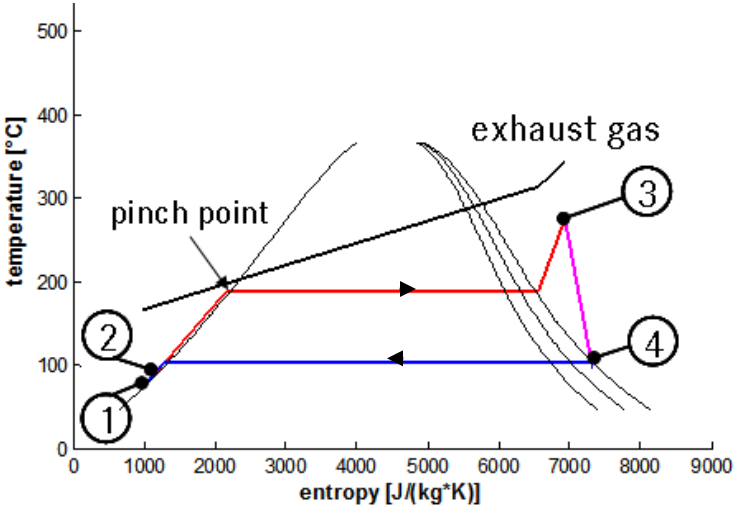
Waste Heat Sources	Quality	Quantity
Exhaust	High	High
EGR	High	Low
Coolant	Low	High
Intercooler	Low	Low

Heat engines…
- Rankine cycle
- Brayton cycle
- Stirling cycle
- …

Heat engine pictorial source: Wikipedia

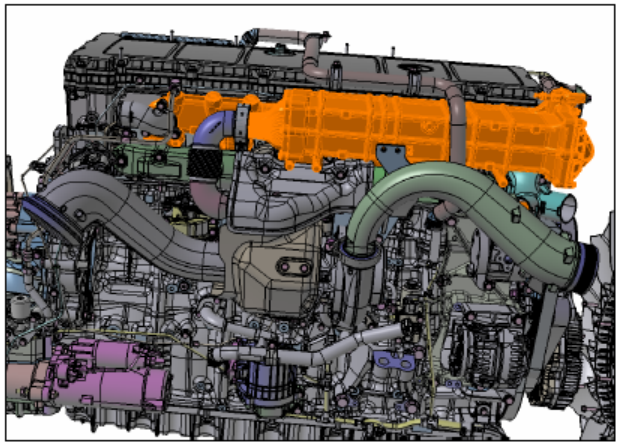
Exhaust Waste Heat Utilization – Rankine Cycle



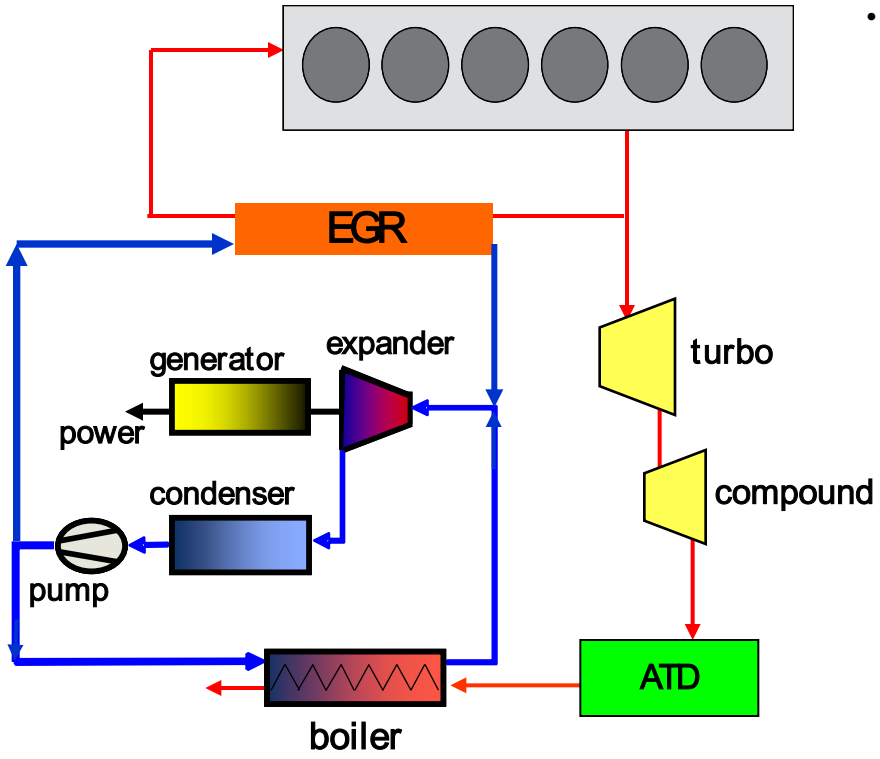


EGR Waste Heat Utilization

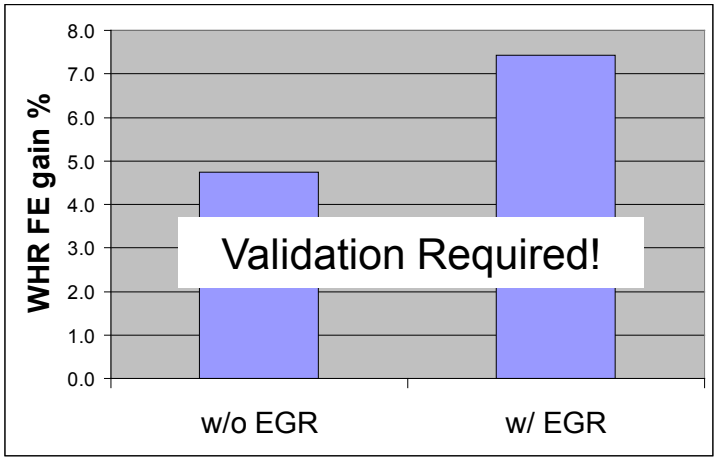
- High temperature, high quality
- Energy content contingent on matching of EGR, air and aftertreatment (ATS) systems
  - Low EGR – high efficiency ATS
  - High EGR – low efficiency ATS
- Smaller engine radiator, bigger Rankine condenser
- Can boost fuel economy advantage of WHR, but increased complexity



Is EGR WHR Required?



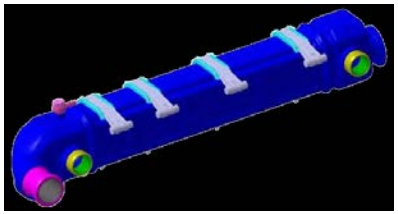
- EGR WHR increases design and control complexity
- Improvement in overall BTE
  - Simulations have been performed
  - Strong function of system efficiency and EGR flow rates



Rankine Major Components

Evaporators

Low pressure drop
Avoid local hot-spots

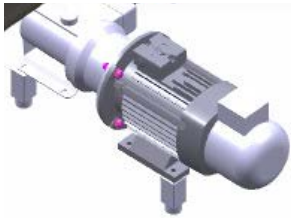


Expander

Handle 2-phase flow
Speed matched to generator
Hermetically sealed

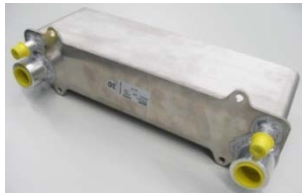
Working Fluid

Low environmental impact
Thermodynamically suitable
for Rankine cycle



Hermetically sealed

Pump



Indirectly cooled (not working fluid to air)
Matched to vehicle cooling capacity

Condenser

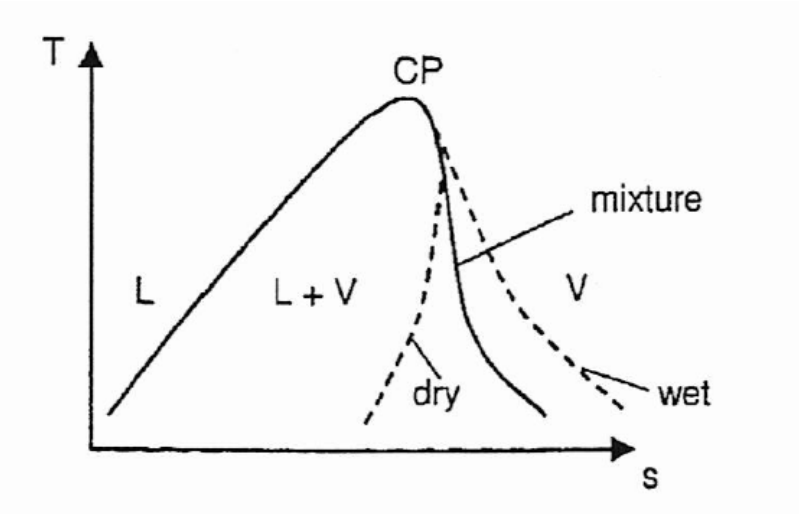
Expanders + Generators

- Several expander technologies have been studied: screw, turbine, piston, scroll, etc.
- Piston and scroll expanders are primary candidates
- Scroll expander
  - High efficiency
  - Hermetically sealed
  - Handles two-phase flow

- Piston expander
  - High pressure ratios
- Wound field synchronous generator (WFSG) for high voltage DC output to hybrid truck
- Magnetic coupling between generator and expander – simplifies sealing and design issues for generator

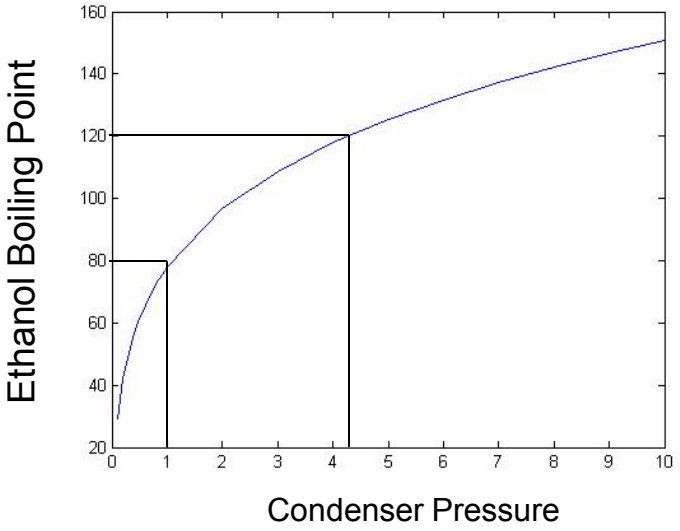
Working Fluid Selection

- Selection criteria …
  - Low environmental impact
  - Thermodynamic performance
  - Saturation vapor curve with positive slope
  - Acceptable operating pressures
  - High stability temperature
  - High vapor density
  - …
- Ethanol Selected



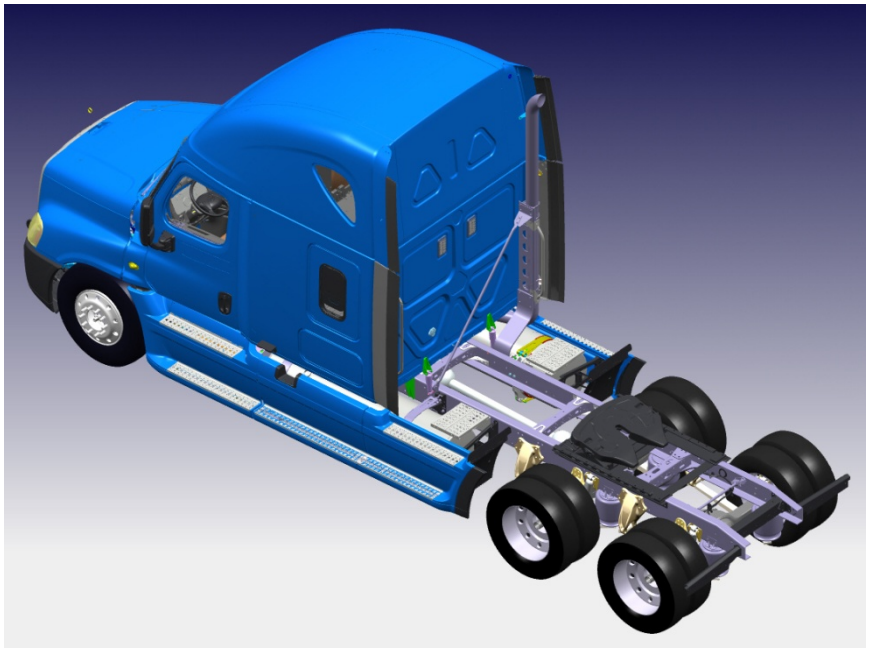
Condenser Cooling and Vehicle Impacts

- Significant under hood cooling burden
  - A portion of exhaust heat recovered as work
  - Majority tail-pipe exhaust heat rejected under hood
- Re-sizing and/ or addition of radiators, pumps, and fans required
- Engine coolant can be used for condenser cooling for certain working fluids and systems
- A low temperature cooling circuit is also being considered

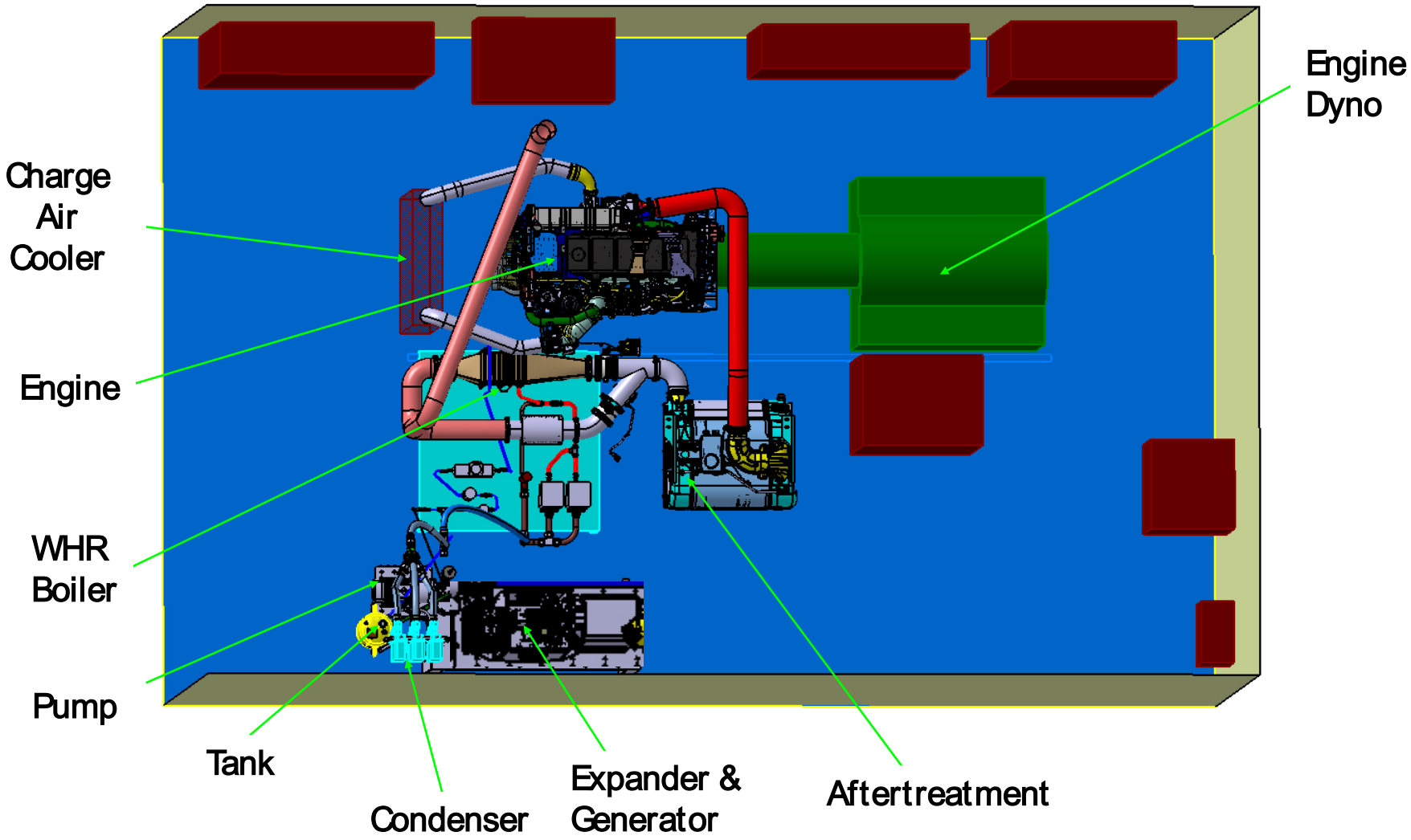


Vehicle Cooling Strategies

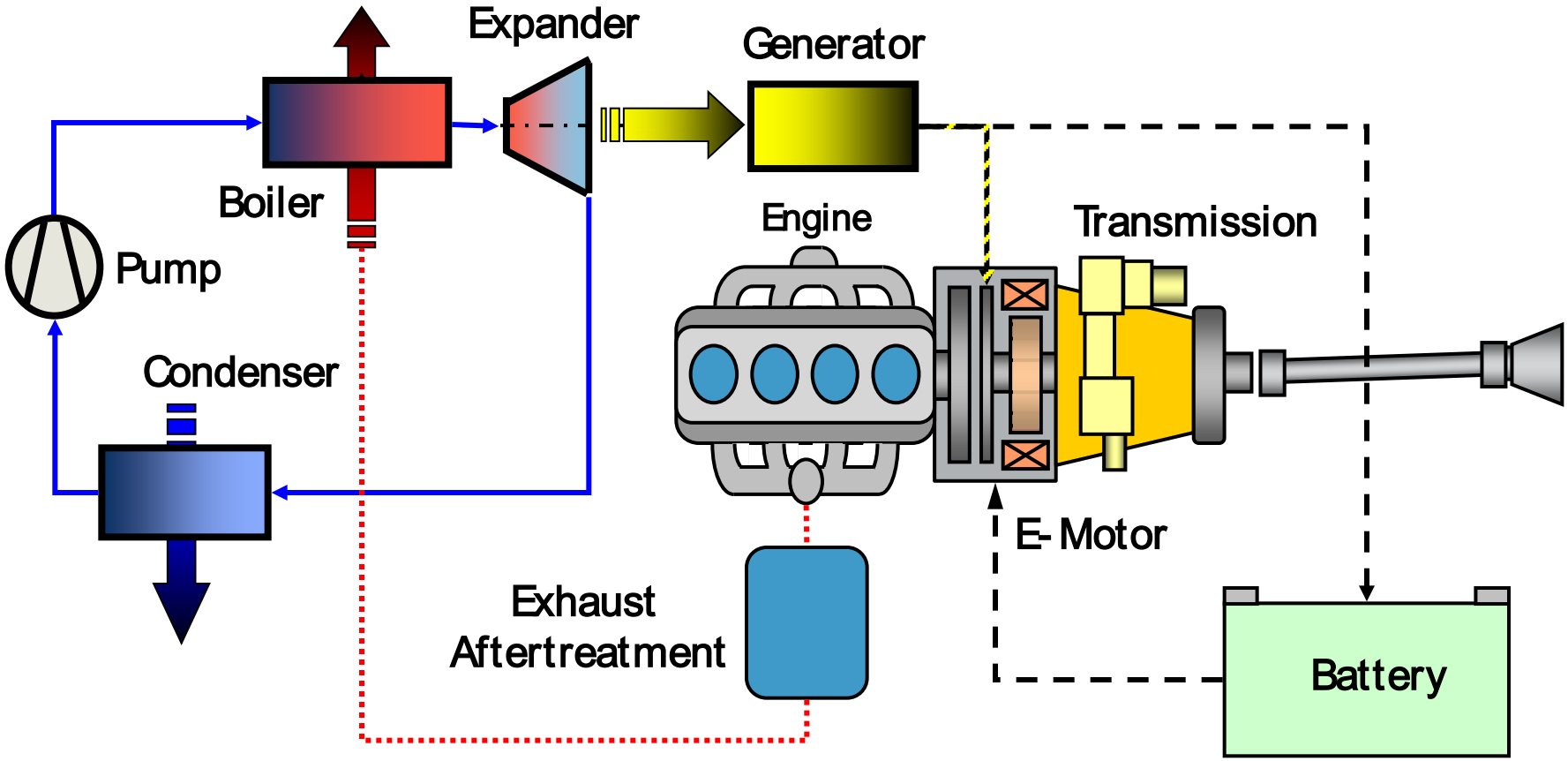
- Majority of former tail pile heat now rejected under hood
- Besides conventional ram air, alternate strategies can be considered
  - Under chassis
  - Side of the frame
  - Back of the cab
  - Etc.
- Trade-offs due to weight, packaging, special ducting, fan on time, and aero complexities



Waste Heat Recovery Test Stand



Power Generation and Hybrid Integration



Vehicle Integration & Challenges

- Vehicle integration is a very significant challenge
  - Increased tractor weight (+350 lbs = -1% fuel economy)
  - Packaging space
  - Condenser cooling
    - Cooling capacity will be challenged
    - Bypassing some waste heat is being considered
  - Integration of electrical power generation with a hybrid vehicle
  - Controls implementation and interactions

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