Heavy Duty Truck Engine

High Engine Efficiency at 2010 Emissions

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Background - Program Goals and Timing

Phase I

- Demonstrate
  - **45%** BTE
  - **2002** Emissions
    - 2.5 gm BSNOx
    - 0.1 gm BSPM

Complete

Phase IIA

- Demonstrate
  - **45%** BTE
  - **2007** Emissions
    - 1.2 gm BSNOx
    - 0.01 gm BSPM

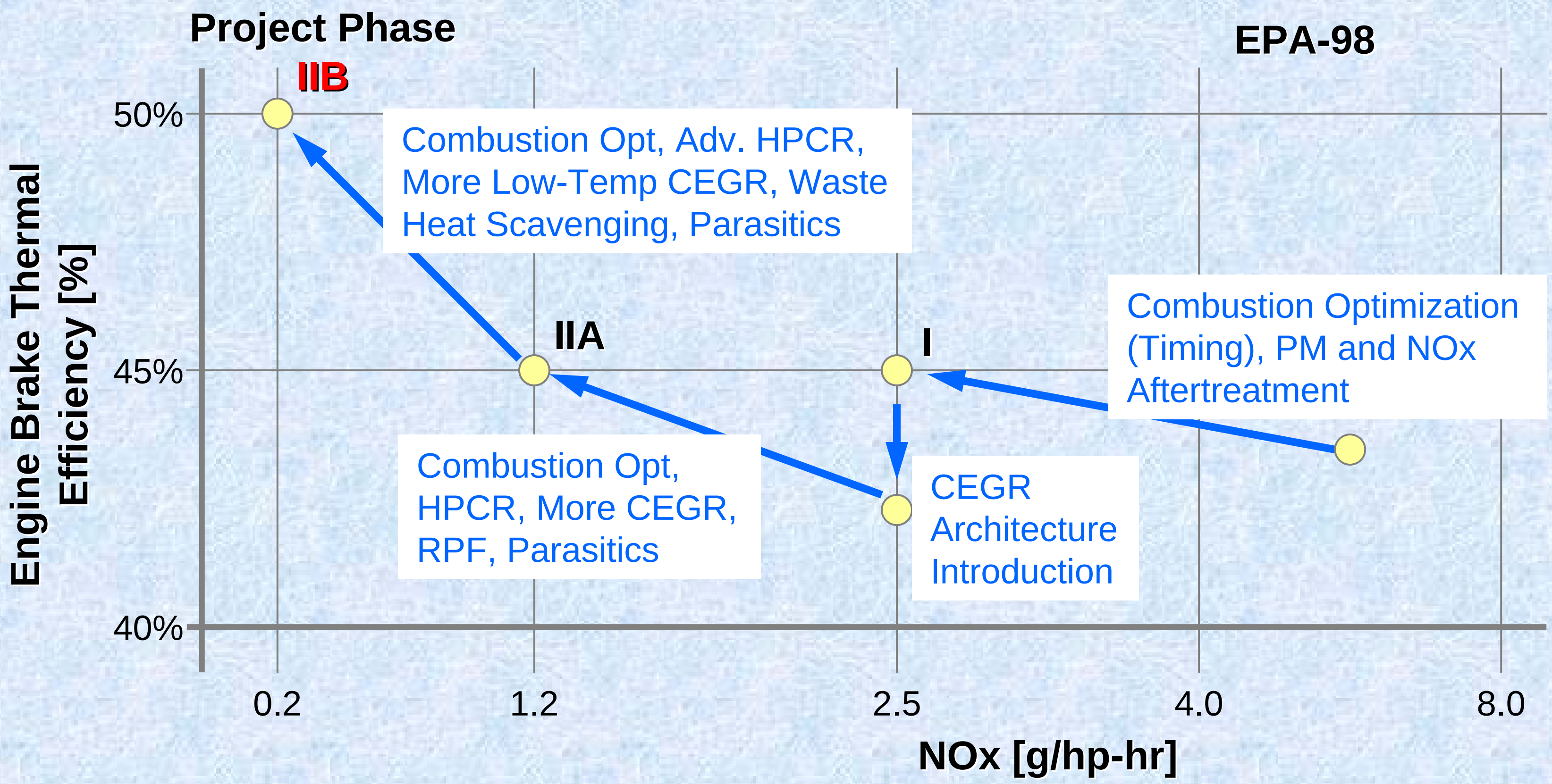
Complete

Phase IIB

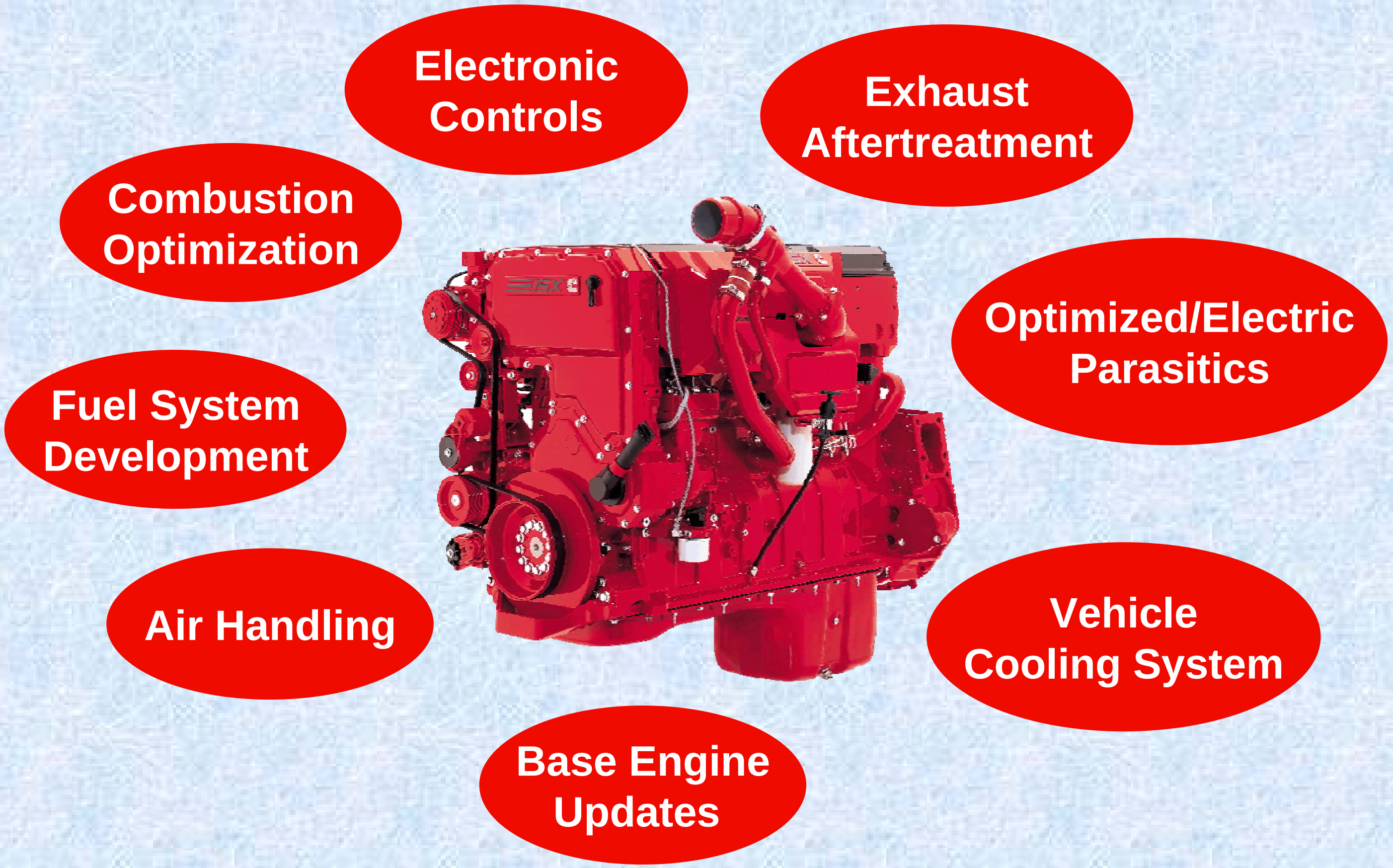
- Demonstrate
  - **50%** BTE
  - **2010** Emissions
    - 0.2 gm BSNOx
    - 0.01 gm BSPM

In-Progress

Program Technology Roadmap

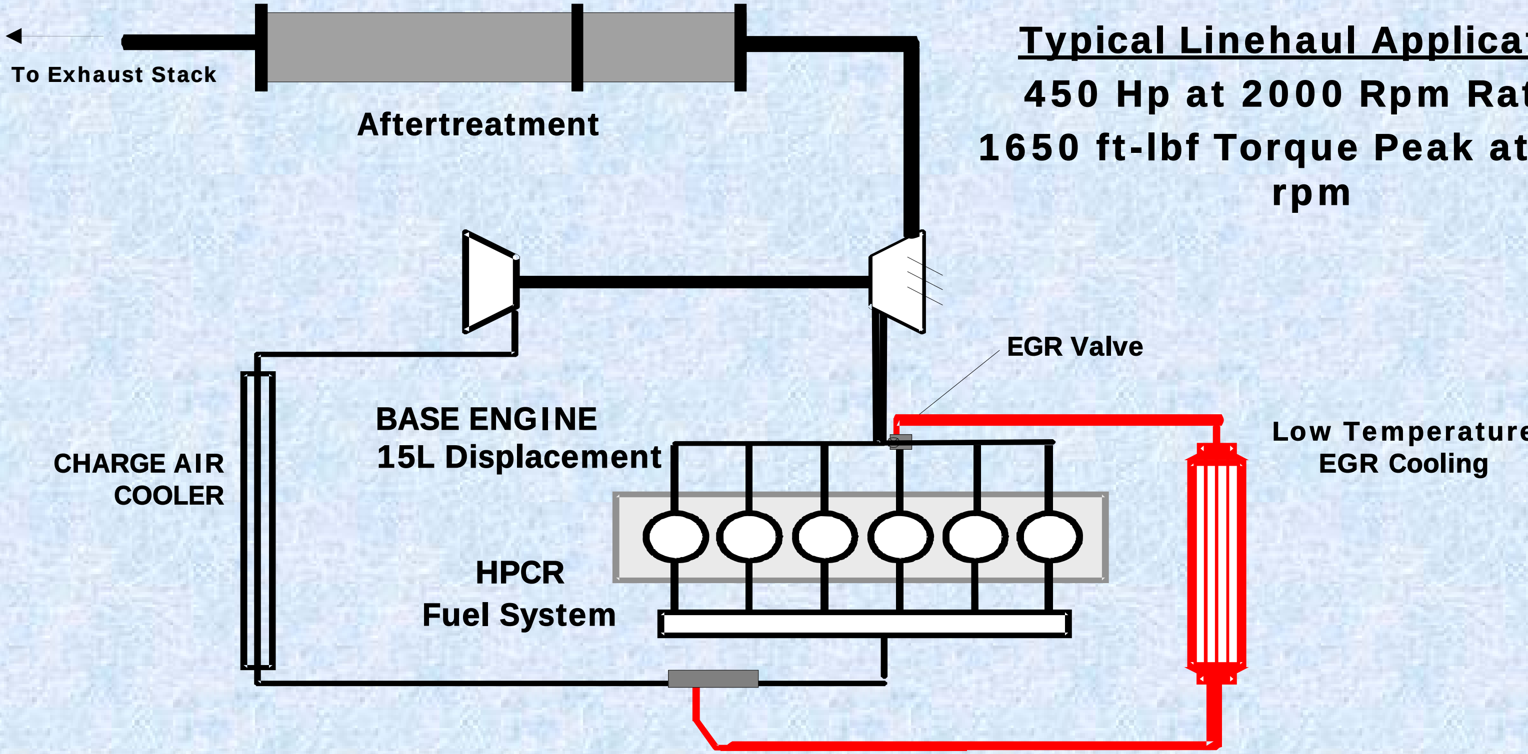


ISX Engine Architecture



System Integration is key

Ultra-Low NOx ISX: Phase IIB Demo - Base Engine Architecture



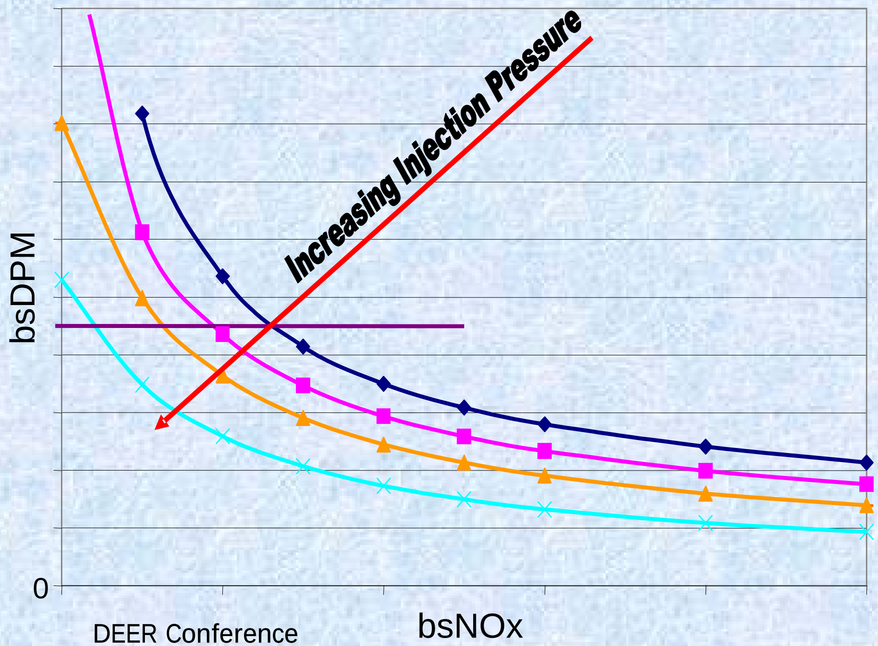
Typical Linehaul Application

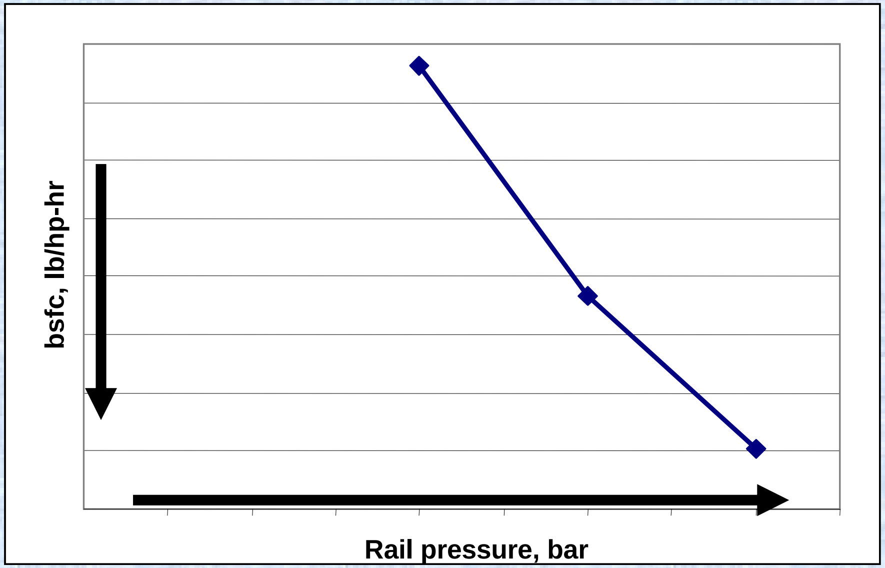
450 Hp at 2000 Rpm Rating

1650 ft-lbf Torque Peak at 1200 rpm

A combination of strategies is being investigated –

- Use of Pre-Mixed combustion to control NOx at light loads with conventional combustion at cruise/higher loads
- As NOx is reduced, higher injection pressure needed for smoke control and this improves fuel consumption
- Exploring higher pressures for better NOx control and fuel economy.
    - More NOx reduction in-cylinder will minimize aftertreatment needs/cost.





Aftertreatment Options

- NOx Reduction Techniques
  - Urea-SCR
  - NAC
- PM Reduction Technologies
  - Very similar to technology applied to Phase IIA.
  - Robust RPF (DOC and PF)

➡ Minimize Aftertreatment for lowest system cost/complexity/etc. while considering operating efficiency

Most fuel energy is 'unused' –

Brake Power ~	***42%***
Coolant Energy ~	***15%***
Charge Air ~	***8%***
Exhaust Gas ~	***19%***
EGR Gas ~	***13%***
Friction/Radiation~	***3%***
Total ~	***58%***

- ***Thermal Radiation***
- ***Requires big Radiators***

A solution that minimizes heat rejection needs while improving BTE would be *ideal*.

Energy Recovery Methods

Rankine Bottoming Cycle - Best overall

Also considered:

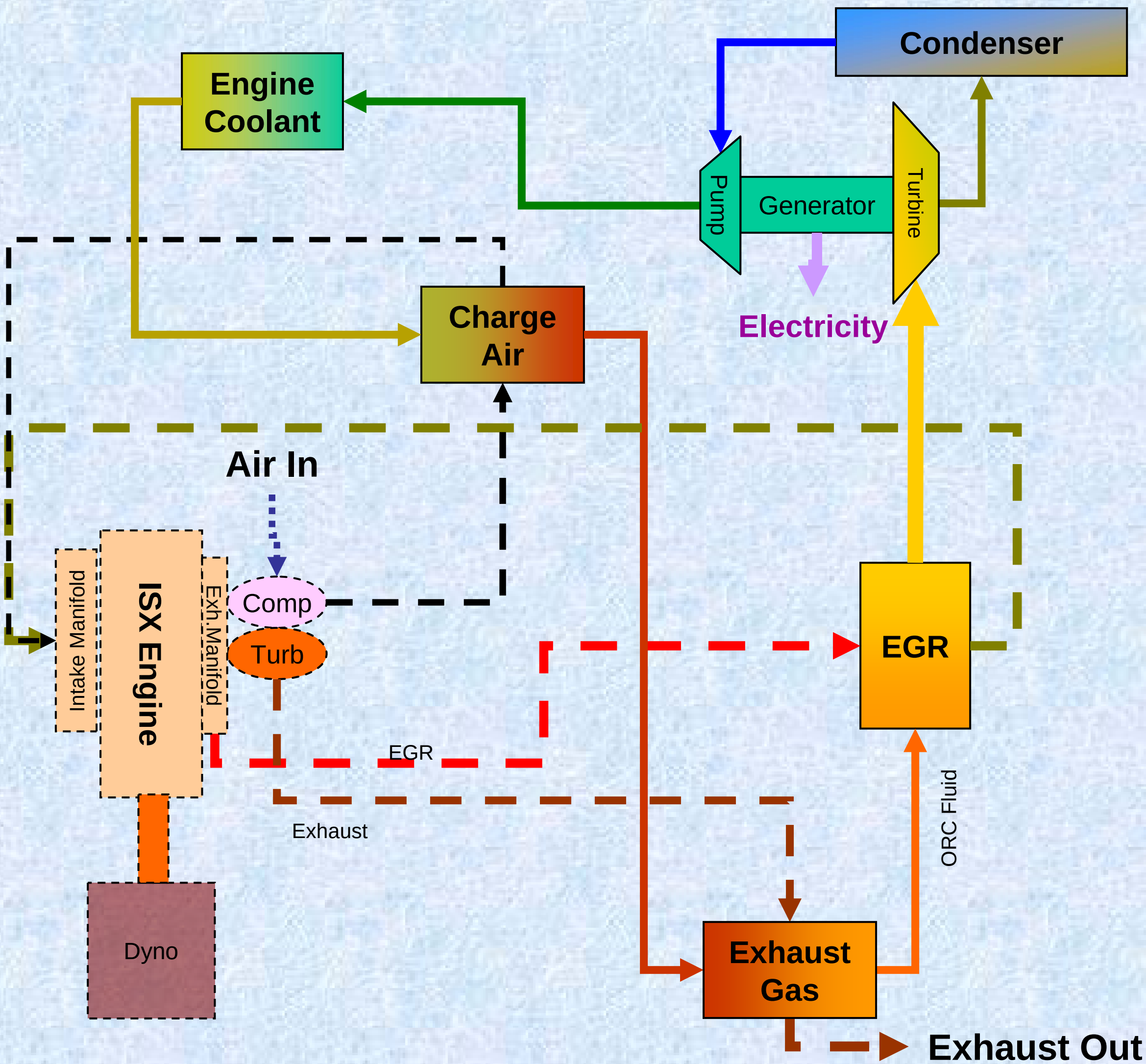
- Rankine Bottoming Cycle with Regeneration
  - More piping
- Rankine Bottoming Cycle with Reheat
  - Even more piping and more complex expansion device
- Thermoelectric recovery
  - Not enough power recovery possible for this project
- Turbocompounding – Mechanical
  - Available energy minimized by pre-turbo EGR, need remaining exhaust gas power for fresh air compression.
- Turbocompounding – Electrical
  - Available energy minimized by pre-turbo EGR, turbo-match for extra turbine power not possible
- Rankine Cycle AND Thermoelectric recovery
  - Most complex plumbing, biggest condenser, power mgmt.

Rankine Cycle Energy Recovery

- Practical and proven concept – Previous examples in literature, used in other industries
- Capable of recovering and delivering adequate power
- Available technology and methods which can be applied with little ‘new science’
- Addresses increases in heat rejection by capturing and converting thermal energy to useful power.
  - Longer term would help minimize radiator size increases.
- Would be appropriate for this high-BTE demonstration and later in-vehicle integration

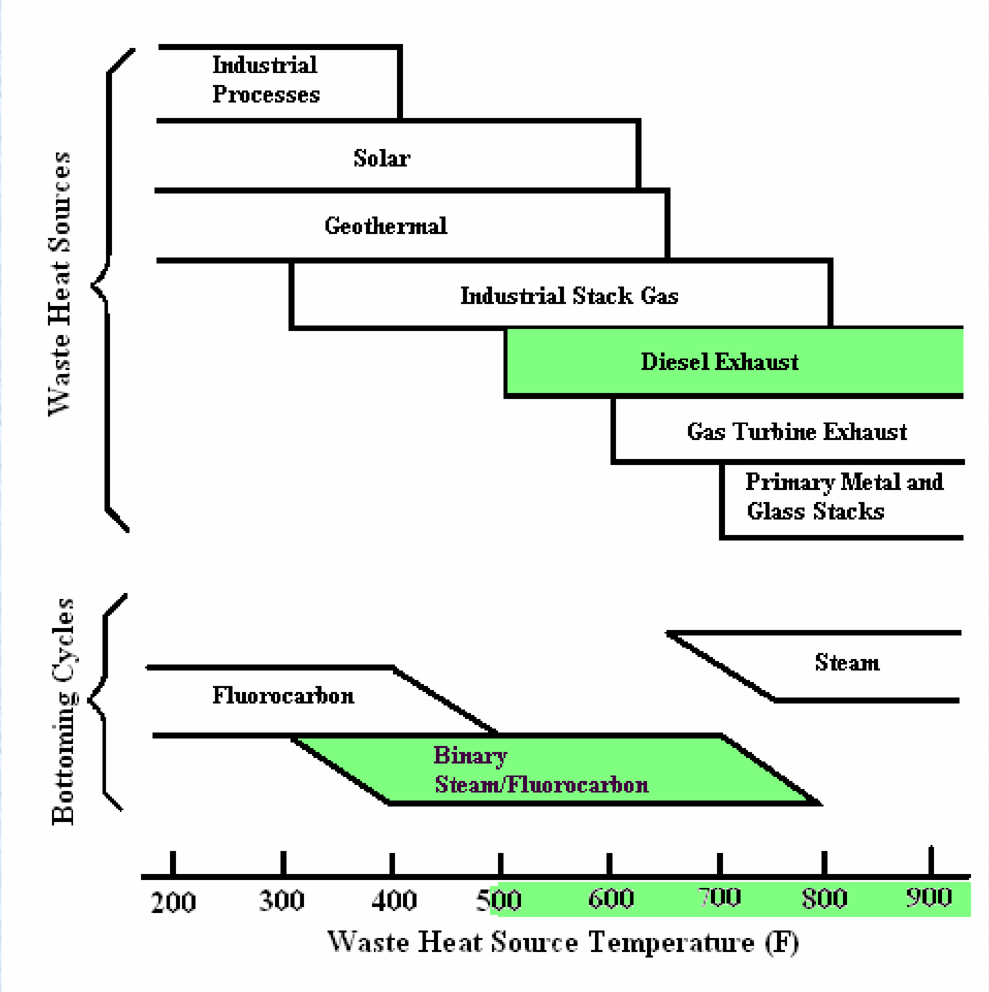
A good ‘carry-forward’ concept.

Lab Demonstration Schematic



Working Fluids

- Lower changes in specific volume
- High energy density
- Positive saturated vapor line slope
- High chemical/thermal stability
- Low toxicity
- Low flammability
- Appropriate Condensing Temp
- etc



Fluorinol

or 2,2,2 Trifluoroethanol

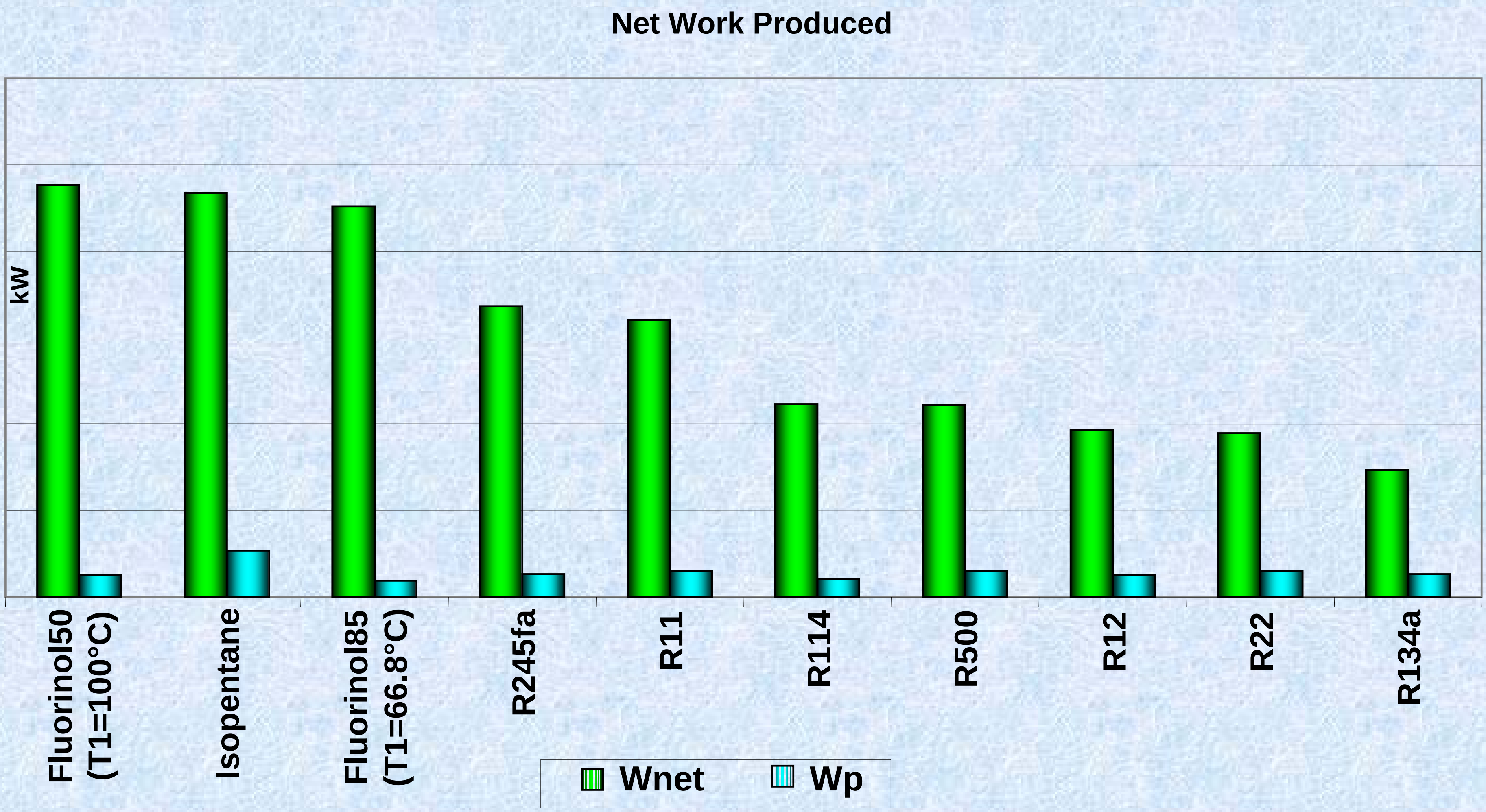
- CAS No. 75-89-8
- Molecular Weight 100.04
- Chemical Formula – F_3CCH_2OH
- Flammable Liquid / Vapor
- More toxic than Ethlyene Glycol

Excellent heat transfer properties with a high thermal stability - >550F

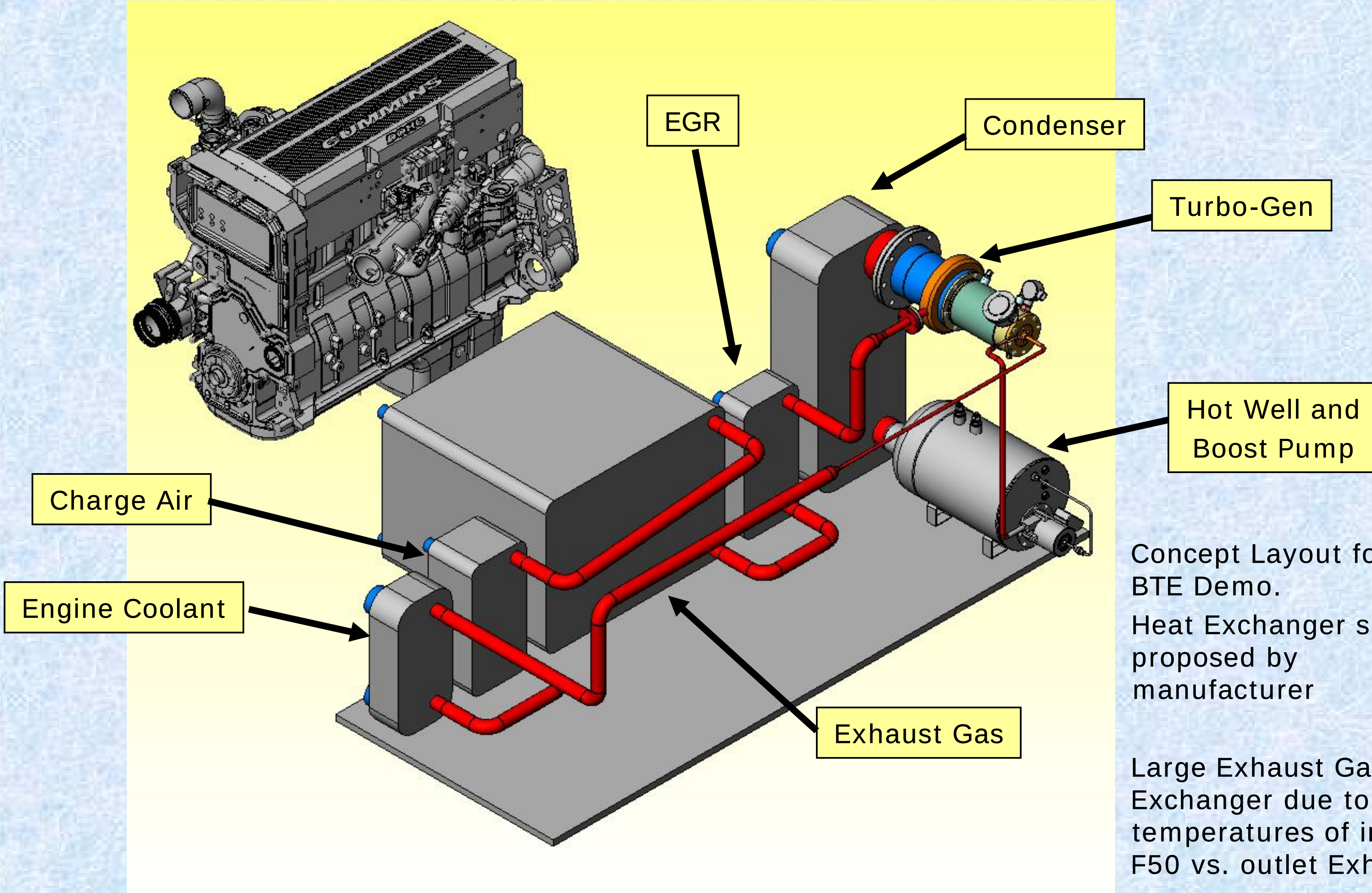
<u>Fluorinol-50</u> (50-50 molal mix of Fluorinol and Water) provided the best performance -

Working Fluid Comparison

Compared on the same cycle with the same heat, Fluorenol-50 was the clear winner -



Engine-Heat Exchanger Comparison
Maximum BTE Demo



Concept Layout for Max. BTE Demo.

Heat Exchanger sizes proposed by manufacturer

Large Exhaust Gas Heat Exchanger due to temperatures of inlet F50 vs. outlet Exhaust

Turbine Generator

50,000 rpm Design Point Speed

400-450 VAC output

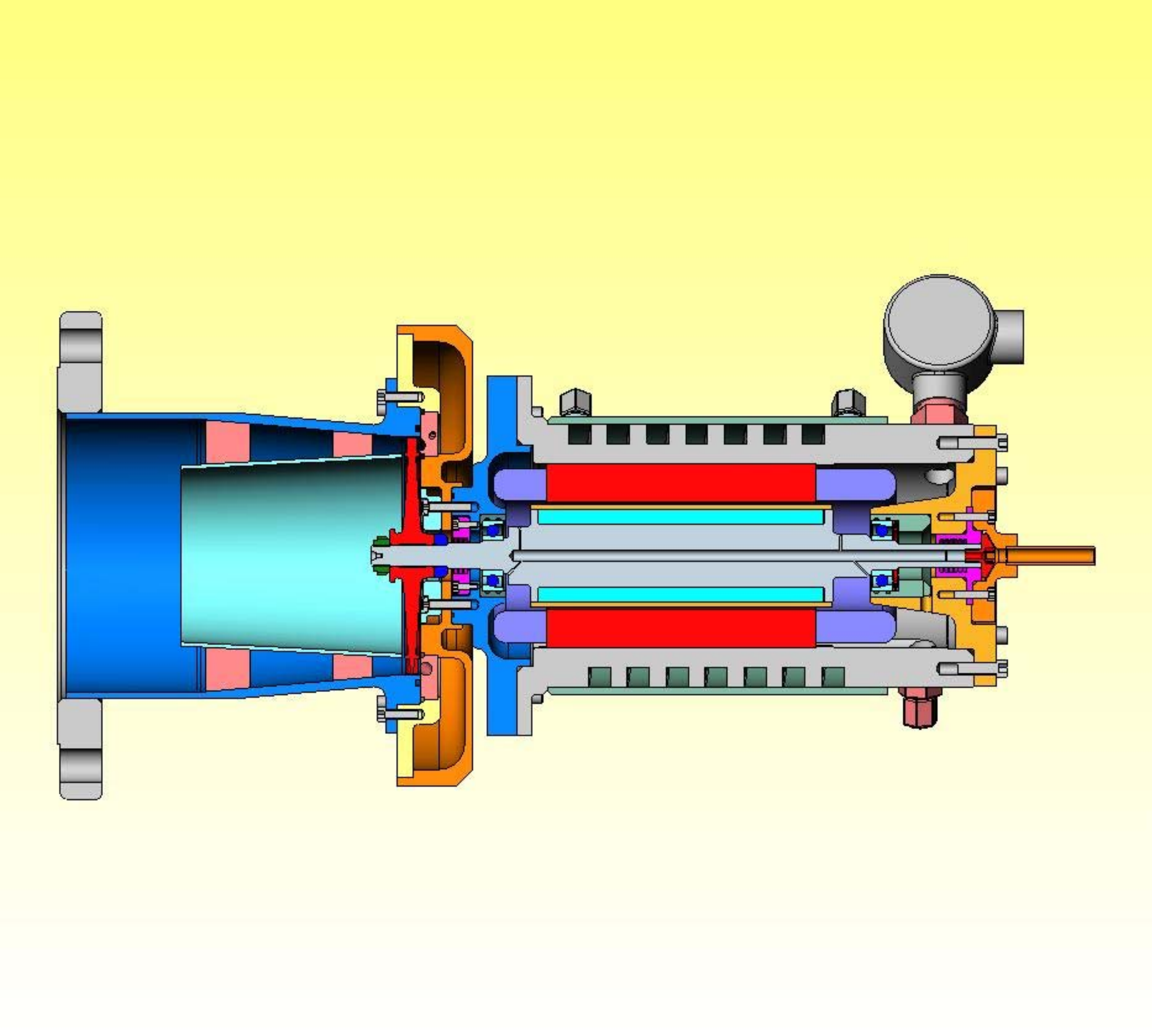
Target Power ~45kWe

77% Turbine Efficiency anticipated at design point.

Fixed nozzle, axial inflow turbine

Fluorinol-cooled bearings and generator

This unit is not designed for in-vehicle application.



Maximum BTE Demonstration Plan

- Single Operating Point Demonstration for Maximum BTE
  - Study currently underway to identify optimum engine operating point to yield maximum recoverable thermal energy.
    - High Engine Efficiency with High Temperature Gas Flows.

- In-Vehicle Demonstration Planned for Base Engine
  - Drivable engine system that meets 2010 emissions is planned
  - Vehicle Integration is now beginning

Summary and Conclusions – Key Work Completed to Date

For Program Phase II B

Base Engine Development

- Base Engine Demonstration Architecture Determined
- Combustion and Air Handling Optimization Proceeding
- Aftertreatment System Studies Underway

Waste Heat Recovery

- Methods analysis and evaluation carried out.
- Working Fluid analysis and evaluation carried out
- System Cycle analysis and Base Engine modeling completed

Thanks to our Sponsors!

Cummins Inc. thanks –

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