2014 DOE Vehicle Technologies Program Review

Heavy Duty Roots Expander Heat Energy Recovery (HD-REHER)

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Eaton Corporation

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Project ID # ACE088

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Overview

Timeline

- Project Start Date: 04/01/2013
- Project End Date: 03/31/2014
- Percent Complete: 70%

Budget Period	Start Date	End Date	% Complete
Phase 1	04/01/2012	03/31/2013	**100**
Phase 2	04/01/2013	03/31/2014	**100**
Phase 3	04/01/2014	03/31/2015	

Budget

- Total Project Funding: $3,357,479
  - DOE Share: $2,500,000
  - Contractor Share: $857,479
- Funding received in FY13: $724,598
- Funding for FY14: $307,284

Challenges

- Improve heavy duty engine efficiency (improvement $\geq$ 5 %) through WHR systems
- Engine efficiency improvement without NOx and PM penalty
- Highly durable waste heat recovery system
- Cost effective ORC system by roots expander

Partners

- Project lead: Eaton Corporation
- Collaborations:
  - AVL Powertrain Engineering
  - John Deere
  - Electricore, Inc

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Relevance
Objectives of this study

Program Objectives

- Demonstrate heavy duty diesel engine fuel economy improvement through "Roots Expander Organic Rankine Cycle Waste Heat Recovery Systems":
  - 5% improvement in fuel economy and reduction in greenhouse gas emissions
- Demonstrate that other pollutants, such as NOx, HC, CO and PM will not be increased as part of the overall engine/WHR/exhaust after treatment optimization
- Minimize ORC system cost through implementation of a lower speed roots expander
- **Phase 2 Objectives**
- Prototype and evaluate the single stage roots expander performance using air bench testing.
- Validate the performance of single stage roots expander design in a water-based ORC system.
- Design and optimize a robust, multistage roots expander for ORC system.
- Model, design and optimize heat exchangers to maximize system performance.

Milestones

Month/Year	Milestone	Status
July 2012	Baseline engine characterization (EGR, injection timing, AFR and back pressure)	Completed
Nov. 2012	WHR architectures evaluation through simulation	Completed
Jan. 2013	Single stage roots expander design and components selection	Completed
July 2013	Single stage roots expander prototyping and testing	Completed
Nov. 2013	Three stage roots expander design	Completed
Apr. 2014	WHR components (expander, heat exchangers, working fluid pump) prototyping and procurement	Completed
FY 14 - 15	**Heat exchangers and other ORC hardware integration in John Deere heavy duty diesel engine and testing**	**In Progress**

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Approach / Strategy

- Using baseline 13.5L John Deere HD diesel engine, characterize and quantify the potential waste energy sources for construction of thermodynamic analysis models - **2012** (**Complete**)
- Evaluate different roots expander ORC WHR system architectures theoretically and finalize optimized system (assess heat exchanger layouts on system performance, leading to specifications of roots expander and other required WHR system components) - **2013** (**Complete**)
- Develop and test expander (utilize CFD analysis, bench testing, calibration, and validation to maximize efficiency and durability) - **2013 and 2014** (**In Progress**)
- Test roots expander ORC system on engine and compare to baseline engine performance - **2014 and 2015** (**Planned**)

Technical Accomplishments and Progress

Accomplishments (2012):

- Completed engine baseline and sensitivity testing (EGR sweeps and exhaust restriction sensitivity)
- Analytical investigation completed – predicted ~6% F.E. improvement for roots-based Rankine cycle system with ethanol working fluid

Accomplishments (2013):

- Prototyped and air tested the single stage roots expander.
- Built and validated ORC test stand for water or ethanol usage.
- A single stage roots expander with water as Working Fluid (WF) was tested.
- Designed multi-stage expander and completed components procurement.
- Selected heat exchanger vendor, completed specification, and kicked-off procurement.
- Completed packaging study of entire ORC system on engine.

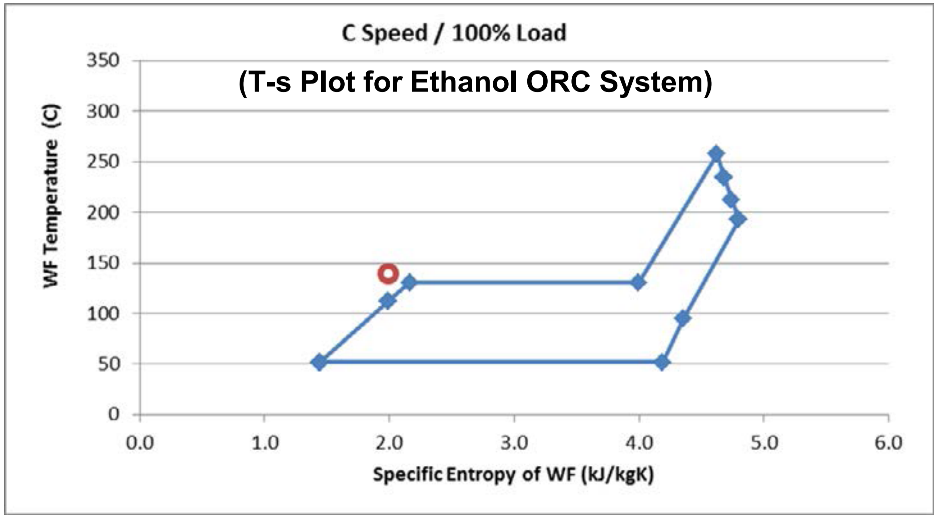
Projected Accomplishments (2014):

- Build and test the three stage roots expander on the Eaton ORC test stand.
- Assemble and test roots expander ORC system on John Deere 13.5L engine.

Technical Accomplishments and Progress - ORC Working Fluid (WF)

ORC thermodynamic analysis has been updated

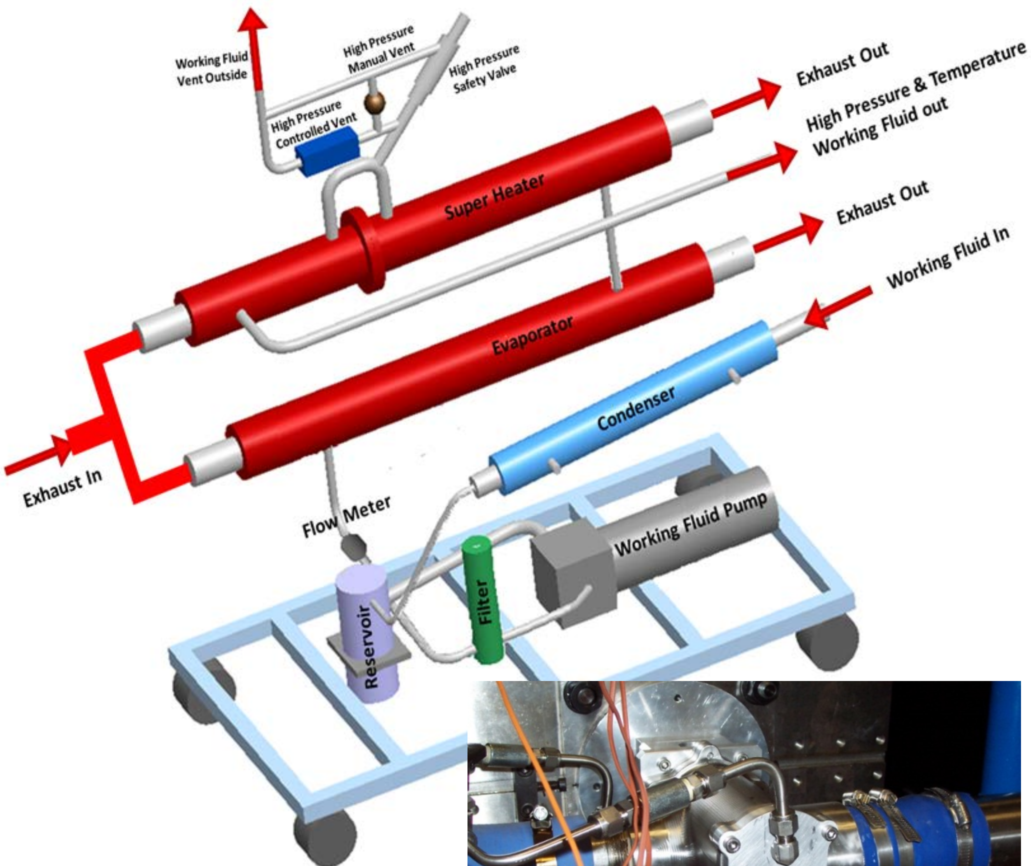
- Thermodynamic properties of WF have been updated from RefProp (NIST).
- The update allowed for detail investigations of different WF combinations.

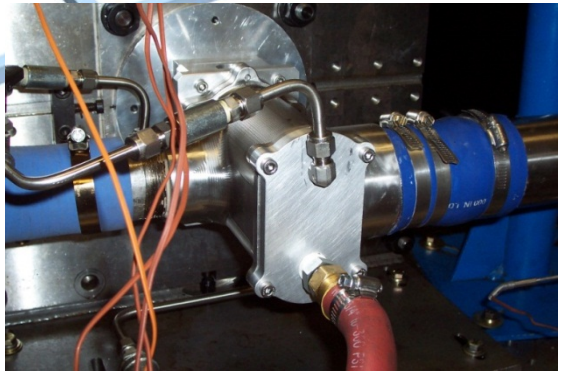


The red circle shows EGR gas temperature at the exit of the EGR heat exchanger

- Roots expander with water as ORC fluid was investigated (**DOE-AMR, reviewer's suggestion**).
  - Water as a WF does not achieve as high a BSFC as ethanol based on the current analytical model (**2.5 to 4%** BSFC improvement analytically)

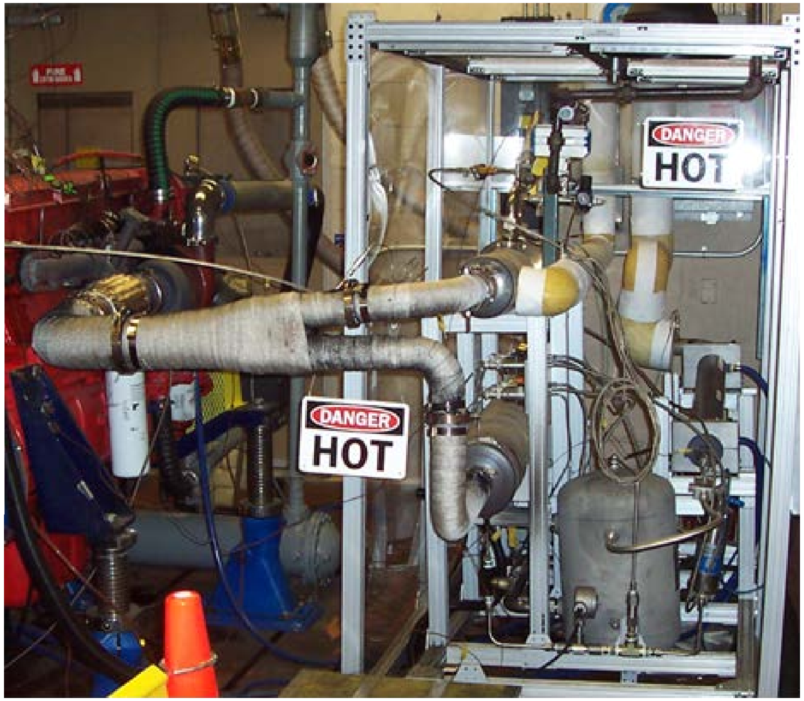
Technical Accomplishments and Progress - EATON ORC Test Stand





Single Stage Expander

- ORC test stand utilized to aid the design and development of the expander.
- The single stage stainless steel roots expander testing was completed.



Eaton ORC Test Stand

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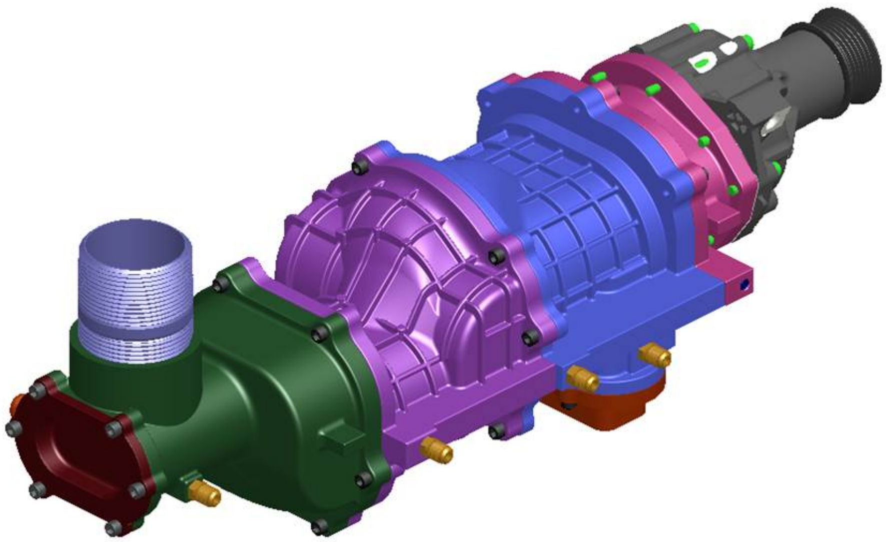
Technical Accomplishments and Progress
- Three Stage Roots Expander



Three Stage Expander

- Improvement made to three stage expander:
  - Reduction and finalization of inlet and outlet ports from 6 ports to 2 through CFD
  - Rotational speed of each expander stage can be modified to achieve the required pressure drop and flow
  - Integrated clutch to reduce ORC system losses during startup
  - Optimized internal flow paths between stages through CFD
  - Lubrication paths added
  - Three stage expander is ready for assembly and test

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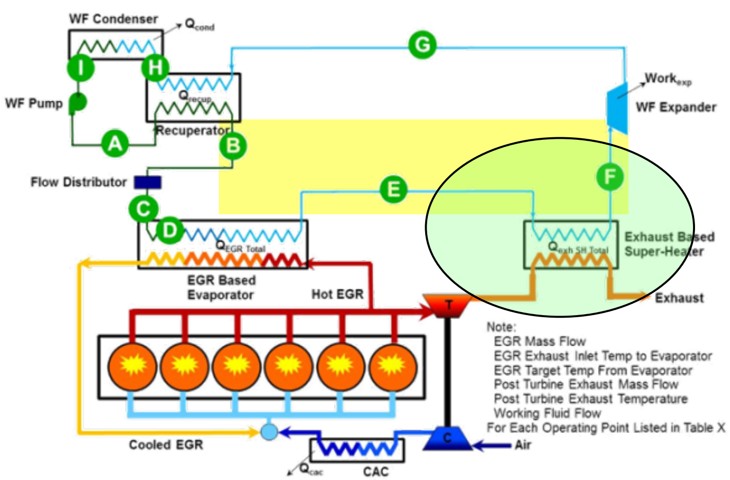
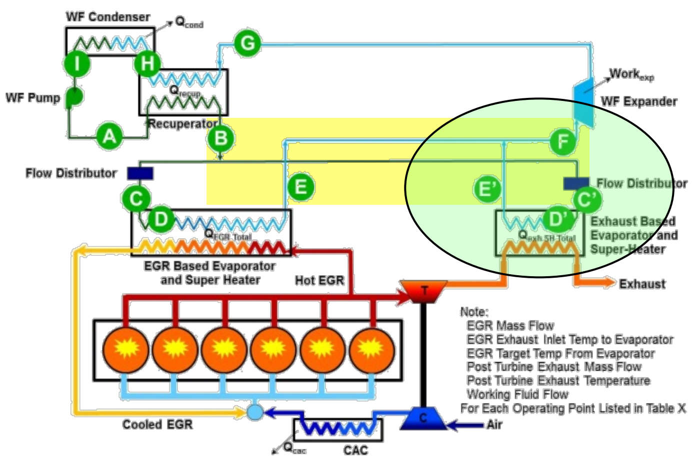
Technical Accomplishments and Progress
- Heat Exchangers

AVL, Modine, & Eaton – Architecture analysis for optimal system performance.

Series Architecture – WF passes through EGR source first (evaporator) followed by post turbine exhaust (superheater).

Parallel Architecture – WF divides between EGR source and post turbine exhaust. Both will evaporate and superheat the WF.





- Parallel system has advantages with respect to controls, system calibration and operation.
- Parallel system allows 'EGR only' recovery system for applications where increased vehicle heat rejection is problematic.

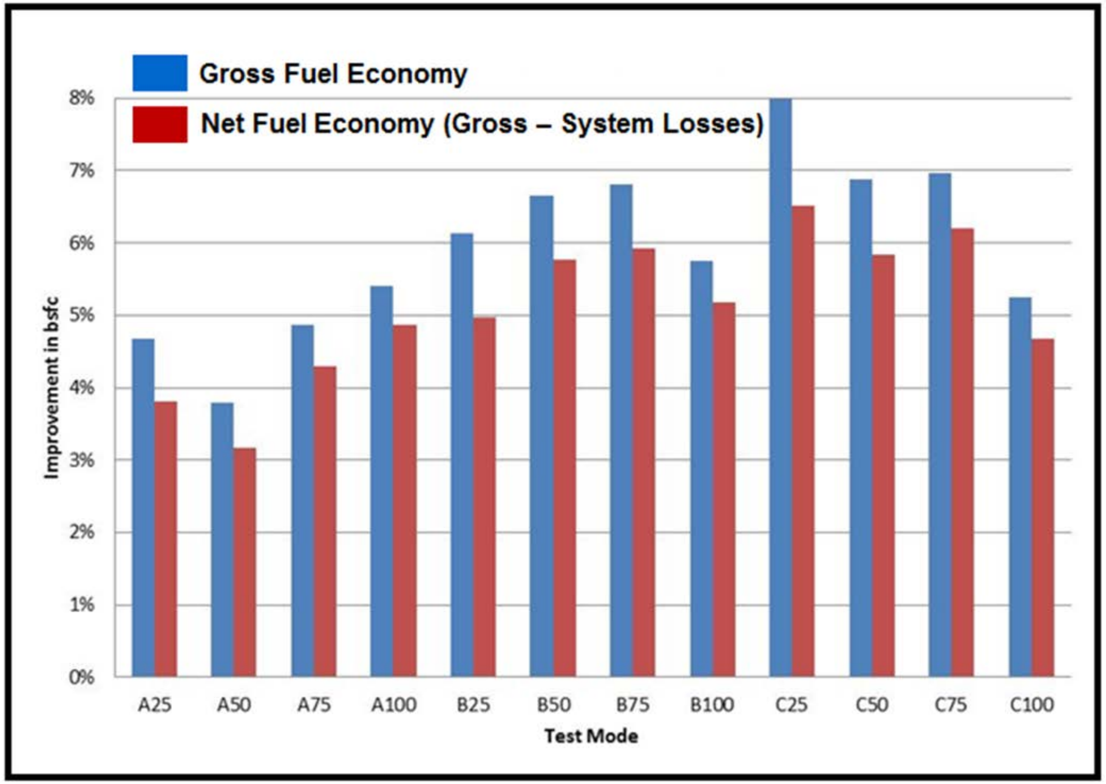
➢ **Parallel architecture has been selected as the prime path for demonstration.**

Technical Accomplishments and Progress
- System Analysis Update

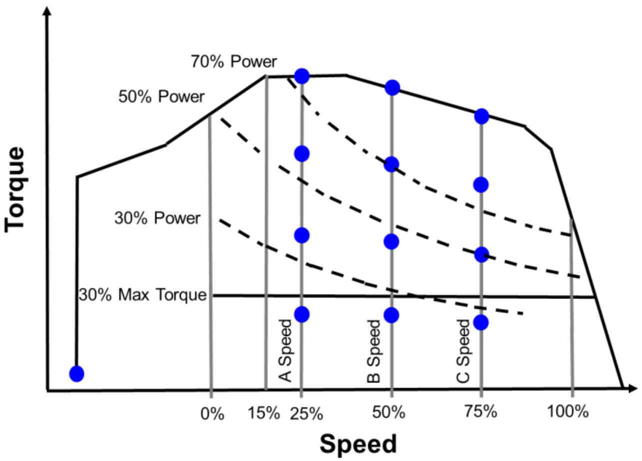
- The model was optimized with the following refinements
  - Heat exchanger vendor supplied heat transfer capacities and WF pressure drops.
  - For each operating mode's evaporation pressure, WF flow & the condensation temperature were adjusted.
  - EGR and Tailpipe boiler were adjusted to simulate the hot WF bypass and EGR or exhaust gas bypass as needed.
  - Estimation of fan loads on net BSFC impact was formulated and implemented.
  - Re-optimization maintained expander volumetric flow (speed) proportional to engine speed to help minimize overall ORC cost, complexity, and risk

Technical Accomplishments and Progress
- Net Fuel Economy Benefit

Roots Expander ORC system F.E. improvement for USEPA duty cycle



An average of 6% Net F.E. improvement has been predicted for most of a vehicle's on-highway operation



USEPA duty cycle

Base Engine Inputs	On-Highway System											
Mode	A25	A50	A75	A100	B25	B50	B75	B100	C25	C50	C75	C100
Speed (rpm)	1307	1307	1307	1307	1609	1609	1609	1609	1910	1910	1910	1910
Torque (N-m)	650	1297	1946	2595	666	1332	1997	2649	587	1174	1760	2331
Power (KW)	88.9	177.6	266.4	355.2	112.3	224.5	336.5	446.3	117.4	234.8	352.1	466.3

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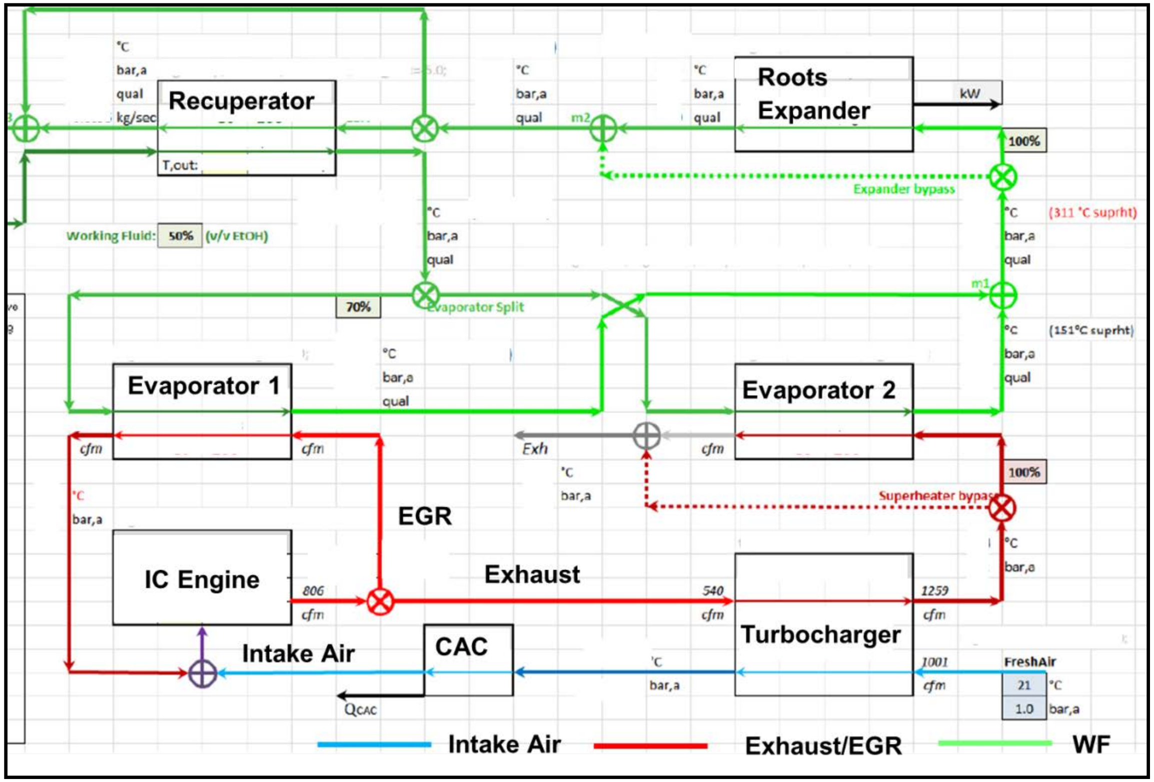
Technical Accomplishments and Progress
- Engine Prototype Control Model



Sensors

Working Fluid Pump Inlet Temperature, Pressure
Working Fluid Pump Outlet Temperature, Pressure
Recuperator Outlet, liquid side Temperature, Pressure
Working Fluid Evaporator 1 Outlet Temperature, Pressure
Working Fluid Evaporator 2 Outlet Temperature, Pressure
Expander Inlet Temperature, Pressure
Recuperator Vapor Inlet Temperature, Pressure

Actuators

Superheater bypass actuator
Expander bypass actuators
Evaporator split control actuator
Recuperator bypass actuator
working fluid flow control actuator

- The control model is in Microsoft Excel with Visual Basic (VB) macro functions for unit code
- Simulation is presently capable with Ethanol/Water mixtures.

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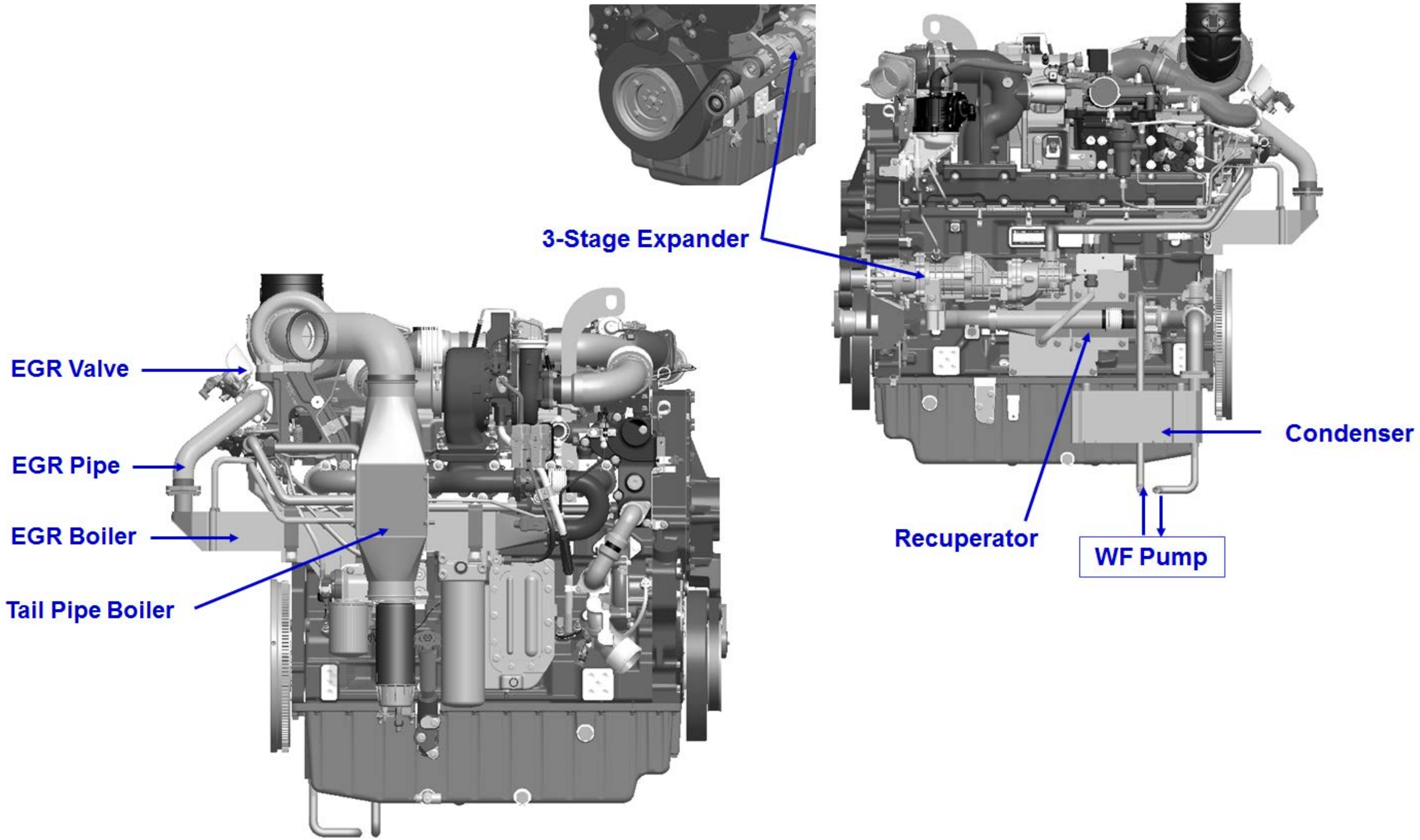
Technical Accomplishments and Progress
- Packaging Layout



Responses to Previous Year Review Comments

Question 1: Approach to performing the work – the degree to which technical barriers are addressed, the project is well-designed, feasible, and integrated with other efforts

Reviewer 1:

This reviewer said that this appears to be a very well developed commercial development project. The reviewer lauds Eaton for putting this together*. This reviewer added that the project has a solid chance of success and that the project is weak on safety technologies for a catastrophic event*.

Response: Modelling -first phase; and WHR components (expander) development-second phase; third phase of this program involve system integration, which will address system safety

Reviewer 6:

This reviewer indicated that it was a good approach to make use of expander, *but it seems that the decisions regarding materials selection and working fluid selection are not quite as fully developed as they could be yet. In particular, the reviewer expressed concern about the ethanol (EtOH)/oil separator for which no details were given.*

Response: Material and working fluid selections were done based on engineering concept selection methodologies. Ethanol–oil separator system is an Eaton proprietary, so details were not given.

Responses to Previous Year Review Comments

Question 2: Technical accomplishments and progress toward overall project and DOE goals – the degree to which progress has been made, measured against performance indicators and demonstrated progress toward DOE goals.

Reviewer 6:

This reviewer said that there was good progress to perform modeling and initial prototyping of single stage device. The reviewer also stated that there are concerns with using engine oil and ethanol oil separator. The reviewer recommended using separate lubrication loop, and to consider alternate designs as risk to engine oil is a significant concern. It is understood that the additional complexity and losses of a separate pump will reduce the value of the system. – **Response:** We are not using engine oil for lubrication. A dedicated lubrication system is being used

The reviewer is unsure about the increase of EGR from base engine calibration for WHR efficiency. The reviewer inquired whether it was possible to increase EGR on the base engine without WHR,. Also, the reviewer expressed surprise to find NOx and HC improvement with exhaust restriction **Response:** The EGR rates being utilized for this project are not problematic. It is possible to deliver and measure these EGR rates with production released components although reliability would need to be re-addressed. Increase in EGR rate has an acceptable impact on soot emissions.

Responses to Previous Year Review Comments

Question 3: Collaboration and coordination with other institutions.

Reviewer 5:

This reviewer said the project had a very complete and comprehensive team. The reviewer said that a possible improvement would be adding an on-highway engine OEM

Question 4: Proposed future research – the degree to which the project has effectively planned its future work in a logical manner by incorporating appropriate decision points, considering barriers to the realization of the proposed technology, and, when sensible, mitigating risk by providing alternate development pathways

Reviewer 5:

The base engine used is one typical of off-road equipment and as a result steady-state tests are being conducted here. it may prove effective to evaluate the performance of the roots expander for vehicular application by performing some transient tests.

Response for both questions: Team has initiated communications with on-road OEMs. Doing a transient performance test will be beyond this DOE program goal.

Collaborations and Coordination

- Baseline engine testing, system modeling, waste heat recovery hardware specification, engine integration and engine final testing
- Engine OEM expertise to develop system requirements and specifications, supply test engine
- Administrative Program Management

Outside Vehicle Technology Program Eaton is working with:

- Modine for WHR heat exchangers
- NSK Bearings for high temperature application bearings
- St. Louis Metalizing company for abradable coatings
- Zatkoff and Eclipse Engineering Inc. for expander seals

Proposed Future Work

- Remainder FY 2014
  - Three stage roots expander will be tested in Eaton ORC test stand
  - All required ORC WHR components will be procured/prototyped for engine testing
  - Roots expander ORC WHR system will be integrated in a 13.5 L John Deere diesel engine

- FY 2015
  - Roots expander ORC system will be evaluated and compared to baseline performance
  - Final report to DOE, Vehicle Technology Office

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Summary

- Highest BSFC of ~ 6% improvement has been predicted with the roots expander ORC system.
- Thermodynamic model has been updated with RefProp to accommodate various working fluids and combinations of working fluids.
- System model has been updated with heat exchanger component pressure drops and fan loss estimates.
- The prime path working fluid to be utilized is ethanol, but testing may also be performed using mixtures of ethanol and water. Heat exchangers shall therefore be sized to handle both working fluids (ethanol as well as water).
- The parallel heat exchanger architecture has been selected for engine testing.
- Detailed packaging study was completed. A relatively simple coupling of the roots expander to the engine crankshaft appears feasible.
- Three stage roots expander components (bearings, seals, rotors and housing) are ready for build and testing.

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Technical Back-Up Slides

Technical Progress – Working Fluid

Working Fluid	**Water**									
Base Engine Inputs		275C Superheat and Ideal Recuperator (leaves Recup with >2C supercooling) June 2013 Software with RefProp Link and provision for component pressure losses								
	Mode	A100	B25	B50	B75	B100	C25	C50	C75	C100
	Speed (rpm)	1307	1609	1609	1609	1609	1910	1910	1910	1910
	Torque (N-m)	2595	666	1332	1997	2649	587	1174	1760	2331
	Power (KW)	355.2	112.3	224.5	336.5	446.3	117.4	234.8	352.1	466.3
	EGR Rate (kg/h)	512.5	404.3	555.7	676.5	744.3	608.5	704.1	976.0	797.5
	EGR Temp (C)	615	399	498	548	612	371	467	523	590
	Available EGR Qrej (kW)	79.4	36.1	65.3	88.9	112.2	47.6	70.4	113.5	113.6
	Exh Rate (kg/h)	1502.2	639.7	1005.8	1576.3	2045.8	873.3	1383.9	1715.6	2178.9
	Exh Temp (C)	408	317	357	364	396	277	321	332	391
	Exh Qrej (kW)	175.34	55.76	100.89	161.22	230.15	64.97	122.09	158.07	241.43
Rankine Cycle and System Operation Inputs										
	Expander Eff (-)	60%	60%	60%	60%	60%	60%	60%	60%	60%
	Pump Efficiency	50%	50%	50%	50%	50%	50%	50%	50%	50%
	Working Fluid Flow (k	0.0336	0.0158	0.0280	0.0376	0.0488	0.0203	0.0300	0.0485	0.0489
	Base Engine EGR Cooler Heat (kW)	79.4	36.1	65.3	88.9	112.2	47.6	70.4	113.5	113.6
		89.2	41.6	76.6	100.3	130.4	54.1	81.0	129.5	131.7
Rankine Cycle Summary	Engine Fuel Economy Benefit	2.62%	2.72%	3.64%	3.07%	3.26%	3.41%	3.35%	3.90%	3.11%

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Technical Progress – Heat Exchangers

- These refined operating parameters were re-evaluated by the heat exchanger supplier at Modes A75, B75 and C100 for EGR boiler and the large tailpipe boiler.
- EGR Boiler performance predicted through theoretical analysis was within 3% of the heat exchanger supplier predictions.
- Tailpipe energy recovery used in the analytical predictions did not exceed the maximum recoverable energy results of the heat exchanger supplier analysis.
- This comparison gives confidence in the recovered energy levels and temperatures used in the AVL analysis.

	EGR Boiler Heat Recovery (kW)		Tailpipe Boiler Heat Recovery (kW)	
	The heat exchanger supplier	Model Predictions	The heat exchanger supplier (Max)	Model Predictions
A75	54.3	54.8	69.9	43.8
B75	86.3	88.6	79.4	79.5
C100	111.2	112.2	110.9	77.1

Comparison of Heat Transfer Rates for Revised Operating Conditions

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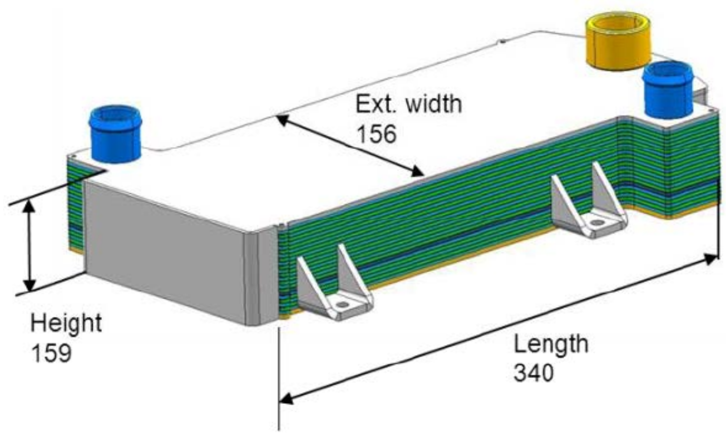
Technical Progress – Condenser & WF Pump

- Initial Condenser Sizing:
  - The condenser sizing was performed for both fluids and both system architectures using C100 as the sizing point (highest heat rejection). The condenser was sized for dyno lab operation using process water as the sink for heat.



Initial Condenser Package (Dyno Lab Use)