2016 DOE Vehicle Technologies Office Review

Affordable Rankine Cycle (ARC) Waste Heat Recovery for Heavy Duty Trucks

Principal Investigator: Swami Nathan Subramanian

Eaton

June 9, 2016

Project ID # ACE097

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Overview

Timeline

- Project Start Date: 11/25/2015
- Project End Date: 01/01/2018
- Phase 1 Percent Complete: 25%

Budget Period	Start Date	End Date	% Complete
Phase 1	11/25/2015	01/01/2017	25
Phase 2	01/02/2017	01/01/2018	

Budget

Total Project Funding: $ 4,027,142

DOE (Eaton): $1,813,571

DOE (FFRDC) : $ 200,000

Eaton Cost Share: $2,013,571

DOE Funding BP1: $1,018,011

DOE Funding BP2: $ 795,560

Barriers

- **Performance:** Improve Heavy Duty engine efficiency (improvement $\geq$ 5 %) through WHR systems
- **Emissions:** Engine efficiency improvement without NOx and PM penalty
- **Cost:** Cost effective Rankine Cycle WHR system

Partners

- Project lead: Eaton Corporation
- Collaborations:
  - PACCAR Inc.
  - Modine Manufacturing Company
  - Purdue University
  - Mississippi State University
  - Kettering University
  - Argonne National Laboratory
  - Shell Global Solutions
  - AVL Powertrain Engineering

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Relevance
Objectives of This Study

Program Objectives

- Demonstrate heavy-duty diesel engine fuel economy improvement through "Roots Expander based Rankine Cycle Waste Heat Recovery Systems ":
  - Using engine coolant as the working fluid for WHR loop
  - 5% Fuel Economy (F.E) improvement
- Demonstrate that other pollutants, such as NOx, HC, CO and PM will not increase as part of the overall engine/WHR/exhaust after treatment optimization
- Demonstrate a plan for 50% cost reduction by incorporation of ARC system

Phase 1 Objectives

- Study the feasibility of engine coolant as WHR working fluid.
- Analyze exhaust heat energy availability in a heavy duty diesel engine through experiments and Quantify the F.E improvement from baseline experimental data
- Design WHR system components (Roots expander, Heat Exchangers) for Rankine cycle based on available exhaust energy to achieve 5% fuel economy improvement

Milestones

Month/Year	Milestone	Status
Feb 2016	Kick off Meeting	Completed
March 2016	Engine Baseline	Completed
June 2016	WHR Architectures Evaluation	Progress
Sep 2016	Two Phase Heat Transfer Correlation Development	Progress
Nov 2016	WHR Components Design/Specification (Working Fluid, Expander, Heat Exchanger)	Progress
Dec 2016	Go/ No Go Review	Planned
FY 17	**ARC hardware integration and testing**	**Planned**

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Approach/Strategy

- Using baseline 13 liter PACCAR HD diesel engine, characterize and quantify the potential waste energy sources for construction of thermodynamic analysis models – **June 2016** (**In Process**)
- Evaluate different ARC WHR system architectures theoretically and finalize optimized system (assess working fluid composition, heat exchanger layouts, expander size) – **Nov 2016** (**In Process**)
- Develop and test WHR components (bench testing, calibration, and validation to maximize efficiency and durability) – **2016 and 2017** (**In Process**)
- Test ARC system on engine and compare to baseline engine performance - **2017** (**Planned**)

Year	Start TRL	End TRL	Justification
2016	2	3	The technology (Roots-based) is starting at TRL2 in BP1 where the concept has been defined for truck application. During BP1, we will conduct detailed analytical studies of the Roots expander with engine coolant and evaluate the F.E improvement, which will allow us to achieve TRL3.
2017	3	4	Starting at TRL3 in BP2 we will integrate the components (Roots expander, heat exchangers) for ORC system to operate with MX-13 heavy duty diesel engine in a laboratory environment and demonstrate feasibility of the concept. This will allow us to achieve TRL4 in BP2.

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Technical Accomplishments and Progress

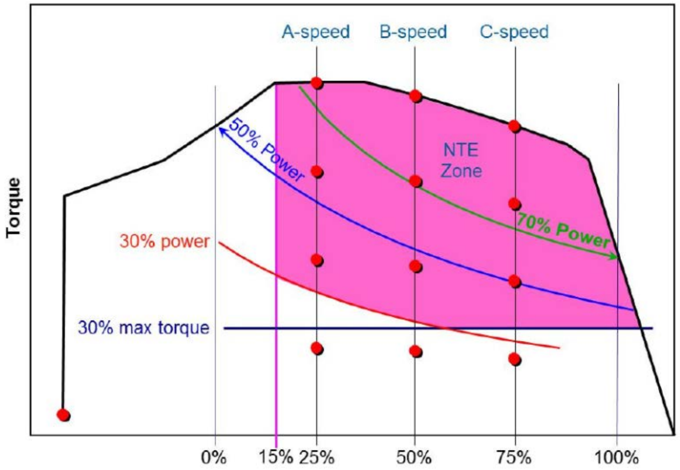
- Baseline engine calibration and experimental data collection
- Coolant feasibility analysis (Progress)
- CFD analysis with engine coolant (two components) in two phase (progress)
- Analytical investigation of ARC WHR architectures (Progress)
- WHR components design and development based on simulation results (Progress)
- Roots expander design including auxiliary components and material selection process (Progress)
- ARC plant model development (Progress)
- Development of two phase heat transfer correlation for ARC (Progress)

Technical Accomplishments and Progress
Engine Specifications and Testing

PACCAR MX13 (I-6) 360kW @ 1700 rpm

24.3bar peak BMEP with #2 diesel

Properties	Value
Charging System	Variable geometry turbocharger
Fuel Injection System	2500 bar Common rail fuel injection system
Bore	130 mm
Stroke	162 mm
Compression Ratio	17.4 : 1
Connecting Rod Length	262 mm
Valve Configuration	4 / cyl



USEPA 13 mode Supplemental Emission Test (SET) Cycle

Collaborations and Coordination

Team Member	Responsibility
Eaton (Prime)	Design, develop, characterize, and deliver Roots expander for ARC system – HDDE exhaust waste heat recovery application.
Paccar	Perform engine baseline testing and provide inputs for basic WHR analysis, ARC system architecture optimization, HDDE performance predictions, and commercialization
Modine	Design, develop, characterize, and deliver Heat exchangers for ARC system – (EGR cooler, Post turbine boiler, Radiator which accommodates two phase condition and liquid to liquid condenser for testing purpose)
ANL	Perform two-phase heat transfer testing and develop correlations for analytical model predictions
MSU	Conduct experiments for working fluid feasibility in engine ORC system and final demonstration
Kettering University	Perform CFD analysis of the Roots expander design as well as inlet and outlet optimization for mixed-phase working fluid
Purdue University	Plant model development and WHR system analysis
AVL	Perform system analysis, optimization and support commercialization analysis
Shell Global Solutions	Conduct coolant analysis, support the project in an advisory role and provide expertise on engine coolant technology (formulations) and physical, chemical, and bench performance testing

Planned Future Work

- Remainder FY 2016
  - WHR architecture analysis
  - Working fluid feasibility analysis
  - CFD analysis – multi component, two phase conditions
  - Two phase heat transfer correlation development
  - ARC analytical model development & F.E improvement prediction
  - WHR components (Expander, Working Fluid & Heat exchangers) design development for ARC system
  - Go/No Go Review (Dec 2016)

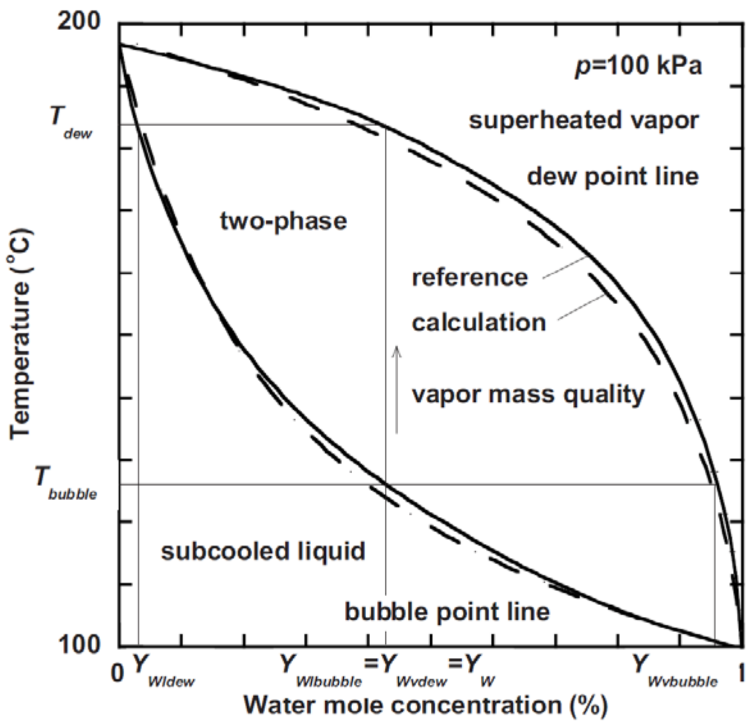
- FY 2017
  - WHR components testing and evaluation
  - WHR system will be integrated in a 13 L PACCAR diesel engine
  - ARC system will be evaluated and compared to baseline performance

Summary

- The baseline PACCAR engine provides an excellent platform for WHR demonstration.
- 50/50 glycol water mixture has been selected as the working fluid
- The preliminary WHR analysis based on engine baseline experiments is in progress
- WHR components design and development is in progress
  - Roots expander sub-components design is in progress, including rotors, housing, seals, and bearings
  - Heat Exchanger design and development is in progress
- A relatively simple coupling of the WHR system expander to the engine crankshaft appears feasible (variable speed coupling can be avoided)

Technical Back-Up Slides

Engine Coolant – Two Phase



Raoult's law for ideal mixtures was used to generate a phase diagram for EG/W mixtures at a constant pressure P =100 kPa

Wenhua Yu, David M. France, and Jules L. Routbort Forced Convective Boiling of Ethylene Glycol/Water Mixtures Inside a Small Tube, Journal of ASTM International, Vol. 8, No. 2

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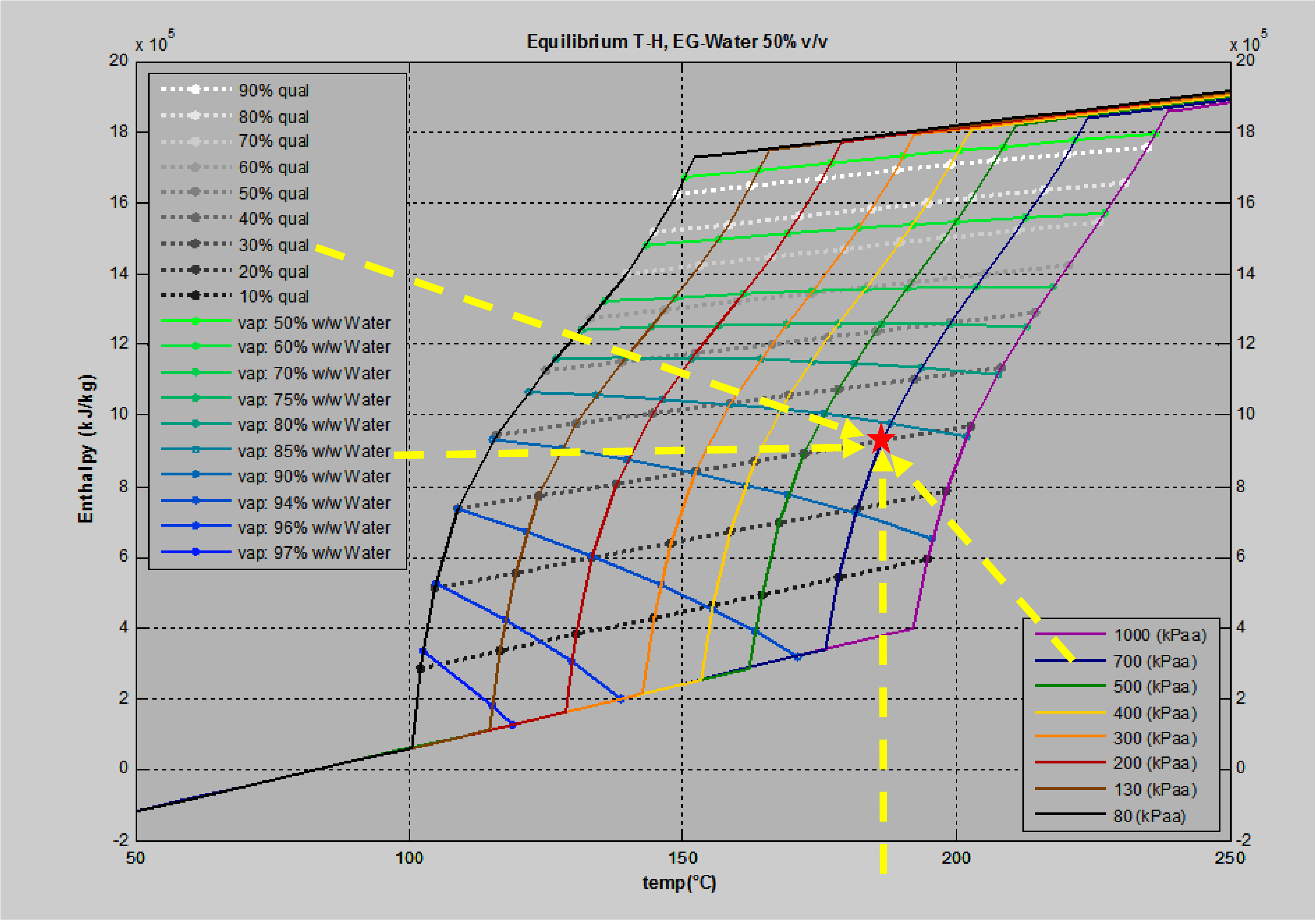
Engine Coolant – WHR Working Fluid



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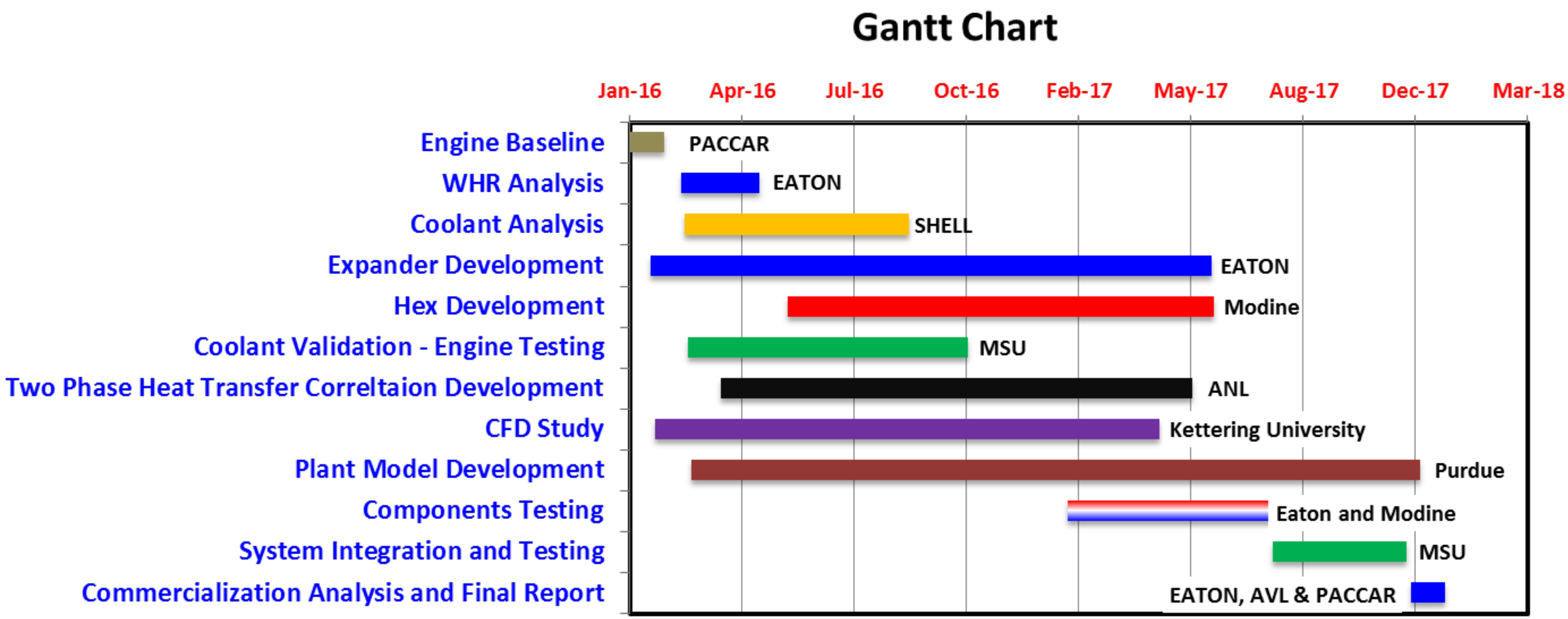
Overall Program Plan



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Overall Program Plan

Tasks in Affordable Rankine Cycle – DOE Funded Program
1.0 Program Management
2.0 Baseline Engine & WHR Characterization
3.0 Coolant Feasibility Analysis
4.0 WHR Component Design and Development
5.0 Two-phase Heat Transfer Correlation Development
6.0 Detailed Plant Model Development and Validation
7.0 WHR Hardware Procurement & Testing
8.0 WHR Integration & Testing
9.0 Final Report Submission

Task Name	Start
2.0 Baseline Engine & WHR Characterization	Wed 11/25/15
Engine Testing for 13 Model SET Points ✔	Tue 1/5/16
WHR Analsyis Based on Baseline Progress	Fri 4/8/16
Working Fluid Pump	Thu 4/28/16
Simple Plant Model	Wed 11/25/15
3.0 Coolant Feasibility Analysis Progress	Wed 11/25/15
Coolant Analsyis & Development - Shell	Wed 11/25/15
Experimenatl Study - MSU	Wed 11/25/15
4.0 WHR Component Design and Development	Mon 1/4/16
Roots Expander	Mon 1/18/16
Heat Exchangers Design & Development	Mon 1/4/16
Others	Wed 8/17/16
5.0 Two-phase Heat Transfer Correlation Development Progress	Mon 1/4/16
6.0 Detailed Plant Model Development and Validation	Thu 3/3/16
Phase 1 Progress	Thu 3/3/16
Phase 2	Fri 10/7/16
Deliverables	Wed 10/4/17
7.0 WHR Hardware Procurement & Testing	Wed 9/28/16
Expander Hardware and Validation	Wed 9/28/16
WHR System Non-Expander Hardware for MX-13 HDDE	Thu 10/27/16
8.0 WHR Integration & Testing	Tue 4/4/17
9.0 Final Report Submission	Tue 10/17/17

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