Achieving and Demonstrating Vehicle Technologies Engine Fuel Efficiency Milestones

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OAK RIDGE NATIONAL LABORATORY
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Overview

Only project devoted to demonstrating 2010 DOE Vehicle Technologies efficiency and emissions objectives.

Timeline

- **Consistent with VT MYPP**
- **Evolves to address OVT efficiency/emissions goals**

Barriers

- **Efficiency/combustion**
- **Engine-system management**
- ➡ **VT performance milestones**

Budget

- **FY 2007 – $400k**
- **FY 2008 – $600k**
- **FY 2009 – $750k**
- **FY 2010 – $750k (in progress)**

Partners / Interactions

- **Regular status reports to DOE and ACEC Tech Team.**
- **VanDyne SuperTurbos on turbo-compounding.**
- **Barber-Nichols on bottoming cycle development.**
- **One-on-one interactions on hardware development (*e.g.,* Cummins) and software issues (*e.g.*, Gamma Technologies).**

Relevance / Milestones

Objective is to demonstrate Vehicle Technologies fuel efficiency performance goals.

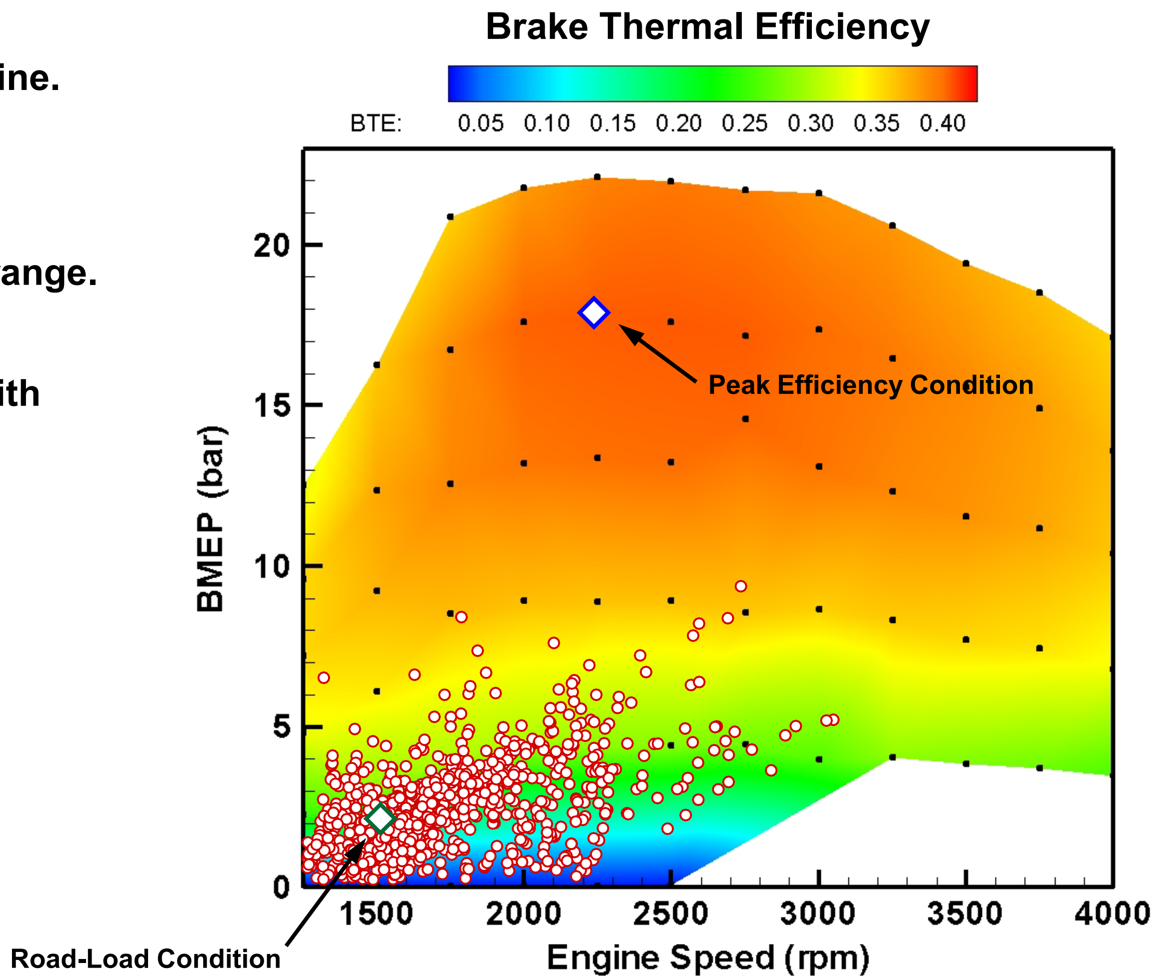
Characteristics	FY 2006	FY 2007	FY 2008	FY 2009	FY 2010
Peak Brake Thermal Efficiency (HC Fuel)	41%	42%	43%	44%	45%
Part–Load Brake Thermal Efficiency (2 bar BMEP @ 1500 rpm)	27%	27%	27%	29%	31%
Emissions	Tier 2 Bin 5	Tier 2 Bin 5	Tier 2 Bin 5	Tier 2 Bin 5	Tier 2 Bin 5
Thermal efficiency penalty due to emission control devices	< 2%	< 2%	< 2%	< 1%	< 1%

- **FY 2009 Q4 – Met**
  Demonstrate 44% peak BTE on a multi-cylinder engine.
- **FY 2010 Q2 – Met**
  Through models and experiments, determine the potential road-load (FTP cycle-simulation point) efficiency gains with an organic Rankine bottoming cycle.
- **FY 2010 Q4 – In Progress**
  Demonstrate 45% peak BTE on a multi-cylinder engine.

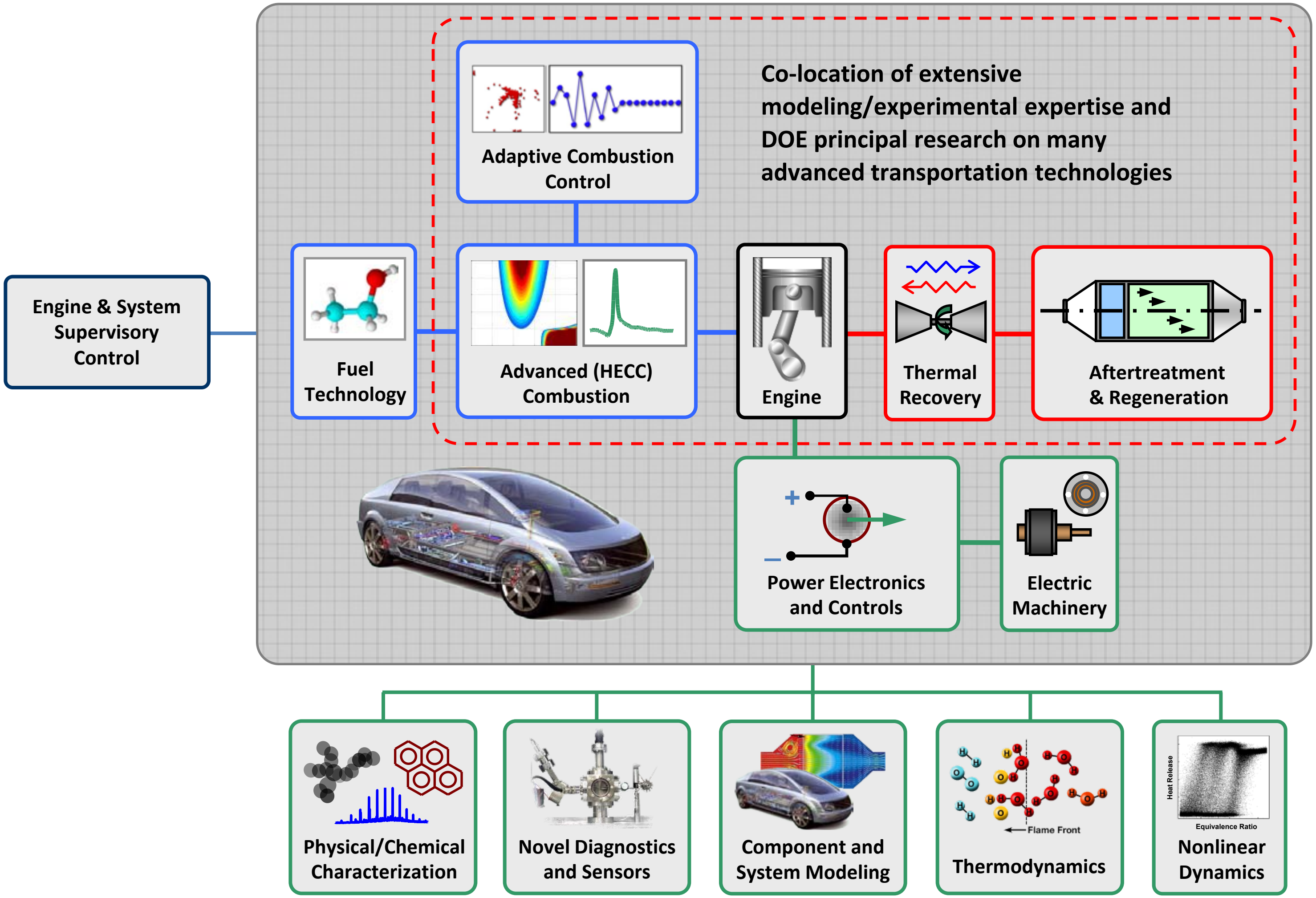
* These are all Joule milestones which are used to track important accomplishments and progress towards Vehicle Technologies program goals.

A major challenge is LD drive cycles do not match well with high engine efficiency

- **Example from GM 1.9-L diesel engine.**
- **LD drive cycle corresponds to low efficiency engine conditions.**
- **Highest BTE in 15 – 20 bar BMEP range.**
- **Focus also includes other modal conditions which are consistent with LD drive-cycles.**



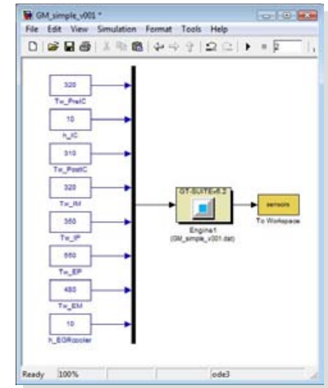
Comprehensive approach to system efficiency opportunities and challenges builds upon on-going activities at ORNL and elsewhere



Simulation + Experiment + Thermodynamics + Collaboration

Simulation to characterize and evaluate efficiency opportunities.

- **Combustion modeling (In-house multi-zone models)**
  - » Guide experiments and interpret data.
- **Engine-system modeling (GT-Power & WAVE)**
  - » Characterize energy distribution and thermodynamic losses, design/evaluate auxiliary systems, evaluate combustion management strategies, etc.
- **Vehicle System modeling (PSAT & GT-Drive)**
  - » Evaluate technologies and operational strategies across simulated drive cycles.



Experiments for development, integration, and demonstration of technologies.

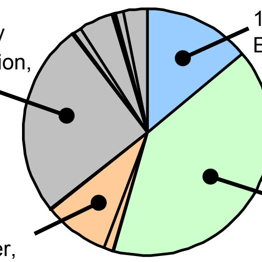
- **GM 1.9-L diesel engine (2)**
  - » Open controls including flexible microprocessor based dSpace system.
  - » Instrumentation for combustion, thermodynamic, and exhaust characterization.
- ***Thermal energy recovery* (TER) hardware**
  - » Integrated organic Rankine cycle for transforming thermal exhaust energy to electricity.

Approach continued

2nd Law Thermodynamics perspective to identify efficiency opportunities.

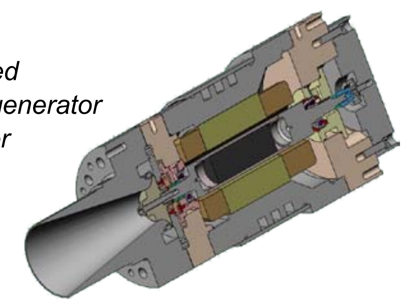
- **Integration into modeling packages**
  - » Provides component-by-component evaluation of thermodynamic losses/opportunities.
- **Evaluation of experimental data**
  - » Characterize recovery potential of thermal energy discarded to the environment and guide the development of TER system(s).
- **Thermal management of engine-system**
  - » Balance several technologies competing for the same thermal resources.

Example 2nd Law Distribution



Collaborations to make best use of available resources.

- **General Motors**
  - » Informal interactions on engine controls.
- **VanDyne SuperTurbos**
  - » Turbo-compounding.
- **Barber Nichols**
  - » Development of integrated turbine/generator expander.



Integrated turbine/generator expander

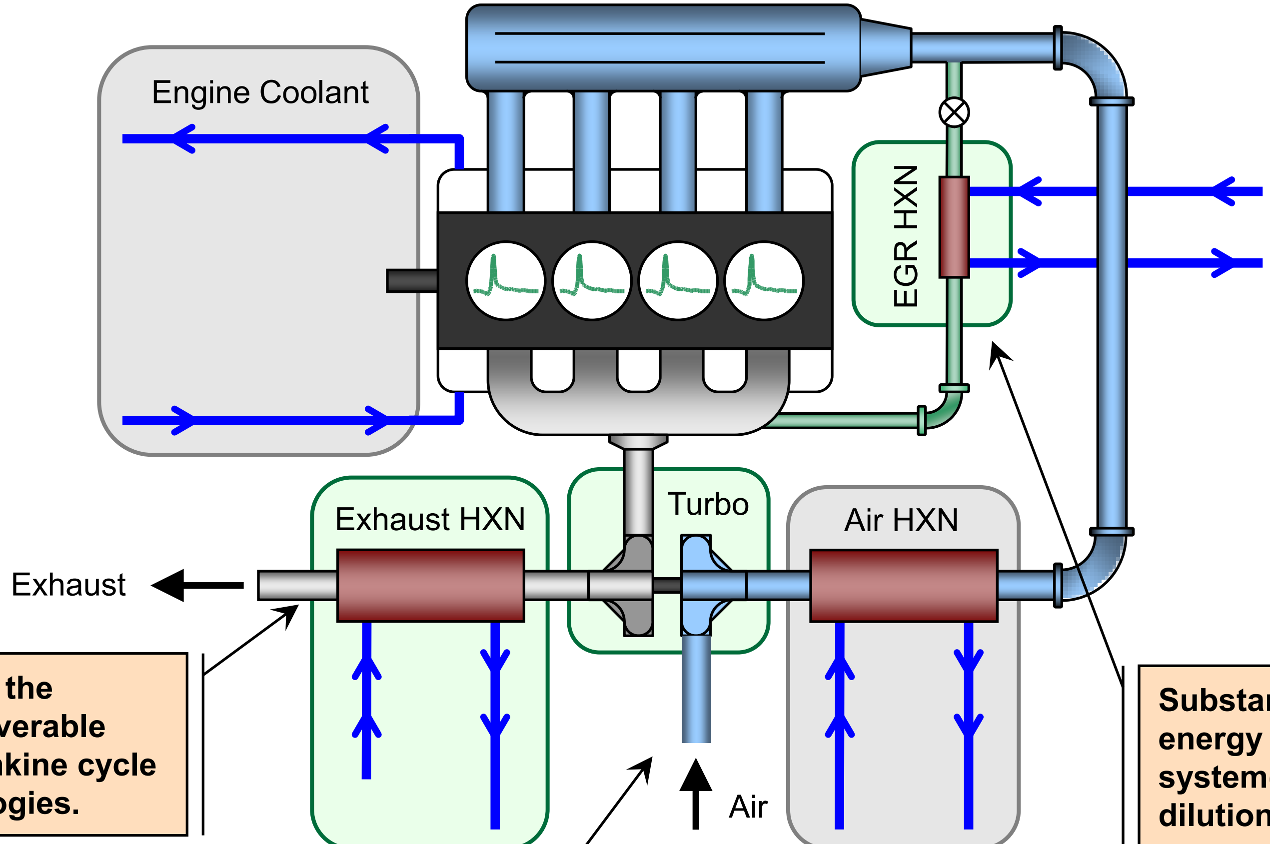
GM ECU/ETAS controller

Technical Accomplishments Summary

- **Designed and fabricated an organic Rankine cycle (ORC) for converting thermal exhaust energy to electricity.**
- **Demonstrated 44.3% combined peak BTE and on path to 45.0% BTE this FY.**
- **Developed transient capable ORC model and coupled to GT-Power engine model.**
- **Modeled the potential efficiency improvement of an ORC under road-load conditions and across an FTP drive-cycle.**
- **Modeled turbo-compounding concept by VanDyne SuperTurbos. VanDyne is planning on supplying hardware to ORNL for evaluation (not discussed in this presentation).**

FY 2009 included discussion of efficiency contributions of fuel properties, advanced lubricants, re-optimized engine operation, and electrification of components. These topics will not be discussed today.

With less than ½ of fuel energy converted to useful work, substantial efficiency improvements will require a reduction in losses to the environment



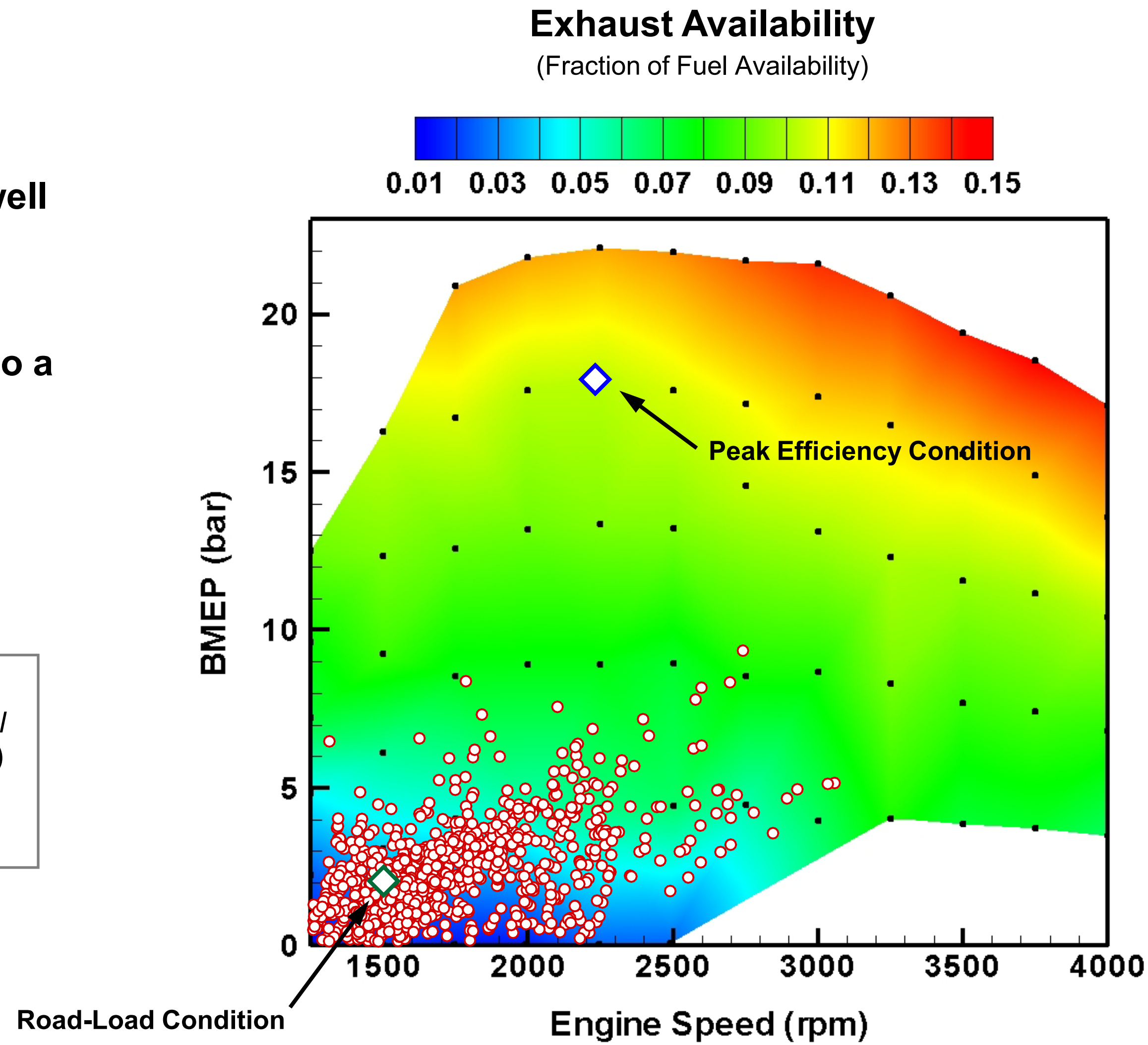
Thermal energy from the exhaust system recoverable using an organic Rankine cycle and/or other technologies.

Substantial thermal energy in EGR system(s) for high dilution combustion approaches.

Turbo-compounding technologies also under investigation through informal collaborations.

Significant energy discarded to the environment, particularly under high BMEP conditions

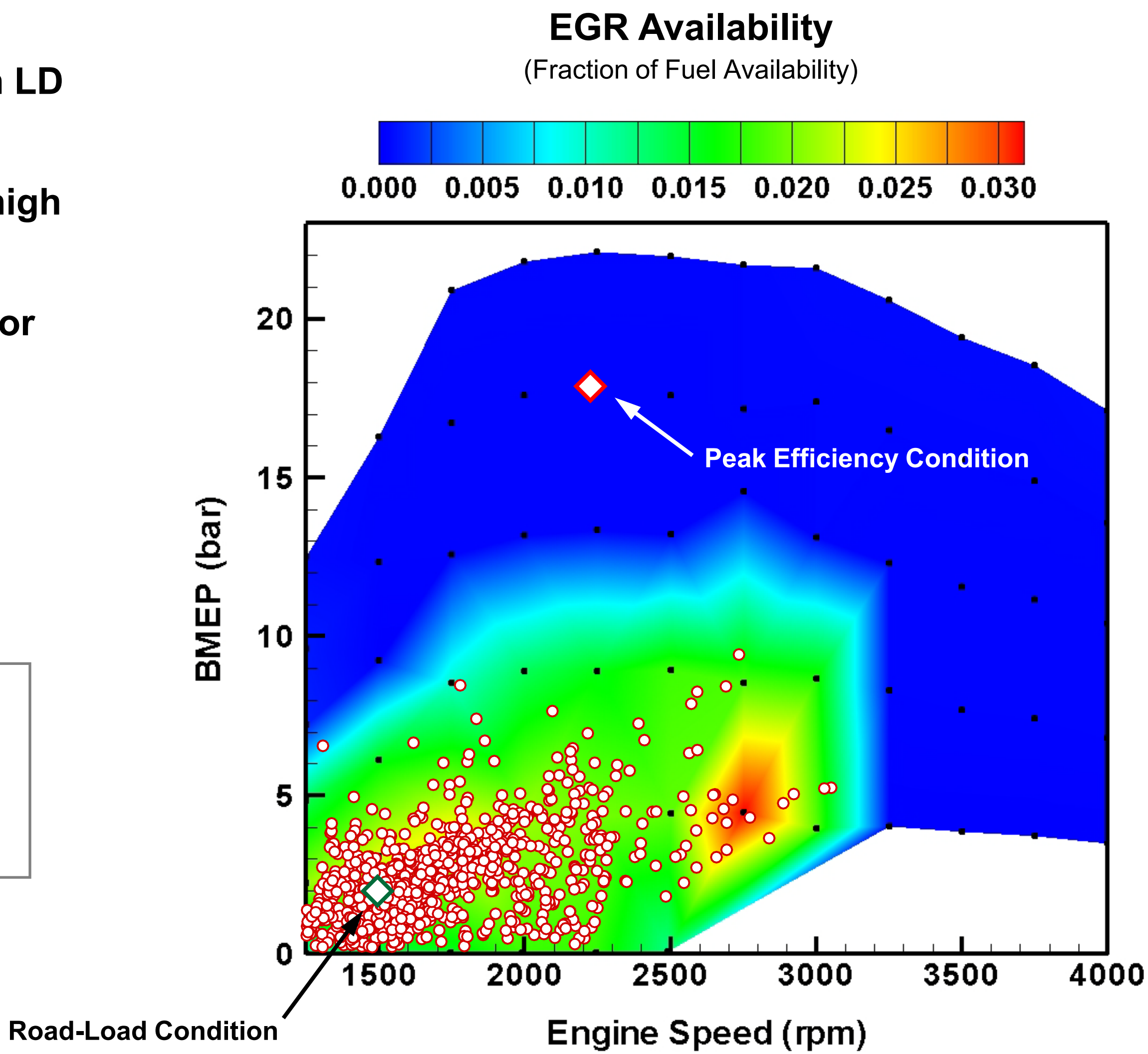
- **Exhaust energy quality is low for much of LD drive-cycle.**
- **Peak BTE operation of engine is well matched with high exhaust availability.**
- **Transients (scatter in data) are also a challenge.**



<u>Working Definition</u>: ***Availability*** *(a.k.a. exergy) is a measure of a system's potential to do useful work due to physical (P, T, etc.) and chemical differences between the system and the ambient environment.*

For much of LD drive cycle, a non-negligible fraction of fuel energy is discarded through the EGR system

- **EGR Availability well matched with LD drive schedule.**
- **Better match for LTC modes with high levels of dilution.**
- **Again, transients will be an issue for thermal energy recovery.**



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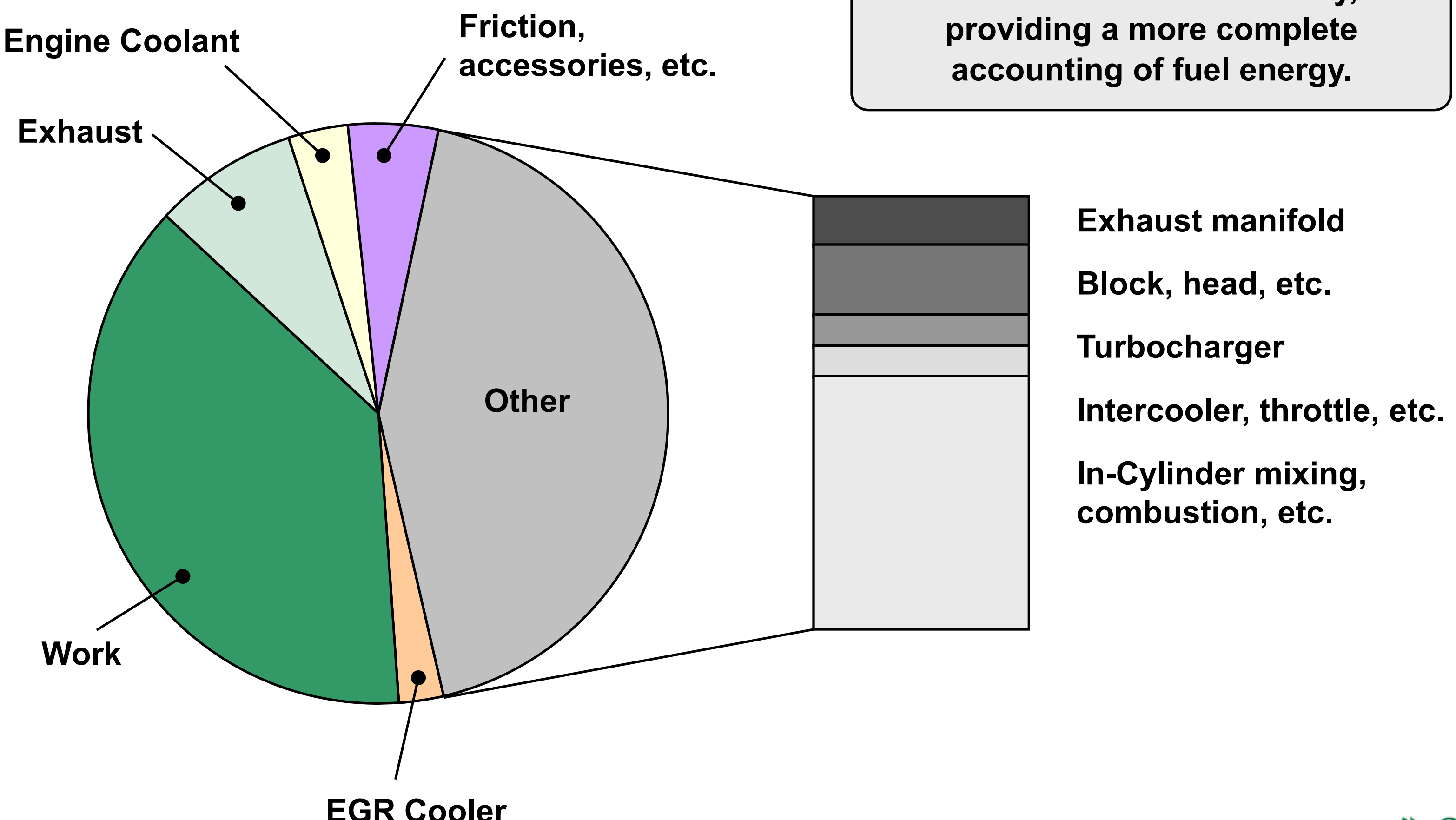
Combination of experimental data and system modeling used to guide efficiency technology development

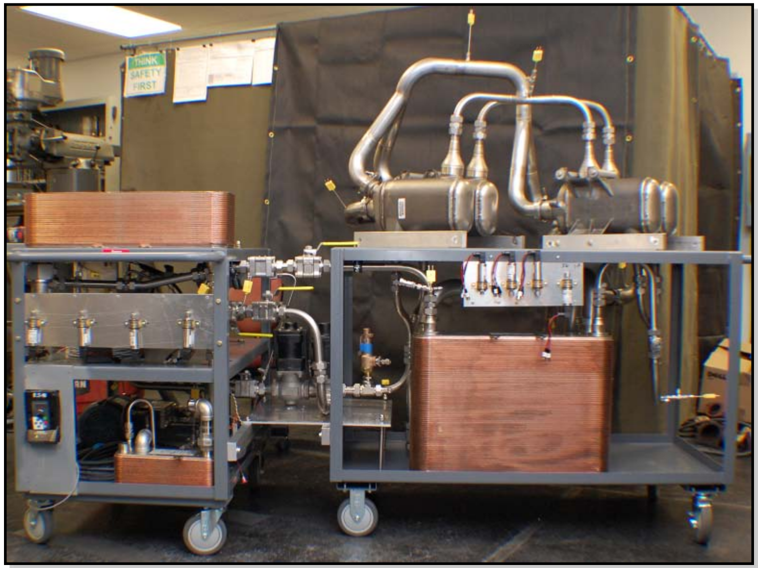
Significant portion of fuel availability is difficult to account for with experimental measurements.

Simulation adds missing details related to combustion, mixing, and heat transfer irreversibility, providing a more complete accounting of fuel energy.



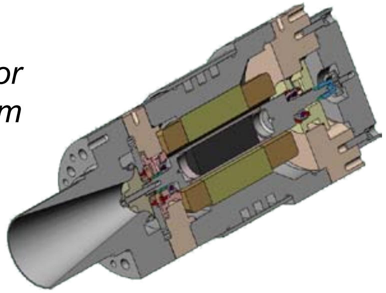
A bottoming cycle has been designed and constructed for on-engine recovery of exhaust energy

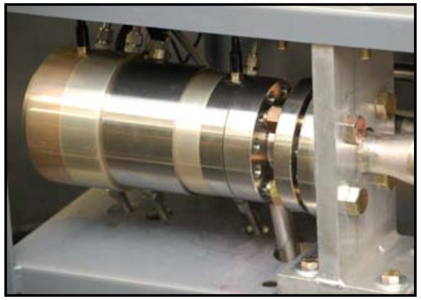
- **Organic Rankine cycle (ORC) with recuperation.**
  - Working fluid R245fa selected based on performance, safety, and environmental criteria.
  - System sized for peak efficiency condition of engine (2250 rpm, 18 bar BMEP).
- **Laboratory-scale system with industrial grade components.**
- **Conservative thermodynamic analysis shows potential of achieving 45% peak BTE with thermal recovery of exhaust energy.**



ORC before installation on the engine.

Turbine/generator system

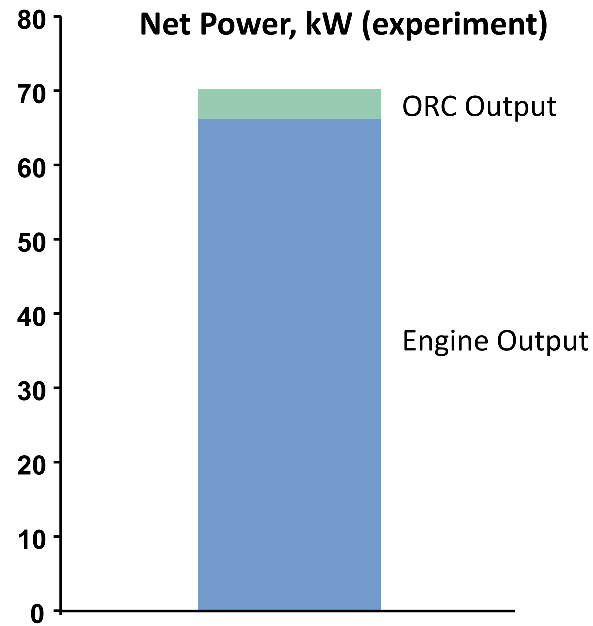




ORC performance for peak BTE condition (2250 rpm, 18.0 bar BMEP)

ORC Performance

- **Turbine inlet pressure: 300 psi**
- **Condenser target pressure: 13 psi**
- **Design cycle efficiency: 12.8%**
- **Best repeated ORC performance:**
  - » Gross generator power: 4420 W
  - » Pump power: 478 W
  - » Net power from cycle: 3942 W
  - » ORC cycle efficiency: 11%



Engine-ORC System Performance

- **Experimentally observed combined efficiency.**
  - » Engine-only 41.8% BTE produces 66.2 kW.
  - » Addition of 3.9 kW from ORC is **combined efficiency of 44.3%**.
- **Engine-only BTE low due to insufficient cooling tower capacity.**
  - » An engine-only 43% BTE demonstrated on this engine in FY 2008.
  - » A combined 45% BTE requires an engine-only 42.5% BTE + 3.9 kW from ORC.
  - » Cooling tower issues being addressed with next round of experiments planned for June 2010.

ORC performs well for design condition but is not very effective for off-design operation

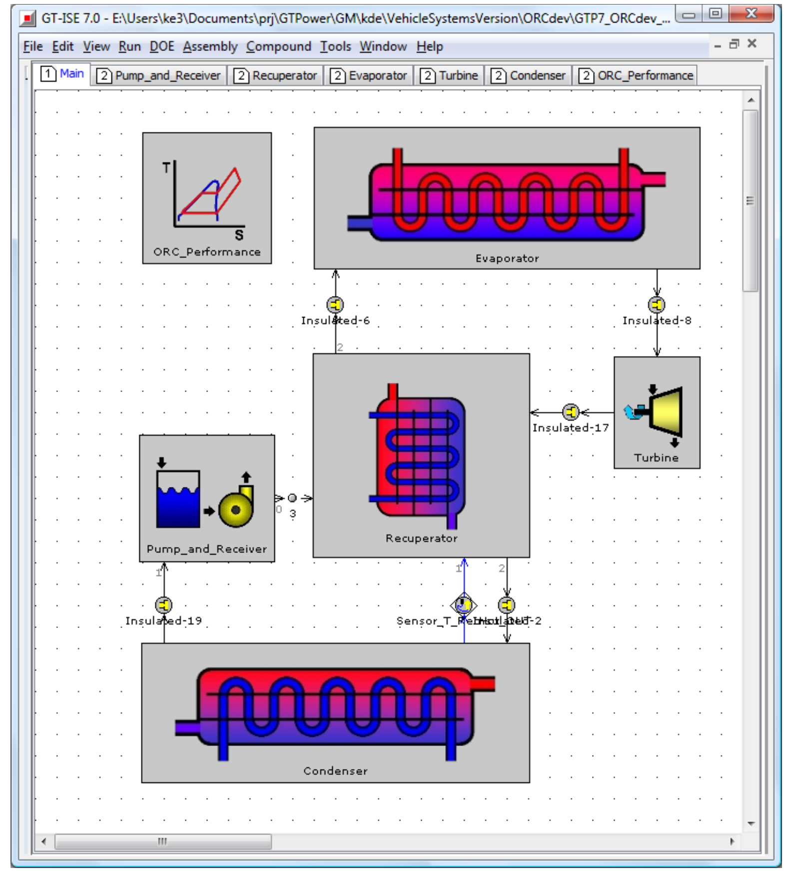
- **System not able to produce positive net power under road-load conditions (1500 rpm, 2.0 bar BMEP).**
  - » Expander turbine design is inefficient for low thermal input of road-load conditions.
  - » Off-design operation is challenge for turbine expander design.
- **Modeling used to better understand potential across LD drive cycle.**

Question: **Why did we not design for the arguably more relevant speed-load condition?**

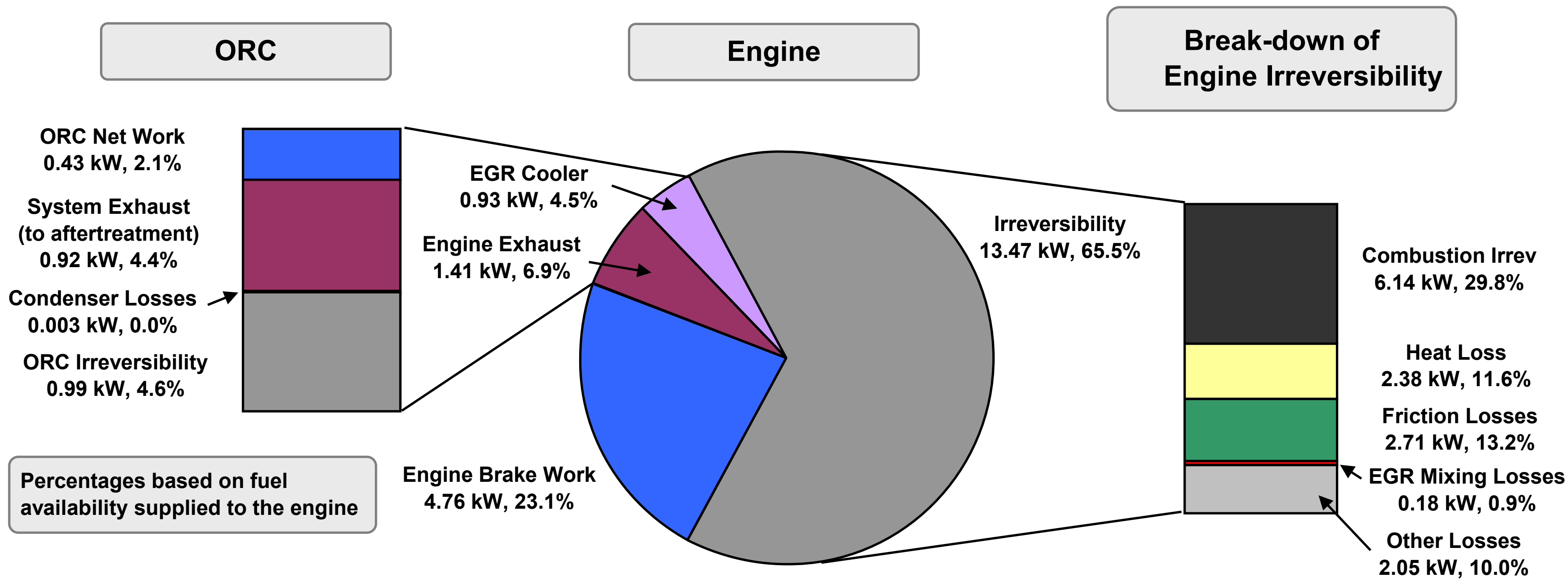
Answer: **Maximum BTE potential is very important to DOE to bound engine-system efficiency so therefore took priority.**

A GT-Suite model was developed to better understand challenges of ORC operation across conditions consistent with a LD drive-cycle

- **Created in GT-Suite V7.0 Build 3.**
- **Heat recovery from exhaust and EGR cooler.**
- **R245fa working fluid.**
- **System assumptions consistent with experience and the literature. Other assumptions include:**
  - » Exhaust temperature maintained above 250 °C to ensure temperature for aftertreatment needs.
  - » EGR temperature maintained above 70 °C to limit fouling.
- **Primary objectives:**
  - » Explore effects of component efficiencies on system performance.
  - » Investigate potential for WHR over normal operating range of engine.
  - » Develop strategies for transient operation over standard drive cycles.



2nd Law system modeling at road-load condition (1500 rpm, 2 bar BMEP) provides insight into efficiency influence of components



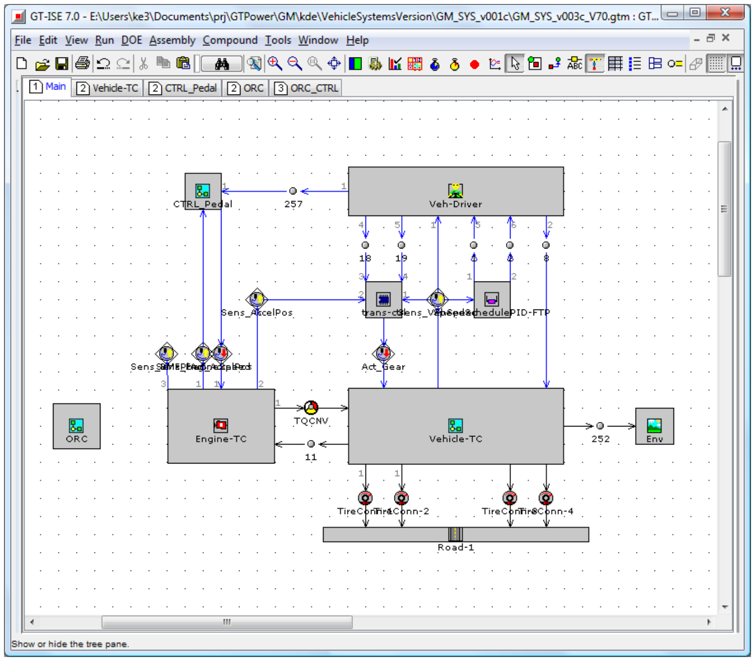
Percentages based on fuel availability supplied to the engine

ORC Component	Influence Coefficient*	2nd Law Efficiency
Pump and Receiver	0.30%	89.9%
ORC Turbine	31.4%	89.1%
Recuperator	45.4%	31.4%
Evaporator	99.7%	72.4%
Condenser	9.8%	0.00%

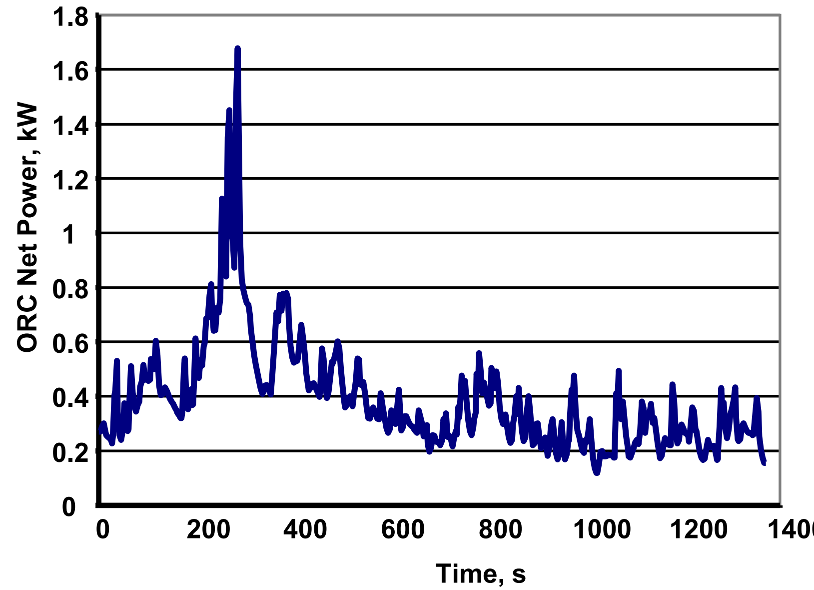
*Influence Coefficient = % ofsystem availability to each component.

- Evaporator component performance has largest influence on ORC efficiency
- Recuperator has lowest non-zero component efficiency
- Condenser and charge air cooler losses are negligible on 2nd Law basis due to low availability.

Transient simulations indicate potential benefit over light-duty drive cycle



Net power output of ORC over simulated warm FTP



- Assumes ORC component efficiency is constant for variable thermal input. This represents a best case.
- Preliminary results from transient simulations suggest efficiency benefits over light-duty drive cycles.
- ORC provides additional 380 W on average over warm FTP.
  - » ORC model allowed to ‘warm-up’ prior to drive cycle simulation.

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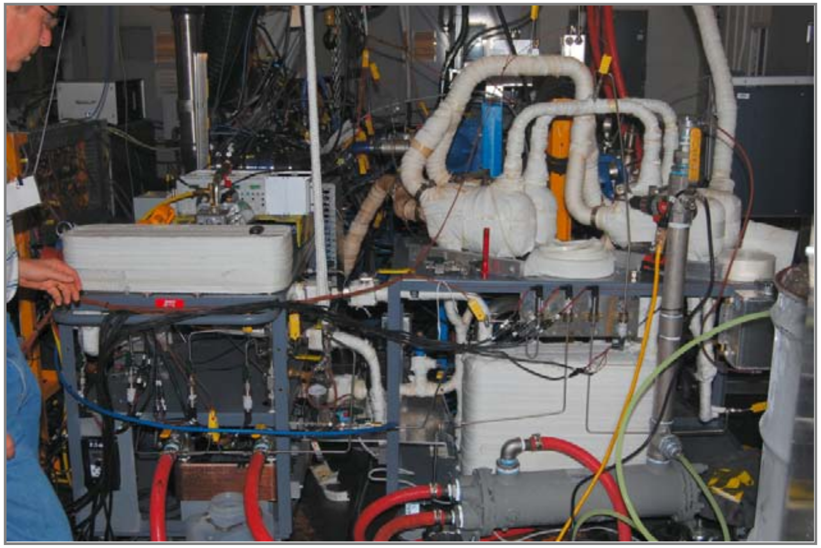
Collaborations and Interactions

- **Industry Tech Teams and DOE Working Groups**
  - Regular status updates to ACEC Tech Team on status of Vehicle Technologies milestones.
- **VanDyne SuperTurbos**
  - Modeling interactions on path to finalizing turbo-compounding design. VanDyne anticipates providing hardware to ORNL for evaluation.
- **Barber-Nichols**
  - Expander/generator construction and input on ORC design and implementation.
- **Gamma Technologies**
  - Many one-on-one interactions for added GT-Power features to enable this level of thermodynamic analysis and bottoming cycle modeling.
- **General Motors**
  - Support of GM 1.9-L engines and open controllers.
- **Other ORNL-DOE Activities**
  - Fuels, emissions, and vehicle systems modeling activities.

Next Steps FY 2010

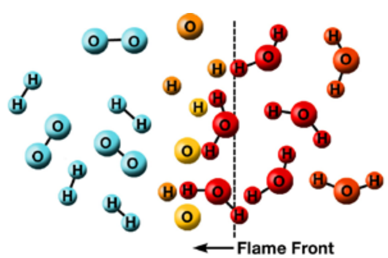
- ***On track*** **to meet milestones end of Q4.**
- **Demonstrate combined engine-system peak 45% BTE.**
- **Further explore ORC potential across LD drive cycle to better understand cycle matching with bottoming cycle.**
- **Make use of simulation tools to explore thermal storage (capacitance) for maximizing thermal energy recovery across transient drive-cycles.**
- **Archive ORC experiments and modeling with series of publications.**

ORC installed on GM 1.9-L engine in FEERC Cell 2. Size would be dramatically reduced with purpose designed heat exchangers.



Future FY 2011

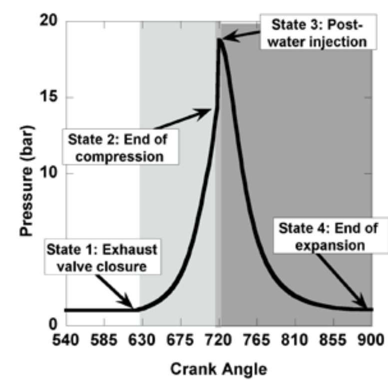
- **Continue to serve in role of demonstrating Vehicle Technologies efficiency and emissions milestones.**
  - Assessment of current state-of-the-art and provide support in defining future Vehicle Technologies goals based on fundamentals.
  - Fundamental thermodynamics approach to understanding high efficiency technologies.
  - Evaluation of advanced combustion concepts to understand fundamental advantages/disadvantages (leveraged with other ORNL projects).
  - Integration of advanced technologies which may include advanced combustion, thermal energy recovery, aftertreatment, thermal management, adaptive controls, and advanced (enabling) materials.
- **Leverage with fundamental expertise and on-going activities to better understand systems integration issues and fuel economy potential.**



Fundamental approaches to combustion

$$\left.\frac{dS}{dt}\right|_{CV} = \underbrace{\sum_{in}\dot{m}s - \sum_{out}\dot{m}s}_{\text{Path Independent}} + \underbrace{\int \frac{\partial \dot{Q}}{T_w} + \frac{\dot{I}}{T_o}}_{\text{Path Dependent}}$$

Characterize state-of-the-art and define efficiency potential of next generation of engines



Advance concepts for maximum useful fuel utilization

Summary

On track to meet FY 2010 Joule milestones.

- **Relevance**
  - » Demonstration of Vehicle Technologies fuel efficiency milestones.
- **Approach**
  - » Comprehensive approach including Modeling + Experiments + Analysis + Collaboration.
- **Technical Accomplishments**
  - » Demonstrated 44.3% combined peak BTE on path to FY 2010 goal of 45% BTE (Q4 milestone).
  - » Modeled and characterized potential efficiency improvements of ORC system under road-load conditions (Q2 milestone) and over a LD drive-cycle.
- **Collaborations**
  - » Regular communication to DOE, industry, and others through technical meetings and one-on-one interactions.
  - » Barber-Nichols, Gamma Technologies, VanDyne SuperTurbos.
  - » General Motors on support of GM 1.9-L diesel engines.
- **Future**
  - » **Continue to serve role of demonstrating Vehicle Technologies efficiency and emissions milestones.**
  - » Support Vehicle Technologies and ACEC Tech Team in characterization of current state-of-the-art and defining future efficiency/emissions targets.
  - » Develop and assess advanced efficiency technologies on multi-cylinder engines.

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