Overview

Duration
- FY 2005 to 2010
- Consistent with VT MYPP

Barriers
- Efficiency/combustion
- Emission control
- Engine management

Budget
- FY 2005 $0k (milestone met)
- FY 2006 $400k (milestone met)
- FY 2007 $400k (milestone met)
- FY 2008 $750k (milestone met)
- FY 2009 $750k (in progress)
- FY 2010 $750k (path defined)

Interactions / Collaborations
- Industry technical teams
- DOE working groups
- One-on-one interactions with industry
- Other ORNL activities
Objective is to identify and demonstrate technologies for improving engine-system thermal efficiency while meeting emissions targets

- Characterize current state-of-the-art light-duty engine technology.
- Improve understanding of ICE efficiency losses.
- Identify promising strategies to reduce losses.
- Implement proof-of-principle demonstrations of selected concepts.

Achieve and demonstrate Vehicle Technologies engine fuel efficiency and emissions milestones.

Current engines

Fuel Efficiency
40 - 42%

Future engines?

Fuel Efficiency
50 - 60%
Milestones consistent with demonstrating DOE Vehicle Technologies efficiency & emissions objectives

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>Peak Brake Thermal Efficiency (HC Fuel)</td>
<td>41%</td>
<td>42%</td>
<td>43%</td>
<td>44%</td>
<td>45%</td>
</tr>
<tr>
<td>Part-Load Brake Thermal Efficiency (2 bar BMEP @ 1500 rpm)</td>
<td>27%</td>
<td>27%</td>
<td>27%</td>
<td>29%</td>
<td>31%</td>
</tr>
<tr>
<td>Emissions</td>
<td>Tier 2 Bin 5</td>
<td>Tier 2 Bin 5</td>
<td>Tier 2 Bin 5</td>
<td>Tier 2 Bin 5</td>
<td>Tier 2 Bin 5</td>
</tr>
<tr>
<td>Thermal efficiency penalty due to emission control devices</td>
<td>&lt; 2%</td>
<td>&lt; 2%</td>
<td>&lt; 2%</td>
<td>&lt; 1%</td>
<td>&lt; 1%</td>
</tr>
</tbody>
</table>

Activity supports a Joule Milestone that is recorded in the DOE budget narrative as well as the FreedomCAR partnership goals. Effort is performed in close communication with the ACEC Tech Team.
Past, present, and path forward

**2005**
- 1999 MB 1.7-L engine

**2006**
- 1999 MB 1.7-L engine with modified operation.
- Development of 2nd Law thermodynamics for engine simulation software.

**2007**
- 1999 MB 1.7-L engine with upgraded hardware VGT.
- 2005 GM 1.9-L engine.
- Modeling component-by-component evaluation of efficiency opportunities.

**2008**
- 2005 GM 1.9-L engine.
- Fuel properties, low viscosity oil, electrification, modified operation.
- Experimental component-by-component evaluation of efficiency opportunities.
- Modeling and hardware development of exhaust bottoming cycle.

**2009 / 2010**
- Low viscosity oil, electrification, modified operation, etc.
- TER with integrated turbine/generator.
- On-engine integration of advanced combustion and aftertreatment activities.
- Demonstration/verification with FTP modal experiments and vehicle system drive cycle simulations.

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**Brake Thermal Efficiency, %**

- **Goal**
- **Demonstrated**

- **2005**
- **2006**
- **2007**
- **2008**
- **2009**
- **2010**

**Characterization** ➔ **Development** ➔ **Integration** ➔ **Demonstration**

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5 Managed by UT-Battelle for the U.S. Department of Energy
Comprehensive approach to system efficiency opportunities/issues builds upon on-going activities at ORNL and elsewhere.

This activity addresses component and system level engine, thermal energy recovery, and aftertreatment interactions through experiment/modeling.

Regular interactions DOE working groups, industry and technical teams.
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) development bench**
  - Evaluate TER concepts and develop hardware in controlled environment before integration to engine-system.
Simulation + Experiment + Thermodynamics + Collaboration (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.

Collaborations to make best use of available resources.

- General Motors
  - Informal interactions on engine controls.

- Woodward Governor
  - Turbo-compounding.

- Barber Nichols
  - Development of integrated turbine/generator expander.

Example 2nd Law Distribution

36% Irreversibility (mixing, combustion, throttling, etc)
14% Availability Exhaust Flow
10% Heat Loss (engine block, head, intercooler, etc)
40% Indicated Work from Combustion

GM ECU/ETAS controller

Woodward SuperTurbo

Integrated turbine/generator expander
Technical Accomplishments/Progress (since February 2008)

• Demonstrated 43% peak BTE and 27% part-load BTE.

• Characterized availability and potential of thermal energy discarded to the environment on a GM 1.9-L engine.

• Estimated potential fuel economy improvements of thermal energy recovery over FTP drive cycle using modal experiments.

• Developed and evaluated on-bench and on-engine a first generation organic Rankine cycle.

• In progress development of bottoming cycle model for GT-Drive to better understand benefits and/or operational issues for optimal efficiency.

• In progress development of turbine/generator system for improved bottoming cycle efficiency in collaboration with Barber-Nichols.
More detail on FY 2008 milestone

Enabling technologies used to meet FY 2008 43% peak and 27% part-load BTE milestones.

**Fuel Properties (~0.3% BTE)**
High CN within range of US market fuels.

**Advanced Lubricants (~0.6% BTE)**
Low viscosity oils.

**Engine Operation (~0.4% BTE)**
Turbo-machinery and fuel parameters. Also contributed in part to 42% peak BTE in FY 2007.

**Electrification of Components (~0.1% BTE)**
Engine coolant pump.

**Thermal Energy Recovery**
Modeling complete and experiments in progress for evaluating potential on exhaust and EGR systems. Not used toward 43%.

* BTE improvement relative to peak BTE of engine.

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GM 1.9-L in ORNL Cell 4

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**Brake Thermal Efficiency, %**

- **Goal**
- **Demonstrated**

<table>
<thead>
<tr>
<th>Year</th>
<th>Goal</th>
<th>Demonstrated</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>34%</td>
<td>36%</td>
</tr>
<tr>
<td>2006</td>
<td>38%</td>
<td>40%</td>
</tr>
<tr>
<td>2007</td>
<td>42%</td>
<td>44%</td>
</tr>
<tr>
<td>2008</td>
<td>46%</td>
<td>46%</td>
</tr>
<tr>
<td>2009</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td></td>
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</tr>
</tbody>
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* BTE improvement relative to peak BTE of engine.
Substantial improvements in engine efficiency will require a reduction in energy losses to the environment.
A 2nd Law thermodynamics perspective provides insight into the recovery potential of energy discarded to the environment.

What about intercooler and engine coolant energy?
Potential improvement in BTE makes thermal energy recovery (TER) a must investigate technology for transportation

- Source data from GM 1.9-L engine.
- Estimates based on 2nd Law availability from exhaust and EGR systems.
- TER efficiency is assumed fixed across the speed-load range to simplify estimates.

Does this make sense for light-duty drive cycle?
Fuel economy improvements over FTP drive cycle estimated using modal experiments and thermal energy recovery assumptions

- Estimates based on steady-state modal conditions (below) and experimental data.
- Assumptions do not account for cold-start, transient phenomena, aftertreatment regeneration, added mass of TER system, etc.
- TER system efficiency assumed constant over speed-load range.

<table>
<thead>
<tr>
<th>Point</th>
<th>Speed / Load</th>
<th>Weight Factor</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1500 rpm / 1.0 bar</td>
<td>400</td>
<td>Catalyst transition temperature</td>
</tr>
<tr>
<td>2</td>
<td>1500 rpm / 2.6 bar</td>
<td>600</td>
<td>Low speed cruise</td>
</tr>
<tr>
<td>3</td>
<td>2000 rpm / 2.0 bar</td>
<td>200</td>
<td>Low speed cruise with slight acceleration</td>
</tr>
<tr>
<td>4</td>
<td>2300 rpm / 4.2 bar</td>
<td>200</td>
<td>Moderate acceleration</td>
</tr>
<tr>
<td>5</td>
<td>2600 rpm / 8.8 bar</td>
<td>75</td>
<td>Hard acceleration</td>
</tr>
</tbody>
</table>

Estimated drive cycle fuel savings with TER from exhaust and EGR based on GM 1.9-L engine data.

<table>
<thead>
<tr>
<th>2nd Law (1st Law) TER System Efficiency</th>
<th>Estimated Fuel Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>30% (6%)</td>
<td>8.6%</td>
</tr>
<tr>
<td>50% (10%)</td>
<td>11.4%</td>
</tr>
<tr>
<td>100% (20%)</td>
<td>17.0%</td>
</tr>
</tbody>
</table>

For more information on modal conditions see SAE 1999-01-3475, 2001-01-0151, 2002-01-2884, 2006-01-3311 (ORNL)
Vehicle system models used to assess issues and potential of thermal energy recovery on light-duty vehicles

- GT-Drive and/or PSAT with integrated transient capable TER models.
- Evaluation of thermal damper and/or capacitor technologies for damping thermal transients on energy recovery system.
- Assessment of TER system mass on fuel economy.
- Develop and evaluate strategies for managing technologies which compete for same thermal resources under real-world driving conditions.

Example Chassis Dynamometer Vehicle Data (Saab BioPower)
Organic Rankine Cycle (ORC) model developed to better understand benefits and/or operational issues for optimal efficiency

- **Capable of modeling …**
  - Steady-state operation with GT-Power engine model.
  - Transient (drive-cycle) operation using GT-Drive.

- **Working fluid**
  - Transition to R245fa with introduction of two-phase flow support in GT-Suite 7.0 (release Q2 2009).

- **Transient control**
  - Coolant flow rate to prevent condensation in expander.

- **Next steps include …**
  - Assess impact of ORC system mass on vehicle fuel economy improvements.
  - Investigate thermal damping and thermal management to buffer drive cycle transients.
  - Evaluate synergies and/or issues of TER and aftertreatment interactions.
A first generation organic Rankine cycle has been modeled, designed, built, and installed on a GM 1.9-L engine

- **Modeling and literature show potential for 45% BTE with exhaust energy recovery.**
  - Requires ~10% 1st Law (30% 2nd Law) recovery efficiency.

- **Working fluid**
  - R123 near-term for comparison with literature.

- **Component selection**
  - Exhaust heat exchanger – From EGR system of HD diesel engine.
  - Expander – *Multi-vane air motor* and scroll compressor (reverse) from auto AC system.
  - Condenser – Simple shell-and-tube design.

- **Lessons learned**
  - Systems requires higher outlet pressure pump than used in first pass.
  - Off-the-shelf expander components did not meet expectations and exhibited too much leakage.
  - Simple boiler and condenser designs appear adequate.
  - Need improved bench evaluation capability for troubleshooting next generation system.
Expander selection is critical for efficient Rankine system

- Several options explored including piston, scroll, and turbine expanders.

<table>
<thead>
<tr>
<th>Piston</th>
<th>Scroll</th>
<th>Turbine</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Minimal sealing issues.</td>
<td>• Sealing challenges for power generation.</td>
<td>• Proven performance in HD TER applications.</td>
</tr>
<tr>
<td>• Unknown refrigerant compatibility.</td>
<td>• Highly developed for refrigerant applications.</td>
<td>• Not compatible with two-phase flow (control issue).</td>
</tr>
<tr>
<td></td>
<td>• Compatible with two-phase flow.</td>
<td></td>
</tr>
</tbody>
</table>

In progress path is development of integrated turbine/generator expander in collaboration with Barber Nichols. Similar path as used by Cummins for HD applications – leverage DOE investment.

- Combine with 2008 improvements to demonstrate 44% peak BTE in FY 2009.
- Improved turbine blade design (budget constraint in 2009) to demonstrate 45% peak BTE in FY 2010.

Images Source: Cummins,
DEER 2006
More detail on design and implementation of turbine/generator

- Designed for peak BTE operation on GM 1.9-L engine.
  - Part-load BTE potential not fully known but under investigation.

- Radial inflow turbine with direct-driving permanent magnet alternator.
  - Compatible with R245fa refrigerant.
  - Simple power electronics and load bank will be used to measure electrical power.

- BTE of engine-system based on shaft and electrical power.

Integrated turbine/generator system
(figures courtesy Barber-Nichols)
Turbo-compounding also under investigation through informal collaboration with Woodward Governor

- Woodward Governor anticipates supplying ORNL with a prototype system in the Fall of 2009.
- SuperTurbo has potential for improved engine-system efficiency and backpressure control for high dilution operation.
- ORNL is developing GT-Power sub-model for sizing turbocharger components for GM engine and operational range of interest.

*Woodward SuperTurbo rendering

*Turbocharger sizing with WAVE and GT-Power*
Parasitic losses are still significant and provide opportunity in modern engines

- High fuel injection pressures associated with advanced combustion operation require significant shaft energy.
  - Does improvement in emissions and reduction in aftertreatment offset efficiency cost?

- New lubricants and coatings may provide significant reductions in frictional losses.
  - Several activities at ORNL on coatings, ionic liquids, etc.
  - +0.6% increase in peak BTE demonstrated with low friction lubricant.

- Electrification of auxiliary components has potential for more efficient management of coolant and fuel systems.
  - Important for effective thermal management of next generation engines.
  - +0.1% increase in peak BTE demonstrated with electric engine coolant pump.
What about emissions?

- Advanced combustion and aftertreatment are important part of meeting the Vehicle Technologies emissions and efficiency milestones.

- These activities are being presented separately at this review:

  **ACE 17**: next presentation
  *Achieving High Efficiency Clean Combustion in Multi-Cylinder Light-Duty Engines*

  **ACE 31**: Dr. James Parks; May 21, 9:30 am
  *Controlling NOx from Multi-Mode Lean DI Engines*
Path forward to FY 2010 milestones

- **Brake Thermal Efficiency**
  - Thermal energy recovery principal path to peak and part-load BTE.
  - Improved turbo-machinery (Turbo-compounding prototype to be supplied by Woodward in FY 2009).
  - Low friction lubricants/coatings and reductions in other parasitic losses.

- **Emissions**
  - Advanced combustion operation to reduce in-cylinder emissions and corresponding aftertreatment requirements.
  - Integration of appropriate aftertreatment systems.

- **Demonstration & Verification of Milestones**
  - On-engine experiments with thermal energy recovery devices.
  - FTP modal experiments for drive-cycle emissions estimates.
  - Vehicle system modeling with GT-Drive and/or PSAT.
Summary or *take away points*

- **Vehicle Technology Milestones Met**
  - FY 2008 peak and part-load BTE milestones met on time with well-defined path forward to FY 2010.
  - Progress made on emissions targets (separate presentation).

- **Technology Path & Demonstration**
  - Comprehensive path builds on several on-going activities at ORNL and elsewhere.
  - Thermal energy recovery necessary to meet 45% BTE without significant base engine modifications (constrained by budget).
  - Thermal energy recovery being investigated on-engine and with *transient realistic* models using GT-Suite. Modeling also allows for the evaluation of longer term technologies such as thermal dampers and capacitors.

- **Technology Transfer**
  - Aspects of this activity are regularly communicated to DOE, industry, and others through government working groups, technical meetings, and one-on-one interactions.

- **Longer Term**
  - *Need* for more emphasis on the development, integration, and evaluation of advanced transportation technologies to better understand synergies and/or operational issues for optimal efficiency AND lowest emissions.

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