# Achieving and Demonstrating Vehicle Technologies Engine Fuel Efficiency Milestones (ACE 16)


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U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY
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# 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)

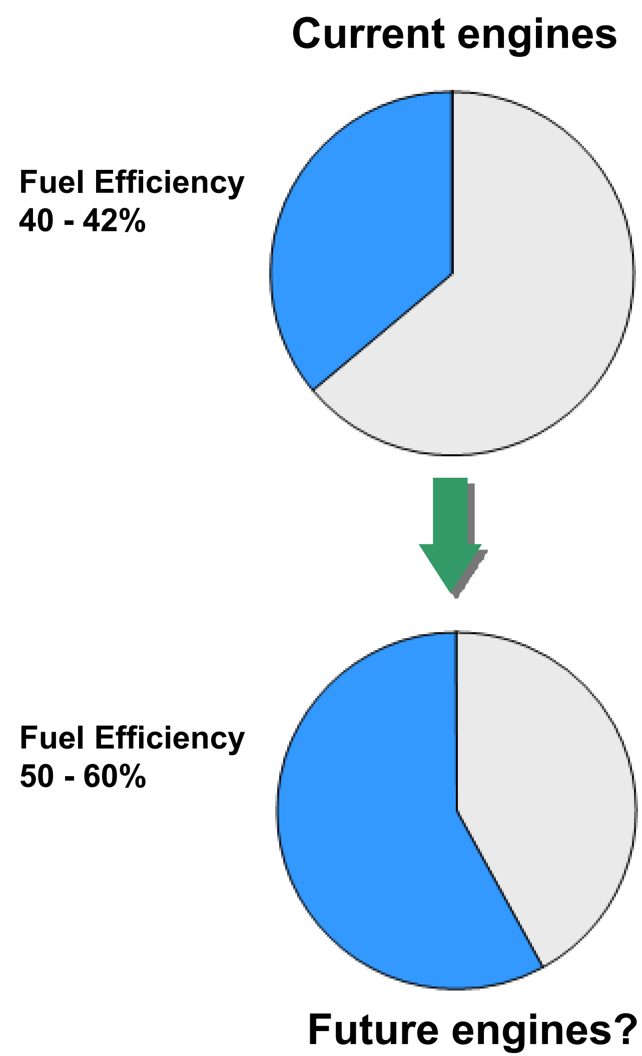
## Interactions / Collaborations

- 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.**



# Milestones consistent with demonstrating DOE Vehicle Technologies efficiency & emissions objectives

*In progress* (FY 2009–FY 2010)

| 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% |


**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

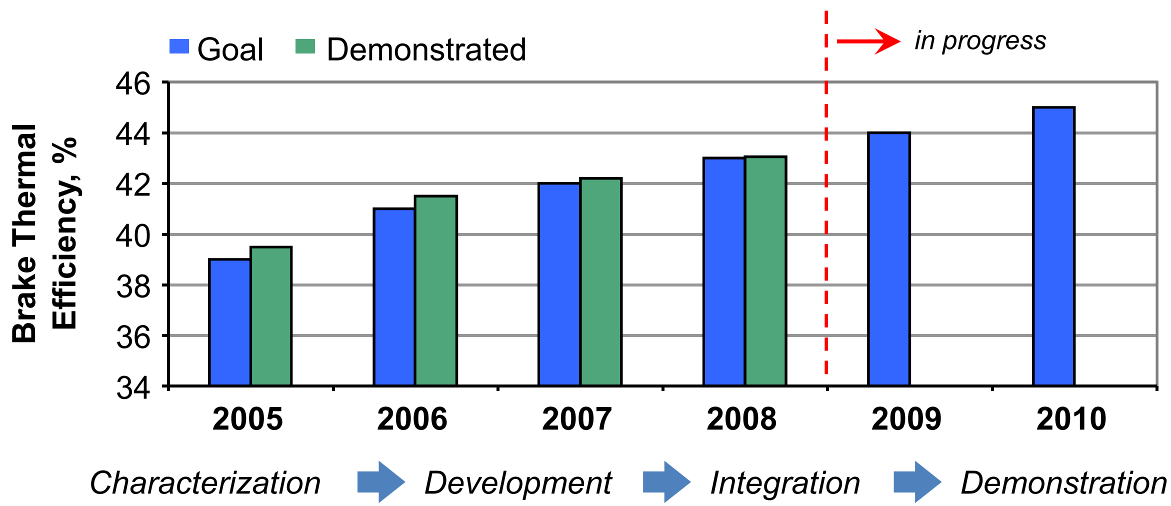
### 2005
1999 MB 1.7-L engine

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

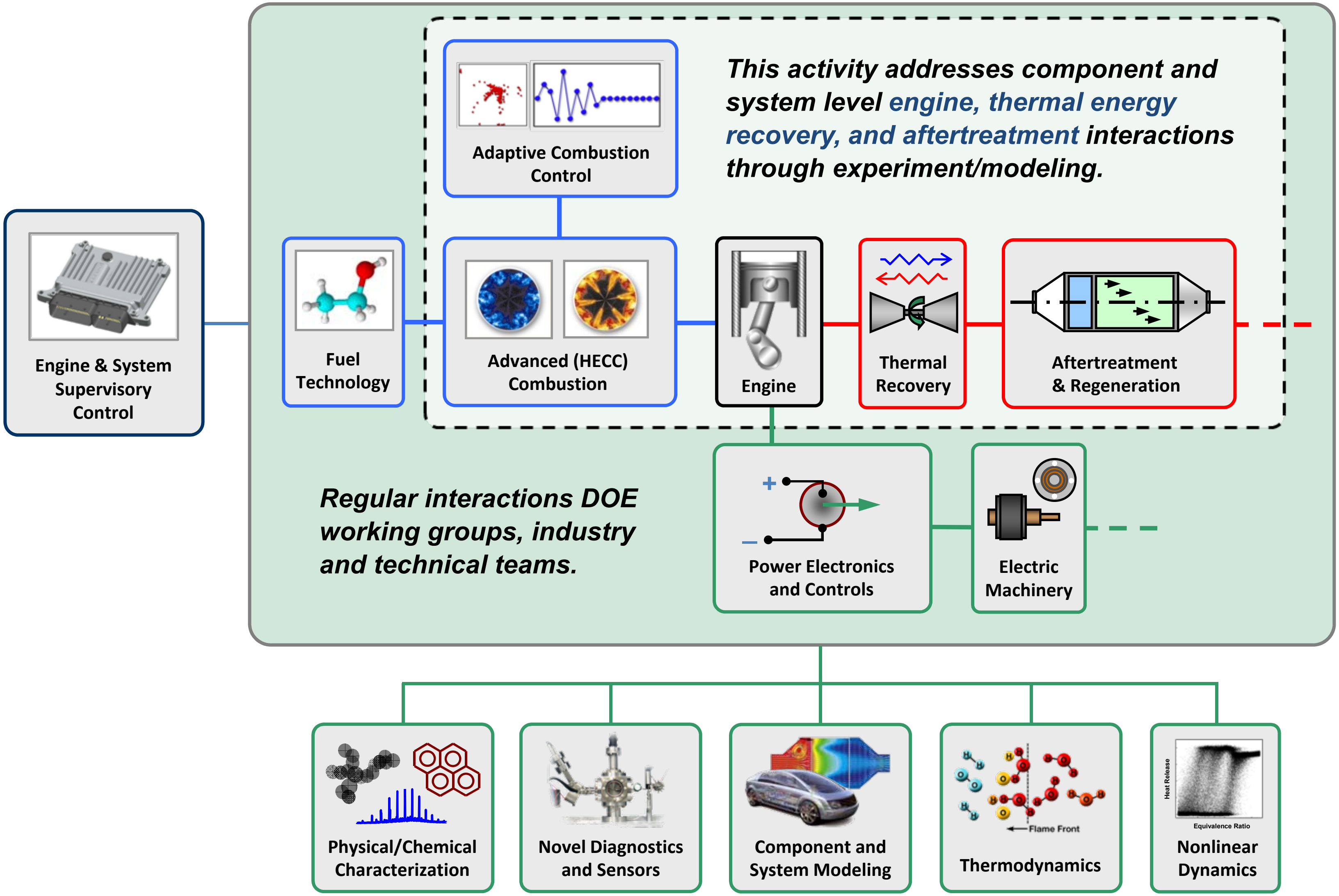
### 2007
- 1999 MB 1.7-L engine with upgraded hardware VGT.
- 2005 GM 1.9-L engine.
- Modeling component-by-component evaluation of efficiency opportunities.

### 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
» 2007 GM 1.9-L engine.
» 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.

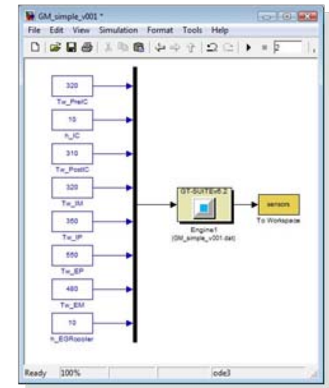


# Comprehensive approach to system efficiency opportunities/issues builds upon on-going activities at ORNL and elsewhere



# 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.**

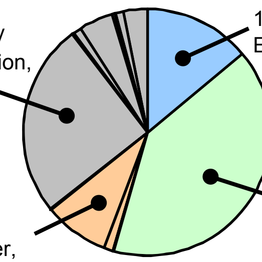
- **GM 1.9-L diesel engine (2)**
  - » Open controls including flexible microprocessor based dSpace system.
  - » Instrumentation for combustion, thermodynamic, and exhaust characterization.
- ***Thermal energy recovery* (TER) development bench**
  - » Evaluate TER concepts and develop hardware in controlled 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.

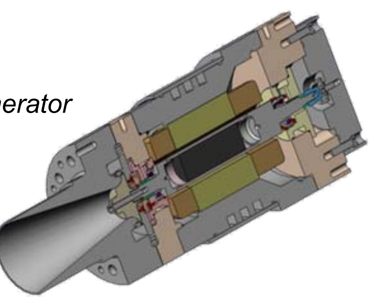
Example 2nd Law Distribution



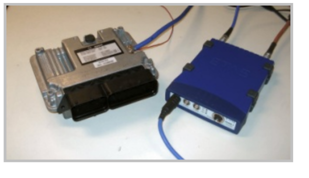

## Collaborations to make best use of available resources.

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

*Integrated turbine/generator expander*



*Woodward SuperTurbo*



*GM ECU/ETAS controller*

# 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.**

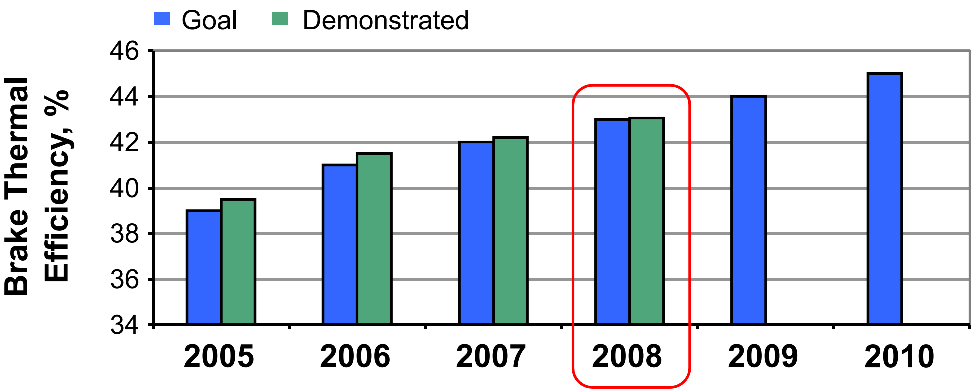
**Fuel Properties (~0.3% BTE)***
*High CN within range of US market fuels.*

**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%.*




*GM 1.9-L in ORNL Cell 4*

*** BTE improvement relative to peak BTE of engine.**



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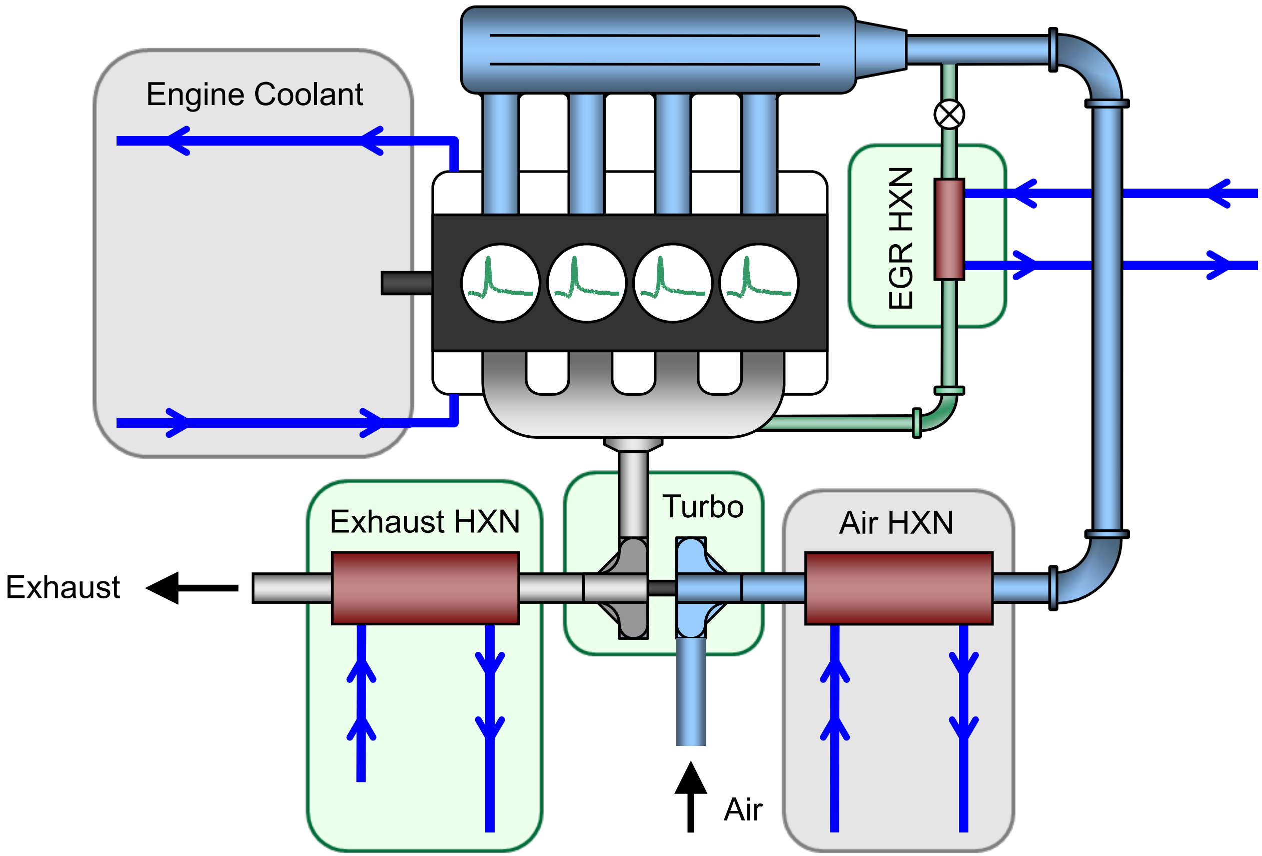
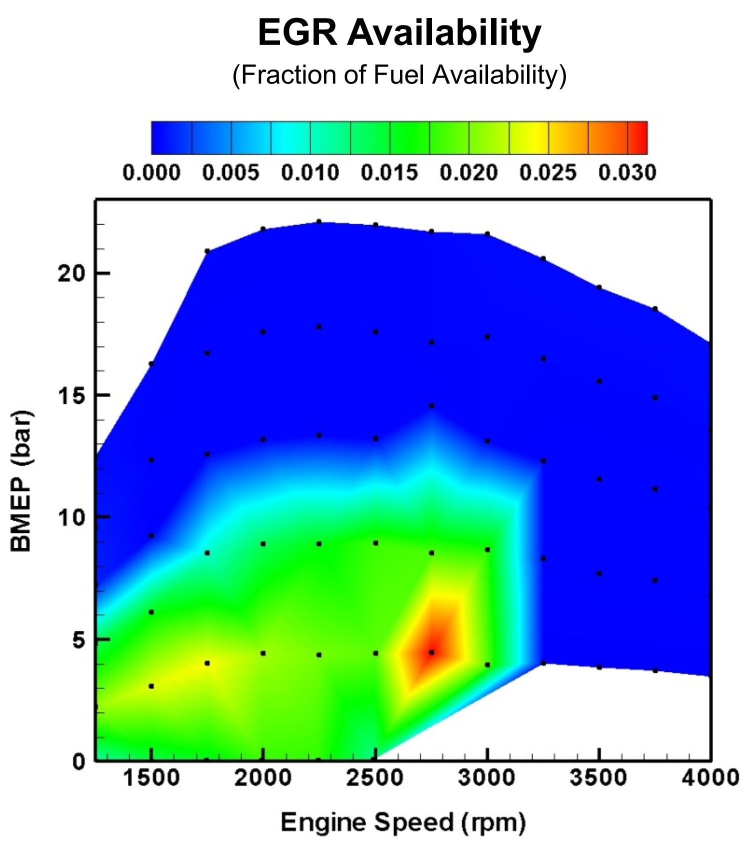
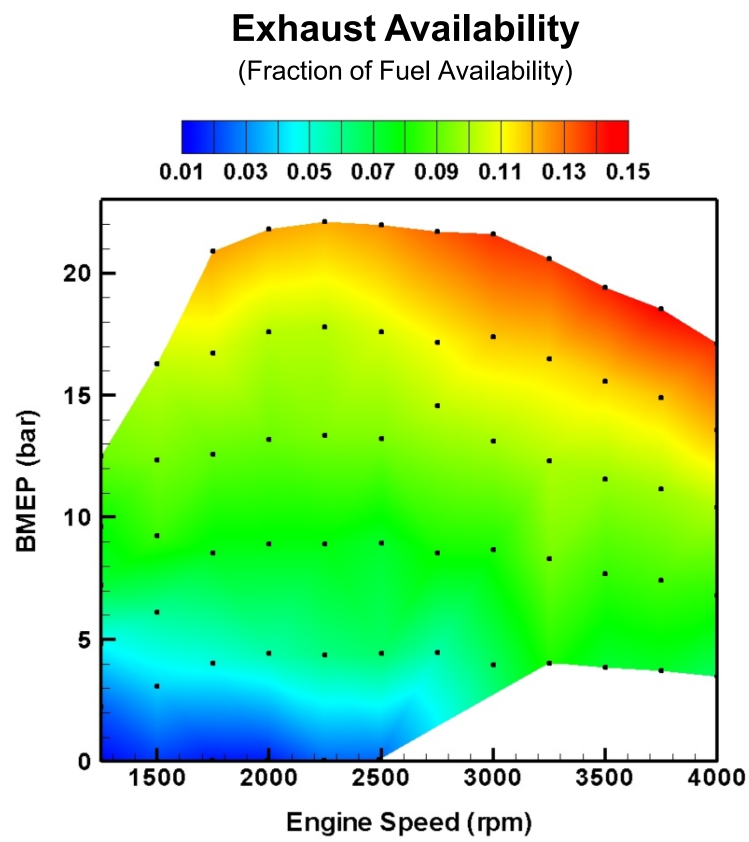
# Substantial improvements in engine efficiency will require a reduction in energy losses to the environment



# A 2nd Law thermodynamics perspective provides insight into the recovery potential of energy discarded to the environment



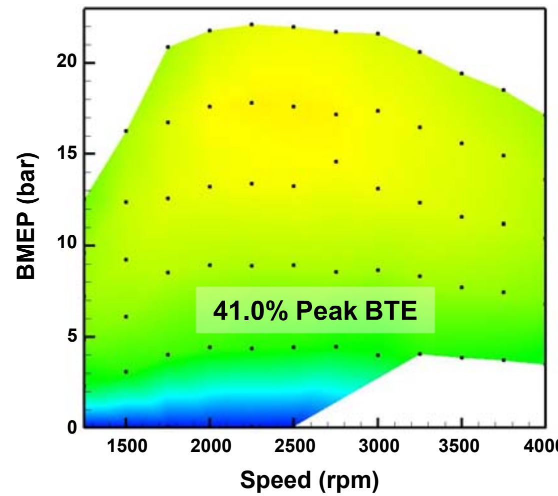

**What about intercooler and engine coolant energy?**

# Potential improvement in BTE makes thermal energy recovery (TER) a *must investigate technology* for transportation

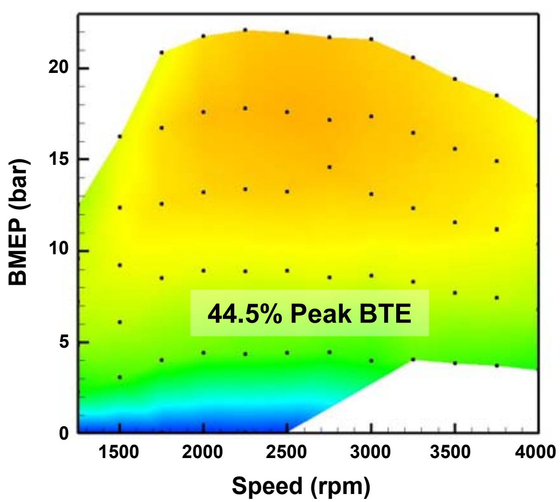
- **Source data from GM 1.9-L engine.**
- **Estimates based on 2nd Law <u>availability</u> from exhaust and EGR systems.**
- **TER efficiency is assumed fixed across the speed-load range to simplify estimates.**

➡ **Does this make sense for light-duty drive cycle?**

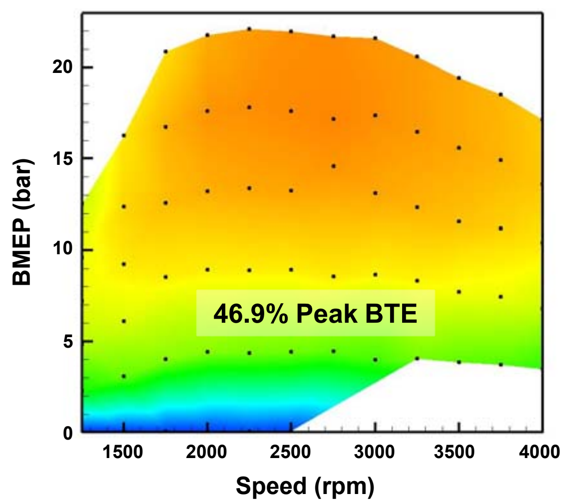
**Base condition**



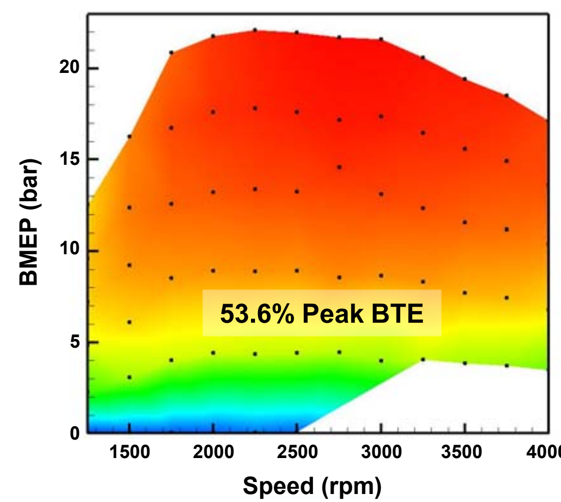

**30% recovery**



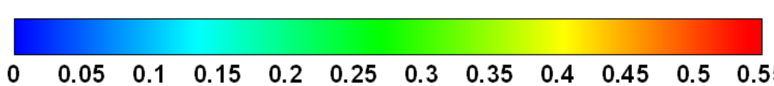

**50% recovery**




**100% recovery**




**BTE Scale:**



# 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.**

| Point | Speed / Load | Weight Factor | Description |
|---|---|---|---|
| **1** | 1500 rpm / 1.0 bar | 400 | Catalyst transition temperature |
| **2** | 1500 rpm / 2.6 bar | 600 | Low speed cruise |
| **3** | 2000 rpm / 2.0 bar | 200 | Low speed cruise with slight acceleration |
| **4** | 2300 rpm / 4.2 bar | 200 | Moderate acceleration |
| **5** | 2600 rpm / 8.8 bar | 75 | Hard acceleration |

For more information on modal conditions see
SAE 1999-01-3475, 2001-01-0151, 2002-01-2884, 2006-01-3311 (ORNL)

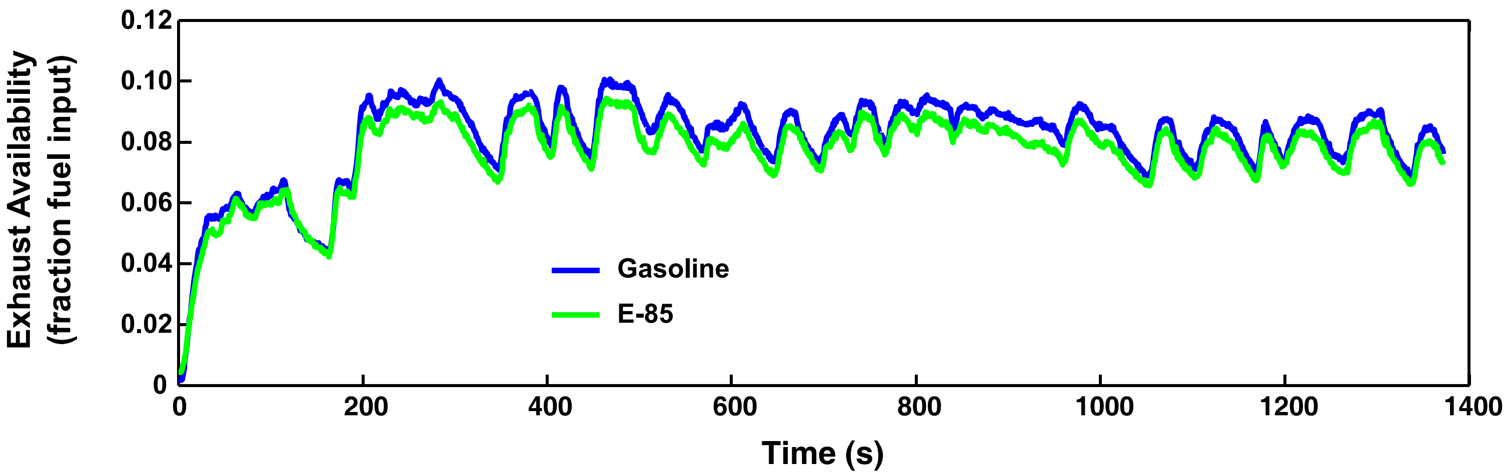
| $2^{nd}$ Law ($1^{st}$ Law) TER System Efficiency | Estimated Fuel Savings |
|---|---|
| **30% (6%)** | **8.6%** |
| **50% (10%)** | **11.4%** |
| **100% (20%)** | **17.0%** |

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

# Vehicle system models used to assess issues and potential of thermal energy recovery on light-duty vehicles

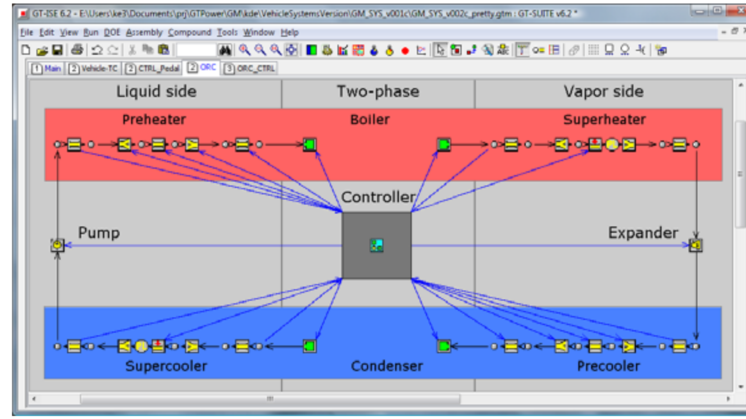
- **GT-Drive and/or PSAT with integrated transient capable TER models.**
- **Evaluation of thermal damper and/or capacitor technologies for damping thermal transients on energy recovery system.**
- **Assessment of TER system mass on fuel economy.**
- **Develop and evaluate strategies for managing technologies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

**Example Chassis Dynamometer Vehicle Data (Saab BioPower)**

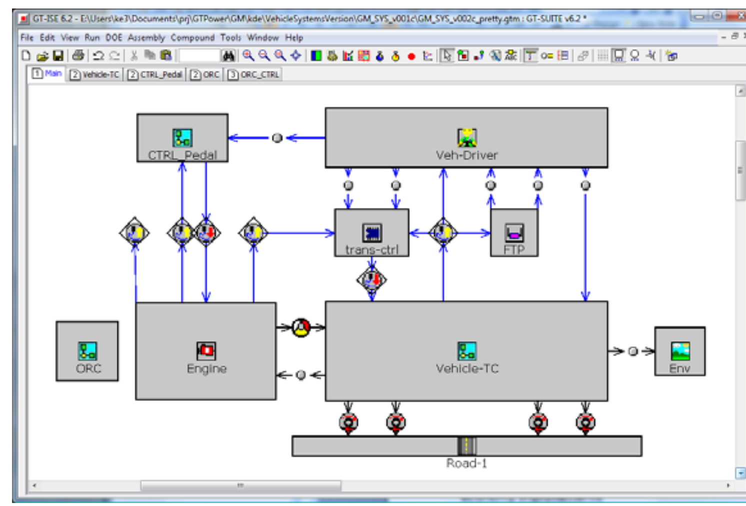


# Organic Rankine Cycle (ORC) model developed to better understand benefits and/or operational issues for optimal efficiency

- **Capable of modeling …**
  - Steady-state operation with GT-Power engine model.
  - Transient (drive-cycle) operation using GT-Drive.
- **Working fluid**
  - Initial model based on water using approach developed by Cummins (2006 Gamma Technologies NA User's Conference).
  - 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.




*Organic Rankine cycle model*



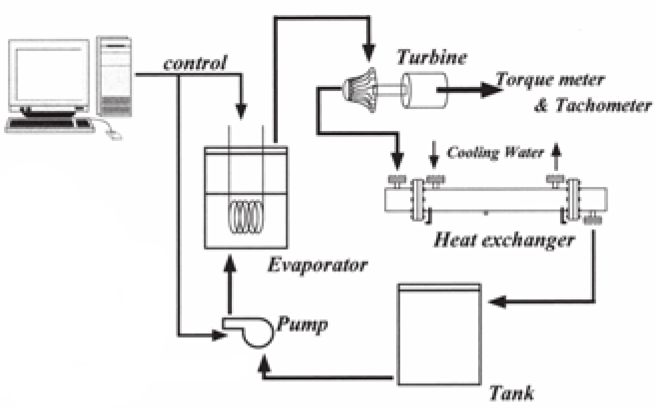

*GT-Suite vehicle system model*

# 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.

*Air motor expander*

- **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.**

**Piston**
- Minimal sealing issues.
- Unknown refrigerant compatibility.

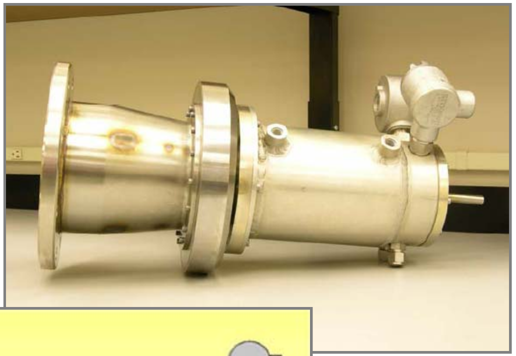
**Scroll**
- Sealing challenges for power generation.
- Highly developed for refrigerant applications.
- Compatible with two-phase flow.

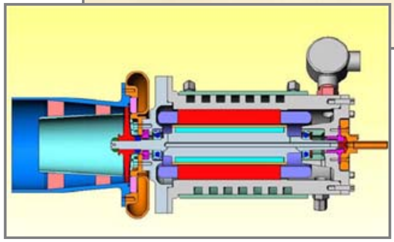
**Turbine**
- Proven performance in HD TER applications.
- Not compatible with two-phase flow (control issue).

➡ ***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.**

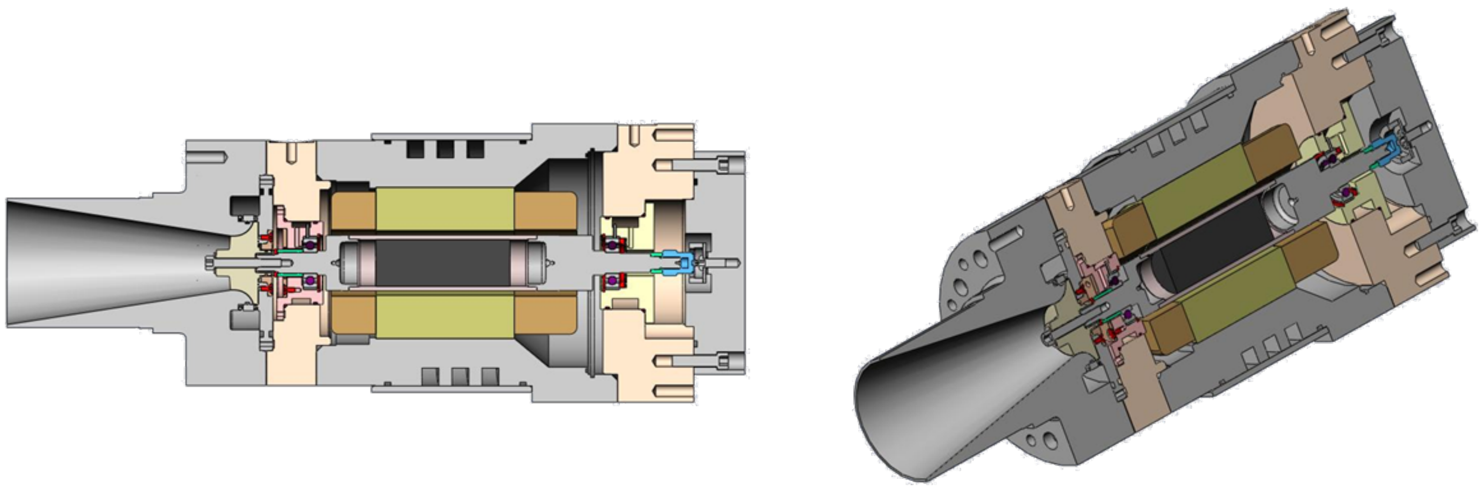




*Images Source: Cummins, DEER 2006*

# 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)*



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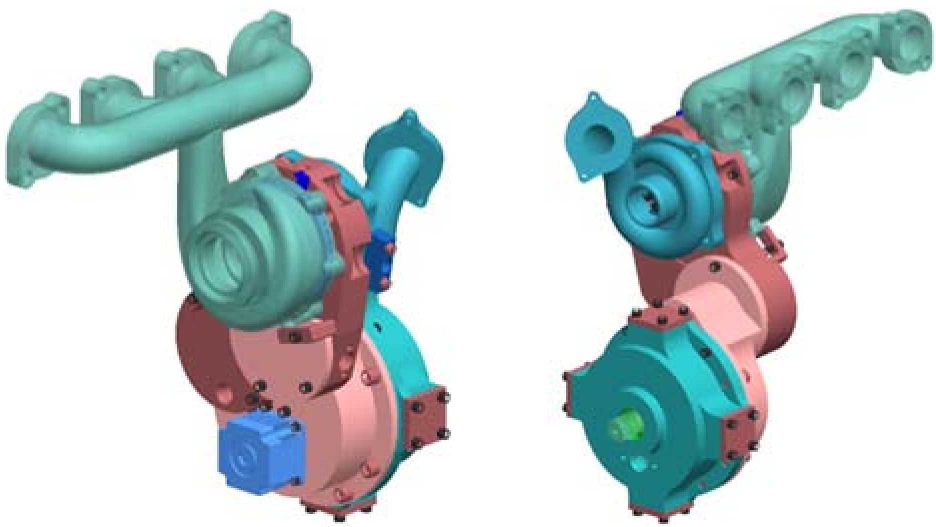
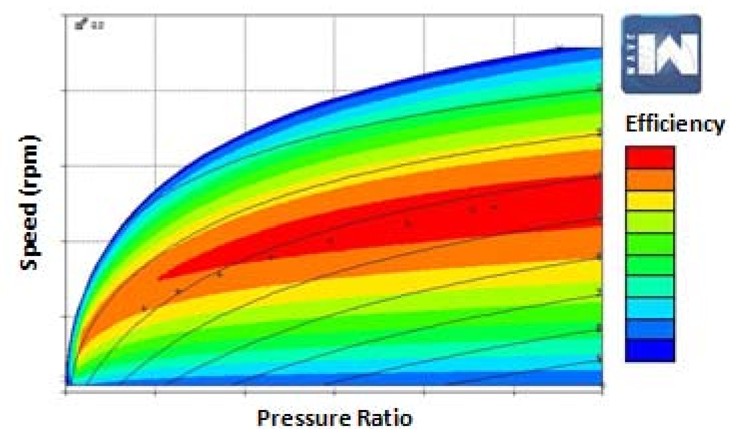
# Turbo-compounding also under investigation through informal collaboration with Woodward Governor

- **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.**






*Turbocharger sizing with WAVE and GT-Power*

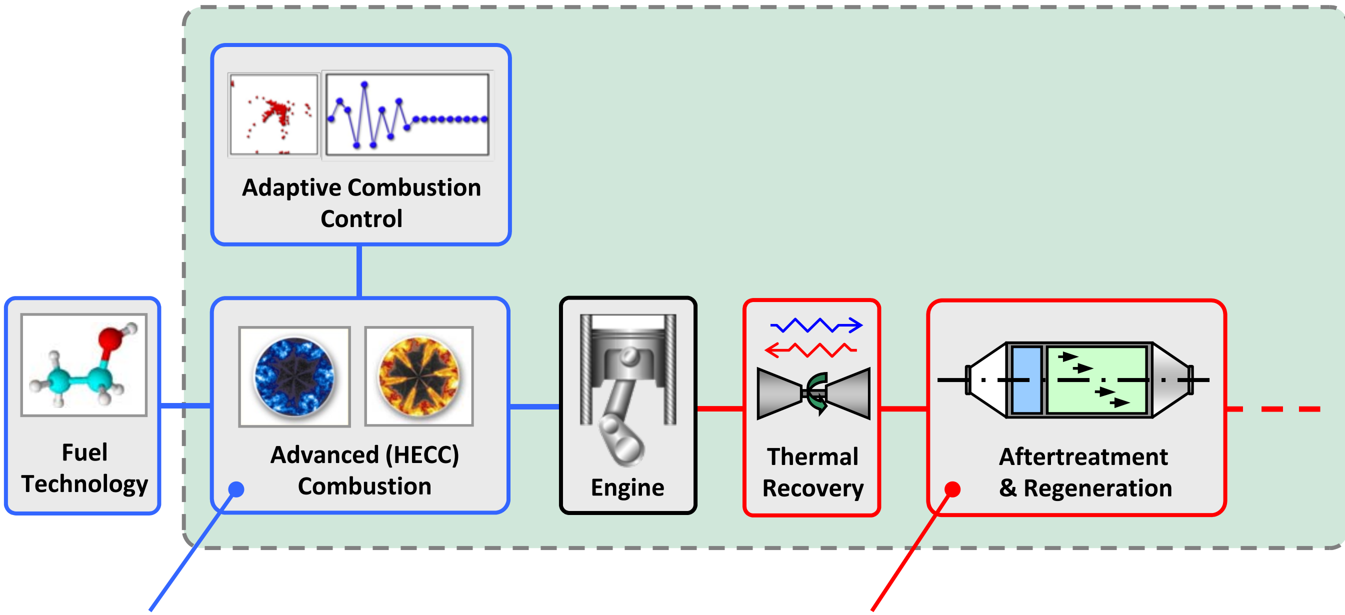
*Woodward SuperTurbo rendering*

# 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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