I. INTRODUCTION

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DEVELOPING ADVANCED COMBUSTION ENGINE TECHNOLOGIES

On behalf of the Department of Energy's Office of Vehicle Technologies, we are pleased to introduce the Fiscal Year (FY) 2007 Annual Progress Report for the Advanced Combustion Engine R&D Sub-Program. The mission of the Vehicle Technologies (VT) Program is to develop more energy-efficient and environmentally friendly highway transportation technologies that enable the United States to use less petroleum. The Advanced Combustion Engine R&D Sub-Program supports this mission and the President's initiatives by removing the critical technical barriers to commercialization of advanced internal combustion engines for light-, medium-, and heavy-duty highway vehicles that meet future Federal emissions regulations. The primary goal of the Advanced Combustion Engine R&D Sub-Program is to improve the brake thermal efficiency of internal combustion engines:

- for passenger vehicles, from 30% (2002 baseline) to 45% by 2010, and
- for commercial vehicles, from 40% (2002 baseline) to 55% by 2013,

while meeting cost, durability, and emissions constraints. R&D activities include work on combustion technologies that increase efficiency and minimize in-cylinder formation of emissions, aftertreatment technologies that further reduce exhaust emissions, as well as the impacts of these new technologies on human health. Research is also being conducted on approaches to produce useful work from waste engine heat through the development and application of thermoelectrics, electricity generation from exhaust-driven turbines, and incorporation of energy-extracting bottoming cycles.

Advanced internal combustion engines are a key element in the pathway to achieving the goals of the President's FreedomCAR and Fuel Partnership for transportation. Advanced engine technologies being researched will allow the use of hydrogen as a fuel in highly efficient and low-emission internal combustion engines, providing an energy-efficient interim hydrogen-based powertrain technology during the transition to hydrogen/fuel-cell-powered transportation vehicles. Hydrogen engine technologies being developed have the potential to provide diesel-like engine efficiencies with near-zero air pollution and greenhouse gas emissions.

This introduction serves to outline the nature, recent progress, and future directions of the Advanced Combustion Engine R&D Sub-Program. The research activities of this Sub-Program are planned in conjunction with the FreedomCAR and Fuel Partnership and the 21st Century Truck Partnership (CTP) and are carried out in collaboration with industry, national laboratories, and universities. Because of the importance of clean fuels in achieving high efficiency and low emissions, R&D activities are closely coordinated with the relevant activities of the Fuel Technologies Sub-Program, also within the Office of Vehicle Technologies.

BACKGROUND

Advanced combustion engines have great potential for achieving dramatic energy efficiency improvements in light-duty vehicle applications, where it is suited to both conventional and hybrid-electric powertrain configurations. Light-duty vehicles with advanced combustion engines can compete directly with gasoline engine hybrid vehicles in terms of fuel economy and consumer-friendly driving characteristics; also, they are projected to have energy efficiencies that are competitive with hydrogen fuel cell vehicles when used in hybrid applications. The primary hurdles that must be overcome to realize increased use of advanced combustion engines in light-duty vehicles are the higher cost of these engines compared to conventional engines and compliance with the U.S. Environmental Protection Agency's (EPA's) Tier 2 regulations which are phasing in from 2004-2009. The Tier 2 regulations require all light-duty vehicles to meet the same emissions standards, regardless of the powertrain. Compliance can be achieved with advanced combustion engines through the addition of catalytic emission control technologies, though these technologies are much less mature than gasoline engine catalysts and are severely affected by sulfur from the fuel and lubricant. Even the recent reduction of diesel fuel sulfur content to below 15 ppm does not assure that catalytic emission control devices will be durable and cost-effective. The Advanced Combustion Engine R&D Sub-Program focuses on developing technologies for light-, medium-, and heavy-duty internal combustion (ICE) engines operating in advanced combustion regimes, including homogeneous charge compression ignition (HCCI) and other modes of low-temperature combustion (LTC), which will increase efficiency beyond current advanced diesel engines and reduce engine-out emissions of nitrogen oxides (NOx) and particulate matter (PM) to near-zero levels.

The heavy-duty diesel engine is the primary engine for commercial vehicles because of its high efficiency and outstanding durability. However, the implementation of more stringent heavy-duty engine emission standards, which were phased in starting 2007 (100% implementation in 2010), is anticipated to cause a reduction in fuel efficiency due to the exhaust emission control devices needed to meet emissions regulations for both NOx and PM. Heavy-duty vehicles using diesel engines also have significant potential to employ advanced combustion regimes and a wide range of waste heat recovery technologies that will both improve engine efficiency and reduce fuel consumption.

Advanced engine technologies being researched and developed by the Advanced Combustion Engine R&D Sub-Program will also allow the use of hydrogen as a fuel in ICEs and will provide an energy-efficient interim hydrogen-based powertrain technology during the transition to hydrogen/fuel-cell-powered transportation vehicles.

Given these challenges, the Advanced Combustion Engine Technologies Sub-Program is working toward achieving the following objectives:

- Advance fundamental combustion understanding to enable design of engines with inherently lower emissions, and eventually advanced engines operating predominantly in low-temperature or HCCI combustion regimes. The resulting technological advances will reduce the size and complexity of emission control devices and minimize any impact these devices have on vehicle fuel efficiency. A fuel-neutral approach is being taken, with research addressing gasoline-based LTC engines as well as diesel-based advanced engines.
- Increase overall engine efficiency through fundamental improvements such as advanced combustion processes, reduction of parasitic losses, and recovery of waste heat.
- Improve the effectiveness, efficiency, and durability of engine emission control devices to enable these engines to achieve significant penetration in the light-duty market and maintain their application in heavy-duty vehicles.
- Develop highly efficient hydrogen engine technologies with near-zero NOx, PM and greenhouse gas emissions.
- Identify that any potential health hazards associated with the use of new vehicle technologies being developed by VT will not have adverse impacts on human health through exposure to toxic particles, gases, and other compounds generated by these new technologies.
- Develop advanced thermoelectric technologies for recovering engine waste heat and converting it to useful energy that will significantly increase vehicle fuel economy.

Technology Status

Recent advances in fuel injection systems have made the diesel engine very attractive for light-duty vehicle use by reducing the combustion noise associated with diesel engines, and consumers are discovering that diesel engines offer outstanding driveability and fuel economy. The change-over to ultra-low-sulfur diesel fuel enables catalytic exhaust treatment devices that virtually eliminate the offensive odors associated with diesel engines and further improve their prospects for wider use in light-duty vehicles. Mercedes-Benz has started selling a diesel passenger car that is certified to Tier 2 Bin 8 in the U.S. using a NOx adsorber and diesel particulate filter (DPF) and has added diesel engine options for its SUVs.

In early 2007, The U.S. Environmental Protection Agency (EPA) finalized its guidance document for using selective catalytic reduction (SCR) employing urea for regeneration (urea-SCR) technology for NOx control in light- and heavy-duty diesel vehicles and engines. This opens the door for the introduction of SCR technology in Tier 2 light-duty vehicles, 2010 heavy-duty engines, and in other future diesel engine applications in the United States. Mercedes-Benz is offering a limited number of urea-SCR 2007 diesel vehicles in California that meet the Tier 2 Bin 5 standard. In 2008, Mercedes-Benz plans to expand availability of these vehicles to all 50 states. Volkswagen, Audi, and BMW also plan to incorporate urea-SCR technology into some of their diesel vehicles in 2008 with some Volkswagen models using NOx adsorber technology. In 2009, Honda plans to introduce a diesel passenger car to the U.S. that meets the Tier 2, Bin 5 standard using NOx adsorber technology and a particulate filter. These products are the direct result of regulation to reduce fuel sulfur content and R&D to develop advanced emission control technologies.

Current heavy-duty diesel engines have efficiencies in the range of 43-45%. These engines have significantly improved efficiency over engines produced just a few years ago. Improvements are being made in a wide variety of engine components such that engines a few years from now may have efficiencies between 47 and 48% without employing waste heat recovery.

In 2007, heavy-duty diesel engines for on-highway commercial trucks have been equipped with DPFs to meet particulate emissions standards. This will be the first very broad application of aftertreatment devices in the trucking industry. In some cases, DPFs are paired with oxidation catalysts to facilitate passive or active regeneration. DPFs are typically capable of reducing PM emissions by 95% or more. For NOx control, aftertreatment devices are not likely to be needed in the heavy-duty sector until 2010 emissions regulations take effect.

Among the options for NOx aftertreatment for diesel engines, urea-SCR is the clear leader because of its performance and superior fuel sulfur tolerance. The U.S. EPA has put regulations in place to assure that users of urea-SCR vehicles don't operate them without replenishing the urea. Using urea-SCR, light-duty manufacturers will be able to meet Tier 2, Bin 5 which is the "gold standard" at which diesel vehicle sales do not have to be offset by sales of lower emission vehicles. Heavy-duty diesel vehicle manufacturers will be attracted to urea-SCR since it has a broader temperature range of effectiveness than competing means of NOx reduction and allows the engine/emission control system to achieve higher fuel efficiency.

The other technology being considered for NOx control from diesel engines is lean-NOx traps (LNTs), also known as NOx adsorbers. LNTs appear to be favored by light-duty manufacturers (as witnessed by the 2007 Dodge Ram light-duty trucks with the Cummins 6.7-liter diesel engine using a LNT and DPF for emission control, and Volkswagen's and Honda's announcements of their intent to use LNTs with their diesel engines in 2008 and 2009, respectively) since overall fuel efficiency is less of a concern than for heavy-duty manufacturers, and because urea replenishment represents a larger concern for light-duty customers than for heavy-duty vehicle users. Other drawbacks to LNT use on heavy-duty vehicles are that they are larger in relation to engine displacement (being over twice as large as those required for light-duty vehicles), the "not-to-exceed" operating conditions generate higher exhaust temperatures which degrade durability, and the fuel used for regeneration adds to operating costs. Research on LNTs has decreased this fuel "penalty," but it is still in the range of five percent of total fuel flow. This problem is exacerbated by the need to periodically drive off accumulated sulfur (even using ultra-low-sulfur fuel) by heating the adsorber to high temperatures, again by using fuel (desulfation). In addition, the high temperature of regeneration and desulfation has been shown to cause deterioration in catalyst effectiveness. LNTs additionally require substantial quantities of platinum group metals, and the cost of these materials has been rising at a concerning rate.

An optimum solution to diesel engine emissions would be to alter the combustion process in ways that produce emissions at levels that don't need ancillary devices for emissions control, or greatly reduce the requirements of these systems, yet maintain or increase engine efficiency. This is the concept behind advanced combustion regimes such as HCCI, pre-mixed charge compression ignition (PCCI) and other modes of LTC, which result in greatly reduced levels of NOx and PM emissions (emissions of hydrocarbons and carbon monoxide still exist and must also be controlled – the lower exhaust temperatures associated with these combustion modes can make hydrocarbon and carbon monoxide control difficult). Significant progress is being made in these types of combustion systems, and performance has been demonstrated over increasingly larger portions of the engine speed/load map. In recent years, DOE has adopted the term "high-efficiency clean combustion" (HECC) to include these various combustion modes since the boundaries among them are difficult to define. The major issues of this R&D include fuel mixing, control of air intake flow and its temperature, control of combustion initiation, and application over a wider portion of the engine operating range. Control of valve opening independent of piston movement appears to be highly desirable for such engines. Most heavy-duty engine manufacturers are employing some sort of HECC in engines designed to meet the 2010 emission standards. Ford has announced that it intends to release a light-duty diesel engine employing HECC before 2012 which may not include any NOx aftertreatment devices.[1] General Motors has demonstrated two driveable concept vehicles, a 2007 Saturn Aura and Opel Vectra, with light-duty HCCI engines using gasoline.[2]

Complex and precise engine and emission controls will require sophisticated feedback systems employing new types of sensors. NOx, PM, and combustion sensors are in the early stages of development and require additional advances to be cost-effective and reliable, but are essential to control systems for these advanced engine/aftertreatment systems. Much progress has been made, but durability and cost remain as the primary issues with these sensors. Start-of-combustion sensors have been identified as a need, and several development projects are underway.

Advanced fuel formulations and fuel quality are also crucial to achieving higher energy efficiencies and meeting emissions targets. The EPA rule mandating that the sulfur content of highway diesel fuel be reduced to less than 15 ppm is a great benefit to the effectiveness, efficiency, and durability of emission control devices. Since October 15, 2006, diesel fuel being sold for highway use in most of the country has less than 15 ppm sulfur (complete phase-in is anticipated by 2010 as small refiner exemptions are phased out). The addition of non-petroleum components such as biodiesel can have beneficial effects on emissions while providing lubricity enhancement to ultra-low-sulfur diesel fuel. Recent tests have shown that biodiesel lowers the regeneration temperature of particulate traps and increases the rate of regeneration with the potential for avoiding or reducing the need for active regeneration and its associated fuel economy penalty. On the other hand, biodiesel use has resulted in some operational problems as well. Fuel filter plugging has been reported under cold conditions for fuels with as little as 2% biodiesel because the biodiesel was not made to specification for blending with diesel fuel. Biodiesel is certain to become more prevalent in diesel fuel due in part to the recent expansion of the Renewable Fuel Standard, which calls for 0.5 billion gallons in 2009 increasing to 1.0 billion gallons by 2012.

Waste heat recovery is being implemented in heavy-duty diesel vehicles. New engines being introduced by Daimler Trucks in late 2007 include turbo compounding technology that uses a turbine to extract waste energy and add to engine power output. The addition of turbo compounding and other engine changes result in a claimed 5% improvement in vehicle fuel economy. Testing has shown that waste heat recovery has the potential to improve vehicle fuel economy by 10% and heavy-duty engine efficiency also by 10%.

Future Directions

Internal combustion engines have a maximum theoretical fuel conversion efficiency that is similar to that of fuel cells; it approaches 100%. The primary limiting factors to approaching these theoretical limits of conversion efficiency start with the high irreversibility in traditional premixed or diffusion flames, but include heat losses during combustion/expansion, untapped exhaust energy, and mechanical friction. Multiple studies agree that combustion irreversibility losses consume more than 20% of the available fuel energy and are a direct result of flame front combustion. Analyses of how "advanced combustion regimes" might impact the irreversibility losses have indicated a few directions of moderate reduction of this loss mechanism, but converting the preserved availability to work will require compound cycles or similar measures of exhaust energy utilization. The engine hardware changes needed to execute these advanced combustion regimes include variable fuel injection geometries, turbo and super charging to produce very high manifold pressures, compound compression and expansion cycles, variable compression ratio, and improved sensors and control methods. Larger reductions in

[1] "Ford, PSA Developing HCCI Diesel" by William Diem, WardsAuto.com, Oct. 11, 2006.
[2] "GM Demonstrates Gasoline HCCI On the Road" Green Car Congress, 24 August 2007.

combustion irreversibility will require a substantial departure from today's processes but are being examined as a long-range strategy.

The other areas where there is large potential for improvements in internal combustion engine efficiency are losses from the exhaust gases and heat transfer losses. Exhaust losses are being addressed by analysis and development of compound compression and expansion cycles achieved by valve timing, use of turbine expanders, regenerative heat recovery, and application of thermoelectric generators. Employing such cycles and devices has been shown to have the potential to increase heavy-duty engine efficiency by 10% to as high as 55%, and light-duty vehicle fuel economy by 10%. Heat transfer losses may be reduced by HECC, and interest in finding effective thermal barriers remains valid.

Fuels can also play an important role in reducing combustion irreversibility losses. Preliminary analyses show that combustion irreversibility losses per mole of fuel are considerably less for hydrogen than for hydrocarbon fuels. This finding is consistent with the understanding that combustion irreversibility losses are reduced when combustion is occurring nearer equilibrium (high temperature), since hydrogen has the highest adiabatic flame temperature of the fuels studied to date. This bodes well for the development of highly efficient hydrogen-fueled internal combustion engines.

Emission control devices for diesel engines to reduce PM and NOx will become widespread over the next few years. Much work still needs to be done to make these devices more durable and to lessen their impact on fuel consumption. Information about how best to employ these emission control devices also continues to evolve with new developments leading to more efficient operation. As engine combustion becomes cleaner, the requirements of the emission control devices will change as well.

Thermoelectric devices that convert waste engine heat to electricity have great potential to improve both engine efficiency and vehicle fuel economy. The electricity generated can be used to drive engine accessories, operate emission control equipment, or used directly to propel the vehicle. The challenges facing implementation of thermoelectric devices include scale-up, manufacturing techniques, and durability to withstand extremes of heat and vibration typical of vehicle environments.

Goals and Challenges

The Advanced Combustion Engine R&D Sub-Program has two activities:

- Combustion and Emission Control R&D
- Solid State Energy Conversion

Combustion and Emission Control R&D

The Combustion and Emission Control R&D activity focuses on enabling technologies for energy-efficient, clean vehicles powered by advanced combustion engines using clean hydrocarbon-based and non-petroleum-based fuels and hydrogen. R&D has been focused on developing technologies for light-, medium-, and heavy-duty engines and is being transitioned to developing technologies for advanced engines operating in combustion regimes that will further increase efficiency and reduce emissions to near-zero levels.

Fuel efficiency improvement is the overarching focus of this activity, but resolving the interdependent emissions challenges is a critical integrated requirement. (Penetration of even current-technology diesel engines into the light-duty truck market would reduce fuel use by 30-40% per gasoline vehicle replaced.) The major challenges facing diesel emission control systems across all three platforms are similar: durability, cost, and fuel penalty (or in the case of urea-SCR, urea infrastructure development). Full-life durability in full-scale systems suitable for 2010 regulations has yet to be demonstrated for either light- or heavy-duty systems, with the exception of very recent announcements by Cummins of a 2007 chassis certified heavy-duty diesel engine certified to the 2010 emission regulations. This is indicative of the progress achieved in the last ten years.

The VT technical targets for advanced combustion engines suitable for passenger vehicles (cars and light trucks), as well as to address technology barriers and R&D needs that are common between passenger and commercial (heavy-duty) vehicle applications of advanced combustion engines include:

- By 2010, for passenger vehicles, develop the understanding of novel low-temperature engine combustion regimes needed to simultaneously enable engine efficiency of 45 percent with a fuel efficiency penalty of less than 1 percent while meeting prevailing EPA emissions standards.
- By 2013, increase the thermal efficiency of heavy truck engines to 55 percent while meeting prevailing EPA emissions standards.

Presented in the following tables are the technical targets (consistent with the goals) for the Combustion and Emission Control R&D activity. The FreedomCAR and Fuel Partnership goals for both hydrocarbon- and hydrogen-fueled ICEs are shown in Table 1. These apply to passenger vehicles (cars and light trucks). The technical targets for heavy truck engines for commercial vehicles are shown in Table 2.

TABLE 1. Technical Targets for Passenger Vehicle Engines

Characteristics	Fiscal Year		
	2007	2009	2010
Reference peak brake thermal efficiency[a], %	32	34	35
Powertrain cost[b,c], $/kW	35	30	30
FREEDOMCAR AND FUEL PARTNERSHIP GOALS			
ICE Powertrain			
Peak brake thermal efficiency, % (Diesel/H_2–ICE) (H_2–ICE)			45/45 45 (2015)
Cost, $/kW - (Diesel/$H_2$–ICE) ($H_2$–ICE)			30/45 30 (2015)
Target peak brake thermal efficiency/part-load brake thermal efficiency (2 bar BMEP[d] @1500 rpm), %	42/29	44/30	45/31
Emissions[e], g/mil	Tier 2, Bin 5	Tier 2, Bin 5	Tier 2, Bin 5
Durability[e], hrs	5,000	5,000	5,000
Thermal efficiency penalty due to emission control devices[f], %	<3	<1	<1

[a] Current production, EPA-compliant engine.
[b] High-volume production: 500,000 units per year.
[c] Constant out-year cost targets reflect the objective of maintaining powertrain (engine, transmission, and emission control system) system cost while increasing complexity.
[d] Brake mean effective pressure.
[e] Projected full-useful-life emissions for a passenger car/light truck using advanced petroleum-based fuels as measured over the Federal Test Procedure as used for certification in those years.
[f] Energy used in the form of reductants derived from the fuel, electricity for heating and operation of the devices, and other factors such as increased exhaust back-pressure, reduce engine efficiency. A cycle average thermal efficiency loss of 1 to 2% is equivalent to a 3 to 5% fuel economy loss over the combined Federal Test Procedure drive cycle.

TABLE 2. Technical Targets for Heavy Truck Diesel Engines

Characteristics	Year			
	2002 baseline	2006	2009	2013
Engine thermal efficiency, %	>40	50	51	55
NOx emissions,[a] g/bhp-hr	<2.0	<0.20	<0.20	<0.20
PM emissions,[a] g/bhp-hr	<0.1	<0.01	<0.01	<0.01
Stage of development	Commercial	Prototype	Prototype	Prototype

[a] Using 15-ppm sulfur diesel fuel

Recovery of waste energy from the engine exhaust represents a potential for 10% or more improvement in overall engine thermal efficiency. Turbochargers strongly influence engine efficiency in several ways, including recovery of part of the exhaust energy. Turbochargers currently have efficiencies of around 50 to 58%, which could be increased to 72 to 76% with enhancements such as variable geometry. Turbocompounding can be configured to produce mechanical shaft power or electric power for additional waste heat recovery. Direct thermal-to-electric conversion could also improve the overall thermal efficiency. Bulk semiconductor thermoelectric devices are currently 6 to 8% efficient. Recent developments in quantum well thermoelectrics suggest a potential improvement to over 20% is possible. A Rankine bottoming cycle for heat recovery is being used in one of the heavy truck engine efficiency projects.

Enabling technologies being developed by the Combustion and Emission Control R&D activity focus on fuel systems, engine control systems, and engine technologies. Fuel systems R&D focuses on injector controls and fuel spray development. The fuel injection system pressure and fuel spray development influence the spray penetration and fuel-air mixing processes and thus combustion and emissions formation within the combustion chamber. Engine control systems R&D focuses on developing engine controls that are precise and flexible for enabling improved efficiency and emission reduction in advanced combustion engines. These control system technologies will facilitate adjustments to parameters such as intake air temperature, fuel injection timing, injection rate, variable valve timing, and exhaust gas recirculation to allow advanced combustion engines to operate over a wider range of engine speed/load conditions. Engine technologies development will be undertaken to achieve the best combination that enables advanced combustion engines to meet maximum fuel economy and performance requirements. These include variable compression ratio, variable valve timing, variable boost, advanced sensors, and exhaust emission control devices (to control hydrocarbon emissions at idle-type conditions) in an integrated system.

The Combustion and Emission Control R&D activity performs the critical role of elevating potential health issues related to advanced combustion engine technologies to the attention of industry partners and DOE/VT management. This portion of the activity ensures that the development of new vehicle technologies, rather than just enabling compliance with existing standards, also considers the possibility of causing negative health impacts:

- To provide a sound scientific basis underlying any unanticipated potential health hazards associated with the use of new powertrain technologies, fuels and lubricants in transportation vehicles.
- To ensure that vehicle technologies being developed by VT for commercialization by industry will not have adverse impacts on human health through exposure to toxic particles, gases, and other compounds generated by these new technologies.

Solid State Energy Conversion

The Solid State Energy Conversion activity focuses on developing advanced thermoelectrics for converting waste heat from engines into useful energy (e.g., electrical energy) to improve overall vehicle energy efficiency and reduce emissions. Effective use of waste heat from combustion engines would significantly increase vehicle fuel economy. In current production passenger vehicles, roughly over 70 percent of the fuel energy is lost as waste heat from an engine operating at full power. About 35 to 40 percent is lost in the exhaust gases and another 30 to 35 percent is lost to the engine coolant. There is an opportunity to recover some of the engine's waste heat using thermoelectric materials that will convert it directly to electricity for operating vehicle auxiliaries and accessories.

The goal of this activity is to develop advanced thermoelectric technologies for recovering engine waste heat and converting it to useful energy that will improve overall engine thermal efficiency to 55 percent for Class 7 and 8 trucks, and 45 percent for passenger vehicles while reducing emissions to near-zero levels. More specifically,

- By 2012, achieve at least 25 percent efficiency in advanced thermoelectric devices for waste heat recovery to potentially increase passenger and commercial vehicle fuel economy by a nominal 10 percent.

This activity also supports the overall engine efficiency goals of the FreedomCAR and Fuel Partnership, and 21st CTP. The technical targets for Solid State Energy Conversion are shown in Table 3.

TABLE 3. Solid State Energy Conversion Technical Targets

Characteristics	Year		
	2003 Status	2008	2010
Thermoelectric Devices			
Efficiency, % • bulk semiconductor • quantum well	5–7	– >15	– >20
Projected cost/output, $/kW (250,000 production volume)	--	500	180
Passenger Vehicle Application			
Fuel economy improvement, %	<4	>7	>12
Power, kW	<0.8	>1.0	>2.0
Projected component life, hours	<10	>5,000	>10,000
Commercial Vehicle Application			
Fuel economy improvement, %	<3	>8	>10
Power, kW	<10	>18	>20
Projected component life, hours	<10	>5,000	>20,000

Achieving these targets requires reduction in the cost of thermoelectrics, scaling them up into practical devices, and making them durable enough for vehicle applications.

PROJECT HIGHLIGHTS

The following projects highlight progress made in the Advanced Combustion Engine R&D Sub-Program during FY 2007.

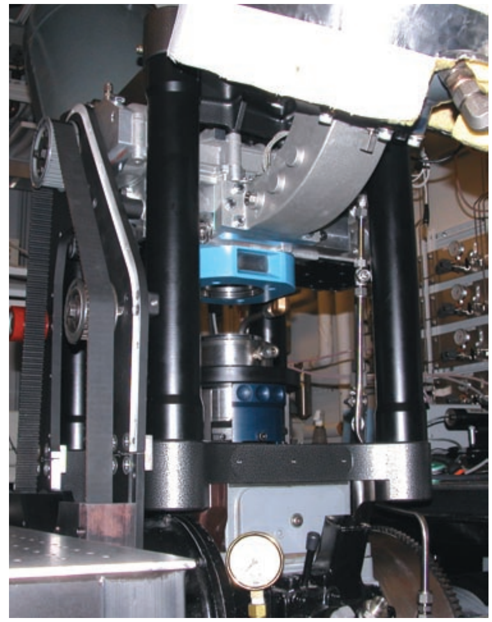
Advanced Combustion and Emission Control Research for High-Efficiency Engines

A. Combustion and Related In-Cylinder Processes

The objective of these projects is to identify how to achieve more efficient combustion with reduced emissions from advanced technology engines.

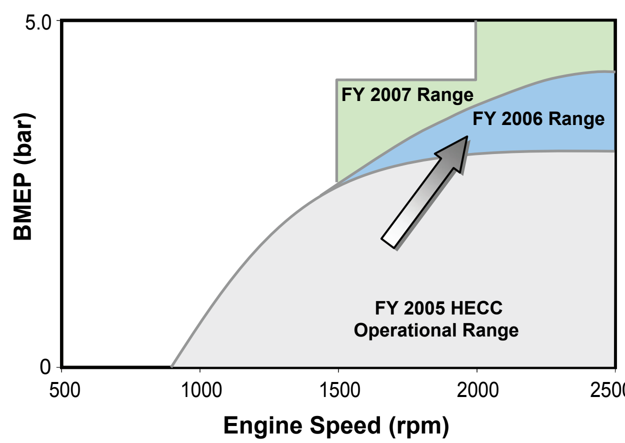
- Argonne National Laboratory's (ANL) first single-shot measurements of sprays were performed and published. These measurements showed that important features of the spray are remarkably reproducible from one spray event to the next. ANL developed a new data analysis technique that allows for the calculation of the average velocity of the fuel in a spray as a function of time. This is one of the few experimental techniques that can measure spray velocity, and can do so in the very-near-nozzle region. In addition, ANL demonstrated that X-ray measurements of full-production 6-hole nozzles can be performed without sacrificing data quality. (Powell, ANL)
- Sandia National Laboratories (SNL) completed their automotive LTC facility upgrade incorporating a GM 1.9-liter production diesel head into an optically-accessible, single-cylinder engine. In addition, a new exhaust gas recirculation (EGR) simulation was installed capable of simulating EGR with H_2O, CO_2, N_2, O_2, CO, unburned hydrocarbons (UHCs) and other trace components. SNL evaluated optical engine performance and emissions for a wide range of operating conditions characterizing both high-dilution and late-injection LTC operating regimes. Lastly, SNL identified operating conditions of interest for future optical studies focusing on the sources of CO and UHC emissions. (Miles, SNL)

- SNL optical experiments showed conclusively that over-mixed fuel near the injector yields significant UHC emissions when ignition occurs after the end of injection because it does not achieve complete combustion. Computer models show improved agreement with experiments at LTC conditions. SNL also initiated a parallel experimental and modeling study of effects of bowl geometry, spray angle, and swirl ratio on in-cylinder LTC processes. (Musculus, SNL)
- SNL quantified the extent of liquid-phase penetration for typical early-injection LTC conditions with various injection durations, nozzle sizes, injection pressures and number of injections. This provides an understanding needed to prevent liquid wall impingement and its negative impacts on emissions and combustion efficiency. SNL also showed that the extent of liquid penetration depends upon the injected mass for short injections less than the steady-state liquid length, rather than the nozzle size or injection pressure. In addition, it was demonstrated that small nozzles actually form more soot than larger nozzles when the injection duration is adjusted such that the mass injected is constant. (Pickett, SNL)



SNL Optically-Accessible Engine with GM 1.9-Liter Cylinder Head

- Oak Ridge National Laboratory (ORNL) demonstrated an increase in speed-load range for HECC operation of a light-duty diesel engine. Mixed-source EGR for controlling intake temperature was characterized and, correspondingly, emissions and efficiency. ORNL explored the relationship between brake specific fuel consumption and combustion noise for HECC operation and commissioned and mapped a modern light-duty diesel engine. (Wagner, ORNL)

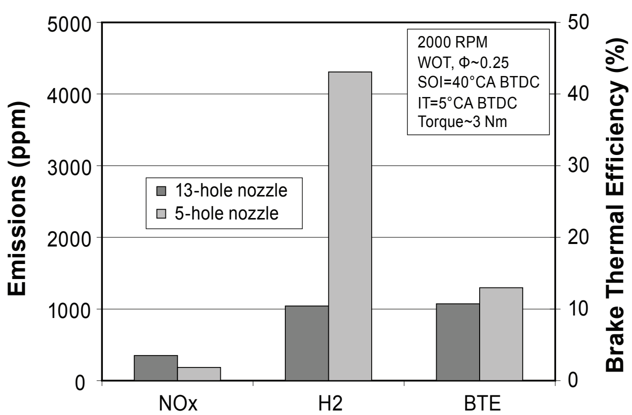


Expansion of HECC Speed-Load Range Accomplished by ORNL with Improved Control of Intake Mixture Temperature

- SNL completed infrastructure and preprocessor modifications to make calculations routine and performed systematic model validation of two fundamental combustion models in collaboration with the DOE Office of Science. SNL continued the sequence of calculations focused on the Combustion Research Facility optical hydrogen internal combustion engine in collaboration with C. White and S. Kaiser and systematically extended effort toward treatment of LTC engine processes. (Oefelein, SNL)
- Lawrence Livermore National Laboratory (LLNL) developed methodologies for experimental measurement of 40 hydrocarbon species in HCCI engine exhaust. LLNL demonstrated high fidelity modeling of the SNL HCCI engine, including unprecedented prediction of 40 measured intermediate hydrocarbon species. Innovative control strategies were demonstrated and applied to the Caterpillar 3406 experimental HCCI engine, showing optimum engine performance and fast transient response. (Aceves, LLNL)
- SNL determined the effects of EGR/residuals and its constituents on combustion phasing for single- and two-stage fuels. SNL showed how HCCI combustion progresses through various phases of autoignition, main combustion, and burnout using a combination of chemiluminescence

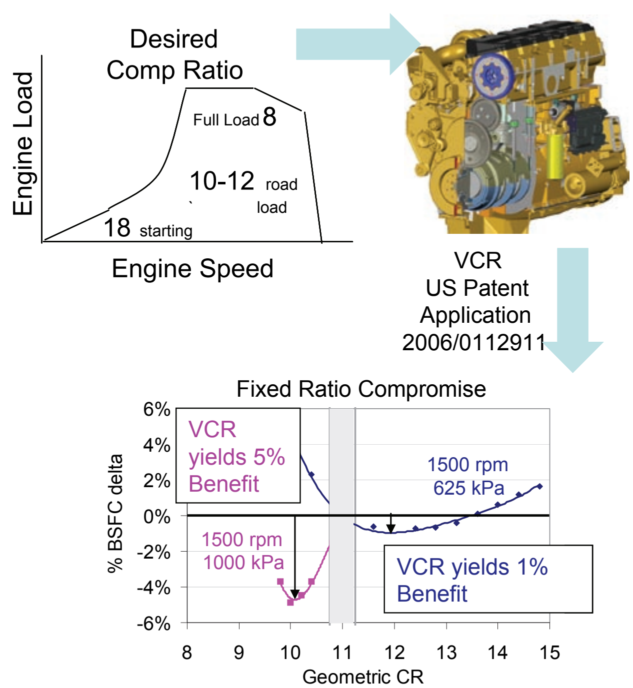
spectroscopy and chemical-kinetic analysis. Several fuel-stratification techniques were investigated to improve combustion efficiency at low loads, using a combination of metal-engine performance data and fuel planar laser induced fluorescence imaging. (Dec, SNL)

- SNL installed negative valve overlap (NVO) cams in an automotive HCCI engine. Tests were conducted to establish the operating range of recompression operation and they tested protocols to allow rapid and safe startup in the optical engine. SNL also created a 1-D cycle-simulation model to aid the selection of stable NVO operating conditions and adapted SNL's linear-eddy model to provide detailed, stochastic predictions of turbulent mixing in the HCCI engine. The model provided valuable insights into the effect of spatial fuel distribution on HCCI combustion and emissions. (Steeper, SNL)
- ORNL developed a data-based method to estimate global kinetic parameters from combustion measurements and form the basis of a low-order dynamic model to be used for prediction and control. Also developed was a Wiebe-based combustion metric to be used for feedback control as well as improving model estimates of global kinetic parameters. (Wagner, ORNL)
- The parallelization of KIVA-4 was tested by Los Alamos National Laboratory (LANL) in realistic geometries including 4-valve pentroof and 3-valve engine geometries. The collocated version of KIVA-4 was parallelized and run in parallel in a vertical valve engine geometry. The University of Wisconsin's chemistry and spray submodels were implemented in KIVA-4 and tested in a 2-D sector geometry and Reaction Design's chemistry package was interfaced with KIVA-4. Converters were developed for the TrueGrid and ICEM software programs. Remapping capability was demonstrated in a cylindrical tetrahedral mesh and reduced spray dependence was achieved by using the grid overset method in KIVA-4. (Torres, LANL)
- LLNL developed a chemical kinetic model for n-hexadecane, a primary reference fuel for diesel fuel, and a realistic representation of n-alkanes in diesel fuels. Also developed was the understanding of the chemical kinetics that control HCCI combustion under boosted conditions using LLNL surrogate fuel models and SNL HCCI engine data. Finally, LLNL developed a chemical kinetic model for methyl decanoate, a realistic component to represent methyl esters contained in biodiesel. (Pitz, LLNL)
- ORNL achieved and demonstrated the 2007 FreedomCAR goal of 42% peak break thermal efficiency on two light-duty diesel engines and completed the installation of a modern engine platform donated to ORNL by General Motors. Thermodynamic analysis methods were developed for use with engine simulation codes as well as experimental data to evaluate potential opportunities for waste heat recovery. ORNL demonstrated a potential of advanced combustion operation for achieving Tier 2 Bin 5 emissions regulations. (Wagner, ORNL)
- SNL developed a linear alternator/multi-level converter configuration calculated to exceed 30 kW power output charging a battery at greater than 95% conversion efficiency. It was determined with collaborators that the opposed piston concept is preferred for hybrid vehicle applications due to its capability to operate independently of other units (due to self balance). (Van Blarigan, SNL)
- ANL characterized the influence of injection timing on engine efficiency and emissions in direct injection operation and determined that nozzle design significantly influences brake thermal efficiency and emissions (2% increase in brake thermal efficiency and 47% decrease in NOx emissions) at low engine load with changed nozzle design. Multiple injection strategy images were captured and refined spectroscopic gas temperature measurements were performed. ANL installed a new cylinder head with central



The Effect of Nozzle Design on Hydrogen Direct Injection Engine Emissions in Testing Conducted by ANL and side injector locations – specific injector nozzles designed and manufactured for either location. (Wallner, ANL)

- Quantitative, instantaneous two-dimensional images of equivalence ratio and corresponding high-quality velocity measurements were made by SNL during the compression stroke with and without direct hydrogen injection. Analysis of the velocity field revealed that the observed substantial fuel stratification for late injection is favored by a relatively stable counter-flow situation created by jet-wall interaction. (Kaiser, SNL)
- Cummins demonstrated 12% fuel economy improvement on their ISB engine and 7% on their ISX engine. The combustion strategy employed to achieve high efficiency is a mixed mode that relies on extending the early PCCI combustion mode to encompass as much of the engine operating range as possible while implementing lifted flame diffusion controlled combustion for the remainder of the higher load operating range. (Stanton, Cummins)
- Caterpillar completed the Phase 2 optical diagnostic experiments and the single-cylinder engine fuels testing on low-cetane diesel boiling-range fuels. A prototype fuel injection system was developed and tested on the single-cylinder engine demonstrating ultra-low NOx and smoke emissions. An advanced multi-cylinder engine with compression ratio flexibility was developed and tested demonstrating benefits for emissions, efficiency and controls. (Milam, Caterpillar)
- International Truck and Engine Corporation demonstrated LTC combustion up to 1,500 RPM and 6 bar BMEP, with plans to extend to the full range of engine operation. NOx levels were limited to below 0.2 g/bhp-hr with soot levels below 2 mg/mm^3. Fuel efficiencies are comparable to 'conventional' operation. (de Ojeda, International)
- GE Global Research demonstrated an advanced fuel injection system to minimize fuel consumption, while meeting Tier 2 emissions levels on a locomotive engine. Changes in nozzle geometry have been proven to allow for further engine performance benefits. For the range studied, the number of holes seemed to have the strongest effect on PM, followed by rail pressure and nozzle flow. Changing the spray cone angle was found to have monotonic but opposing trends for specific fuel consumption and PM. (Primus, GE Global Research)
- ORNL designed and constructed a bench-top experimental apparatus for demonstrating low-irreversibility combustion based on the concept referred to as counterflow-preheat with near-equilibrium reaction (CPER). ORNL continued exploring better ways for recuperating exhaust heat and utilizing compound cycles for extracting work, as well as exercising engine and combustion models to identify combustion modifications that would mitigate exergy losses. (Graves, ORNL)
- Detroit Diesel Corporation (DDC) successfully completed the first part of the Near Zero Emissions at 50% Thermal Efficiency (NZ-50) project. DDC demonstrated 50.2% thermal efficiency with integrated experimental and analytical technologies at EPA 2010 emissions levels at a single operating condition in a multi-cylinder engine configuration. DDC also successfully launched the second part of the NZ-50 project in March of 2007, which focuses on high efficiency clean combustion. (Zhang, DDC)



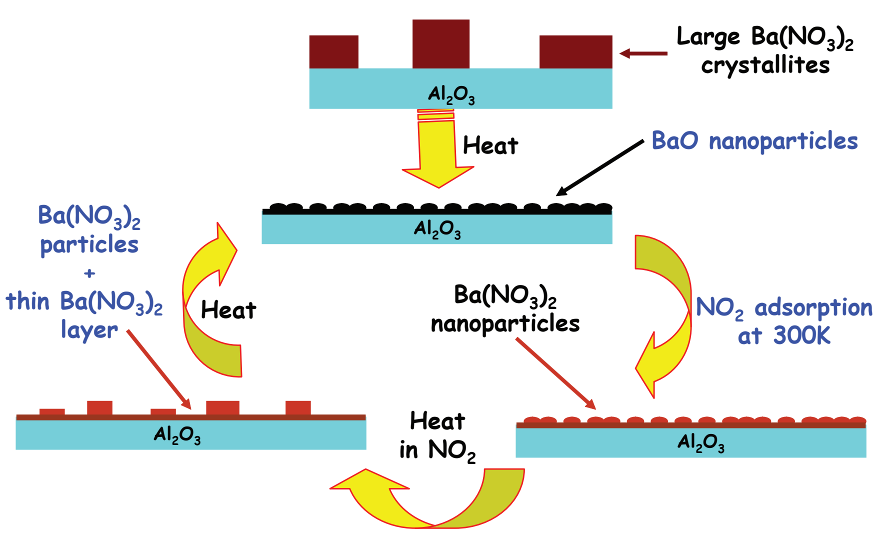
Caterpillar Implemented Variable Compression Ratio to Facilitate HCCI Combustion

- GM developed and demonstrated prototype gasoline and diesel engine hardware which enables operation of HCCI combustion for improved fuel efficiency and emissions performance. Both "two-step" and fully variable valve actuation systems were developed and tested.

B. Energy-Efficient Emission Controls

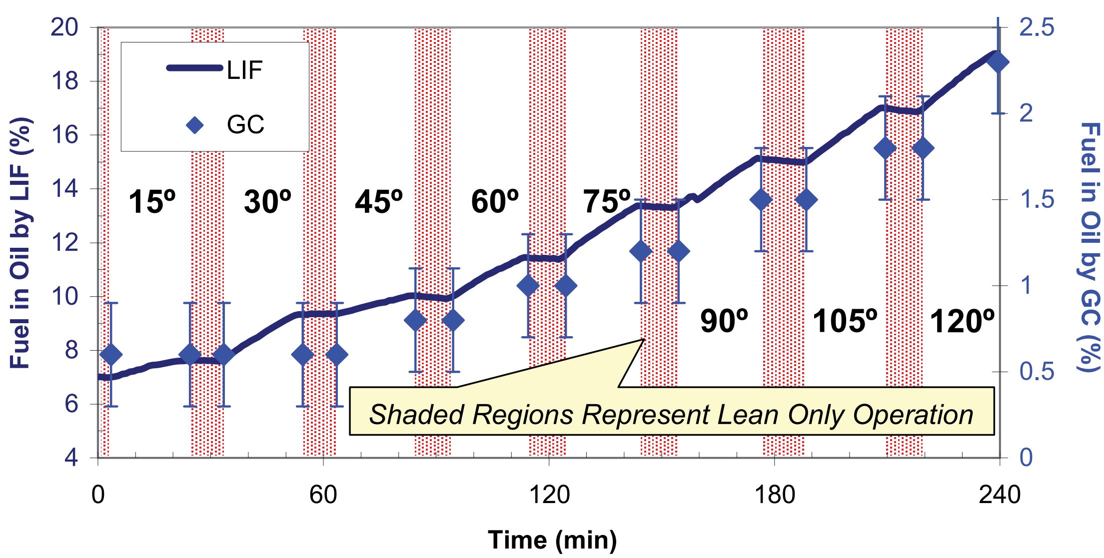
The following project highlights summarize the advancements made in emission control technologies to both reduce emissions and reduce the energy needed for emission control system operation.

- Using a one-of-a-kind very high field nuclear magnetic resonance instrument at Pacific Northwest National Laboratory (PNNL), the nucleation sites for Ba on the γ-alumina catalyst support material have been identified. The chemical form and stability of barium carbonate species formed during stored NOx removal in the presence of CO_2 has been determined. Studies of the effects of water on the decomposition of the deactivating $BaAl_2O_4$ phase show how treatments may be devised to restore performance after deactivation. Also, the relative performance of all alkaline earth oxide storage materials has been determined. (Peden, PNNL)
- PNNL observed a decrease in Pt accessibility for H_2 chemisorption with increasing reduction temperature without a corresponding change in Pt particle size, implying that BaO covers at least part of the Pt surface during reduction. Also observed was an increase in NOx storage capacity up to a reduction temperature of 500°C, which strongly suggests that there is a promotional effect of this (Pt-BaO) interaction on NOx storage. (Peden, PNNL)
- ORNL analyzed model and commercial LNT catalysts on a full-scale engine system with in-cylinder regeneration techniques and measured NH_3 emissions from LNTs and determined the effect of ceria on NH_3 control. They disseminated the data through Cross-Cut Lean Exhaust Emissions Reduction Simulations (CLEERS) to improve models. (Parks, ORNL)
- SNL completed construction and optimization of a thermodynamically consistent reaction mechanism for the precious metal sites on a benchmark LNT catalyst. Tentative mechanisms for the NOx storage and oxygen storage sites on the catalyst were formulated and the corresponding thermodynamic constraints were assembled. Using the combined reaction mechanism together with a Chemkin-based transient plug flow code and the Sandia APPSPACK optimization software, SNL carried out a preliminary evaluation of the storage parameters by fitting simulations of full LNT cycles to experiment
- ORNL with their International T amples in a OR activity is the key parameter limiting low-



Cycle Of Morphology Changes Taking Place during NO_2 Uptake and Release on BaO/Al_2O_3 NOx Storage/Reduction Materials (PNNL) temperature performance of the catalysts studied, established trends in NOx conversion and product selectivity with temperature, space velocity, lean-rich cycle time, and reductant species, and provided input for calibration of operating strategies. (Toops, ORNL)

- ORNL is working to provide a better understanding of the fundamental deactivation mechanisms that result during regeneration and desulfation of LNTs. They recently presented their efforts at the 20th North American Meeting, 2007 AIChE National Meeting, and the DOE Advanced Combustion Engine Merit Review. ORNL also submitted a paper to Catalysis Today. A full sulfation study on model catalysts and a full sulfation study on a commercial LNT were completed (Toops, ORNL)
- ORNL demonstrated real-time on-engine measurements of oil dilution by fuel using a diagnostic and showed that results trend with more conventional but slower-feedback off-line measurements. Also, the impact of sulfation on the spatial nature of various LNT catalyst reactions was characterized and used the results to develop a conceptual model of LNT sulfation which explains integral catalyst performance. (Partridge, ORNL)
- ORNL compared emissions and fuel efficiency for lean-NOx trap catalysis with three combustion modes: no EGR, production level EGR, and HECC. (Parks, ORNL)
- ORNL continued co-leading the CLEERS Planning Committee and facilitation of the SCR, LNT, and DPF Focus Group teleconferences with strong domestic and international participation. Additionally, ORNL continued co-leading the LNT Focus Group and refinement of the standard LNT materials protocol. Key R&D priorities were identified from the CLEERS community, including coordination of the R&D priorities survey with response from 14 DOE Diesel Crosscut Team companies and their partners in January, 2007. (Daw, ORNL)
- ORNL continued refinement and validation of the LNT material characterization protocol in conjunction with the LNT Focus Group, SNL, and PNNL and collaborating suppliers. Benchmarking of Umicore commercial reference LNT material for sulfation and desulfation characteristics was initiated. ORNL continued the in-depth study of the global kinetics of LNT regeneration, with specific emphasis on formation of byproduct N_2O and NH_3, effective fuel penalty, and potential coupling of LNT with SCR. Also, DRIFTS measurements of the fundamental mechanisms involved in S poisoning and desulfation of LNTs was continued. (Daw, ORNL)
- PNNL added catalytic chemistry to their micro-scale DPF models. Side-by-side loading and regeneration experiments were carried out with individual uncatalyzed and platinum-catalyzed DPF channels. Techniques for loading individual filter walls with aerosolized salt particles for fundamental filtration studies were developed. PNNL also participated in monthly CLEERS teleconferences and coordinated the calls focused on DPF technology. (Stewart, PNNL)

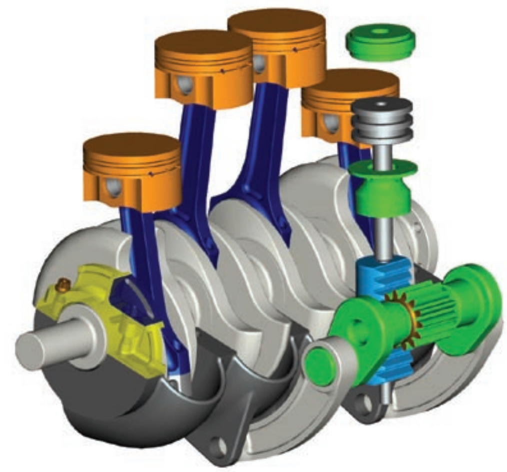


Comparison of Laser-Induced Fluorescence (LIF) Spectroscopy versus Gas Chromatograph Techniques Conducted by ORNL to Measure Fuel in Oil Dilution in Real Time

- GM tested over 8,000 catalyst materials for NOx reduction potential, conducted detailed engine testing, completed phosphorus poisoning studies, and developed specific formulations for lean gasoline applications. (Blint, GM)
- GM developed a DPF regeneration technology using external application of heat that reduces fuel consumption compared with injecting fuel to initiate regeneration.

C. Critical Enabling Technologies

Variable valve actuation (VVA), variable compression ratio, and combustion sensors are enabling technologies for achieving more efficient engines with very low emissions. The following highlights show the progress made during FY 2007.

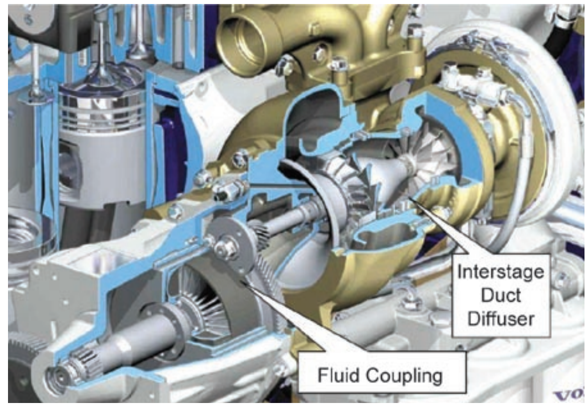


Variable Compression Ratio Mechanism Developed by Envera LLC

- An optimal, cost-effective, VVA system for advanced low-temperature diesel combustion processes was designed and tested. (Gutterman, Delphi)
- Hydraulic pressures in Envera LLC's actuator system were reduced by 86% through system optimization. The reduction in pressure significantly relaxes the demands that will be placed on the hydraulic system and enables cost to be reduced. A test rig was designed and built for evaluating actuator response. Test results indicate that compression ratio can be reduced from 18:1 to 8.5:1 in ~0.35 seconds, and increased from 8.5:1 to 18:1 in ~0.70 seconds. (Mendler, Envera LLC)
- An all-new planar type voltammetric NOx gas sensor was designed by Streamline Automation, LLC and they modified their existing monolithic cermet micro-arrays with new solder-less leads for long-term high-temperature operation. A new ruggedized stainless steel package was designed and prototyped. A new high-speed differencing voltammetry algorithm was engineered and employed for chemical characterization. Also, gas voltammetry was successfully applied to both commercial gas sensors (three) and to experimental gas micro-arrays (two). (Vogt, Streamline Automation, LLC)
- Two engines of same model line/different serial number were tested by TIAX LLC to verify engine-to-engine repeatability of their start of combustion sensor system (a potential drawback of accelerometer-based systems). TIAX also developed an array of algorithms to translate the accelerometer signal into the desired start of combustion value. A library of data has been generated relating engine cylinder pressure to accelerometer events, and the algorithms are being evaluated on the accelerometer data. (Smutzer, TIAX LLC)
- Westport Power, Inc. confirmed that the vertical acceleration of the main bearing caps has the best correlation with the start of combustion timing. An algorithm to obtain the timing for the start of combustion using accelerometers was developed. The targeted start of combustion error standard deviation is 0.5 crank angle degrees (CAD). The current results have largely exceeded this target for all the testing modes. The averaged engine-to-engine variation over all modes is 0.32 CAD with 98.9% confidence level. (Mumford, Westport Power, Inc.)
- John Deere is exploiting the flexibility of electrical coupling to the turbocharger to optimize system performance as a function of both engine speed and load. A smaller, higher performing turbo generator has been designed that exhibits considerable simplification. A series turbocharger system that provides improved performance and range was also successfully designed and modeled. (Vuk, John Deere)
- Cummins Inc. completed a system thermodynamic analysis across the engine's operating map to define the architecture of the waste heat recovery (WHR) system. The analysis results eliminated engine coolant and charge air as potential recovery sources and focused our efforts on waste energy

recovery from EGR and the engine's main exhaust gas stream. Also completed was a first generation component analysis and design for an on-engine system which will recover heat from the engine's EGR stream, thereby relieving the engine's jacket water system of this heat load and providing 6% fuel efficiency improvement (model-based results). (Nelson, Cummins)

- Through simulation, Volvo has demonstrated an engine efficiency increase of 8.2% when operating over a road cycle and 10.5% during steady-state operation over the European Standard Cycle at U.S. 2010 NOx levels (0.2 g/bhp-hr). Added investment for the continuously variable transmission and energy recovery devices will be returned in less than 1.5 years assuming fuel prices of $2.50 per gallon. (Habibzdeh, Volvo)



Schematic Close-Up of the Volvo D12 500 HP Engine Showing the Turbocharger, Interstage Duct Diffuser and Turbocompound Device

- Caterpillar Inc. designed, procured, and tested a novel nozzled/divided turbine stage, demonstrating a 5% improvement in turbine efficiency over standard production turbines. Caterpillar also designed, procured, and gas-stand tested a novel mixed-flow turbine stage, demonstrating the ability to shape the turbine efficiency characteristic to better match engine requirements. Lastly, Caterpillar designed, procured, and gas-stand tested a high efficiency compressor stage, demonstrating a 2-3% improvement in compressor efficiency over standard production compressors. (Kruiswyk, Caterpillar)
- Volvo Powertrain's Air-Power-Assist (APA) engine experimental setup was completed. In addition, the APA engine was made functional and preliminary testing was completed. (Kang, Volvo)

D. Health Impacts

The Health Impacts activity studies potential health issues related to new powertrain technologies, fuels, and lubricants to ensure that they will not have adverse impacts on human health. The following are highlights of the work conducted in FY 2007.

- ORNL measured mobile source air toxics (MSATs) from the European Saab Biopower vehicle that is optimized for performance with E85 (85% ethanol and 15% gasoline) fuel to provide information on the health impact of ethanol fuel introduction. Additionally, ORNL characterized MSATs from HECC on a diesel engine to determine any health impacts of advanced diesel combustion modes. (Parks, ORNL)
- The National Renewable Energy Laboratory (NREL) obtained support from the American Chemistry Council Petroleum Additives Product Approval Protocol Task Group to provide new and aged engine lubricating oils for all vehicles that will be tested. The scope of the project was increased to include medium-duty vehicles and E10 and biodiesel fuel testing as part of the overall project. (Lawson, NREL)
- Lovelace Respiratory Research Institute (LRRI) evaluated the health effects of inhaled nanoparticles from new and used diesel crankcase oil, and sulfate. It was discovered that oil and sulfate nanoparticles had little lung toxicity, but altered responses of immune cells elsewhere in the body. LRRI also completed

Saab 9-5 Biopower Vehicle on a Chassis Dynamometer Tested by ORNL

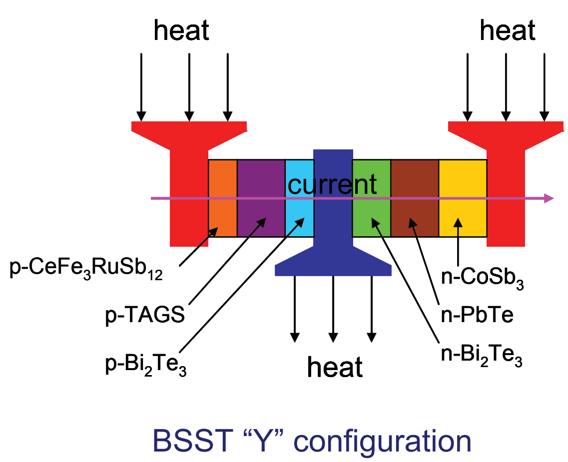
analysis of results from a comprehensive study of the effects of repeated inhalation exposure to laboratory-generated gasoline emissions. It was discovered that inhaled nitrogen oxide and carbon monoxide can duplicate some effects of gasoline emissions on blood vessels outside the lung. (Mauderly, LRRI)

- The Health Effects Institute (HEI) received four test engines from participating engine manufacturers at Southwest Research Institute (SwRI) and finalized the 16-hour test day cycle developed by West Virginia University based on a combination of Federal Test Procedure and California Air Resources Board cycles. Additionally, the emissions characterization protocol was finalized with the CRC ACES Panel and the investigators' team at SwRI and approved a revised testing plan from SwRI. (Greenbaum, HEI)

Solid State Energy Conversion

Several projects are being pursued to capture waste heat from advanced combustion engines in both light- an heavy-duty vehicles using thermoelectrics. Following are highlights of the development of these technologies during FY 2007.

- General Motors Research & Development Center (GM) found that existing bulk thermoelectric (TE) materials in an exhaust generator can meet the minimum 350 W requirement; the exhaust TE waste heat recovery has higher, but not significantly higher, cost than the existing fuel economy improving technologies. GM also found that low quality heat at the radiator makes recovering significant heat cost prohibitive using existing materials, and requires both TE figure of merit enhancement and cost reduction. Material selections for the exhaust TE waste heat recovery subsystem were finalized. (Yang, GM)
- A fractional BiTe thermoelectric generator module (TGM) has been built by BSST and tested that produced 130 watts of electric power. A full-scale BiTe TGM was built and tested that produced over 500 watts of electric power. A fractional high temperature TGM has been built using PbTe/TAGS that produced 20 watts electric power. A fractional high temperature TGM has been built using PbTe/TAGS/BiTe that demonstrated 10% conversion efficiency. (LaGrandeur, BSST)
- Systems for material synthesis, powder processing, hot pressing, leg preparation, material mechanical and thermoelectric property characterization, and couple fabrication have been demonstrated at Michigan State University (MSU). Systems are in place to produce a 40 W module in one week. Using the measured properties of known materials for the temperature range of operation, MSU estimates that a segmented couple can provide a conversion efficiency of over 12%. (Schock, MSU)



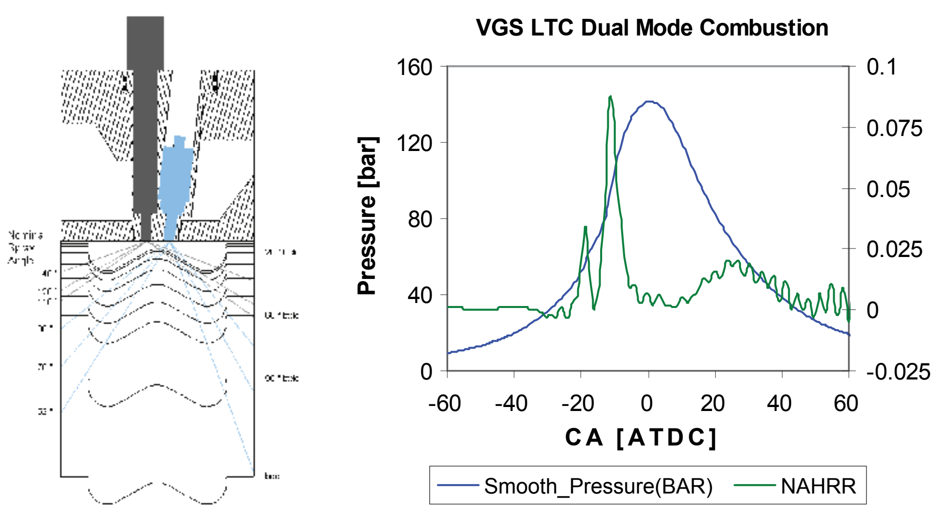
BSST High Density Thermoelectric Subassembly

University Research

- Multi-cylinder supercharged engine operation for high-load limit extension has been demonstrated at the University of Michigan (UM) using port fuel injection. Initial experiments up to 1.7 bar intake pressure have shown proportional load increases. Combustion control is provided by an intake air cooler/flow splitter arrangement. Single-cylinder experiments have achieved low-load extension by fuel injection during negative valve overlap. Further, varying the timing of the injection affects the combustion phasing and shows promise as a control tool. (Assanis, UM)
- The University of Wisconsin-Madison has formulated combustion models and reaction mechanisms and has applied them to analyze and optimize low emissions diesel engine operation. In-cylinder

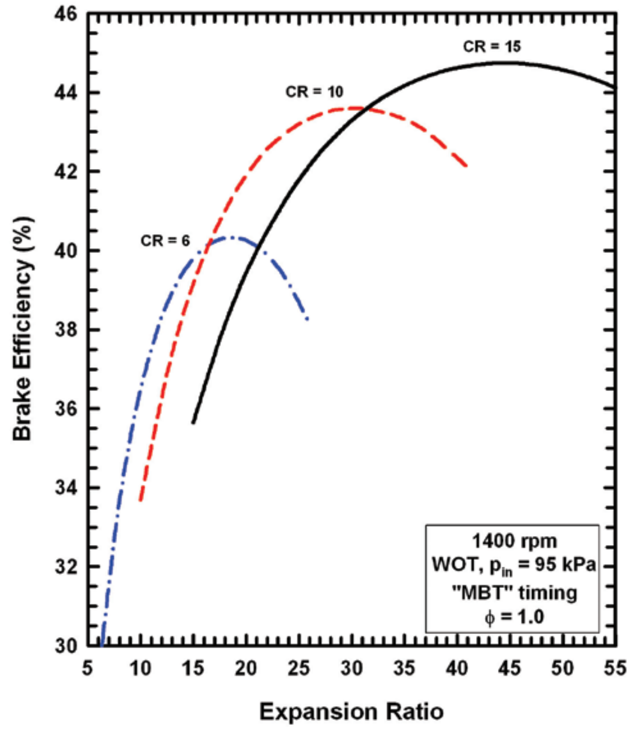
optical diagnostics have been developed for H_2O species, and temperature and turbulence dissipation measurements, for use in chemistry and turbulence model validation. A two-stage combustion strategy has been formulated and demonstrated with modeling and experiments to achieve 2010 emissions levels with low-temperature combustion operation. (Reitz, University of Wisconsin-Madison)

- West Virginia University (WVU) implemented simple models for LTC and diesel engines to obtain the pressure and temperature data required for the evaluation of efficiency for each type of engine. Values of energy losses in the LTC engine were compared with energy losses of a diesel engine with half the displacement of the LTC engine. Energy losses assessed in this model include friction, auxiliaries and heat transfer. A model to evaluate the total cooling burden was developed to assess the impact of the energy losses in the fan energy requirements, which is also powered by the engine. Model results showed that the total cooling burden on a LTC engine with higher displacement and lower power density was 15.6% lower than the diesel engine for the same amount of energy addition in the case of high load (43.57 mg fuel/cycle). (Clark, WVU)
- The University of Houston carried out a comprehensive experimental study of the steady-state behavior of the NO/H_2 and $NO/H_2/O_2$ reaction systems on model Pt and Pt/Ba monolith catalysts. Integral conversion and selectivity data were obtained over a range of temperatures, feed compositions, and catalyst loadings (Pt, BaO). The analytical system was upgraded to include a mass spectrometer, enabling the measurement of N_2 and H_2 in addition to the remaining species measured by Fourier transform infrared spectroscopy. (Harold, University of Houston)
- Bench reactor tests were performed at the University of Kentucky on a series of model monolith catalysts, in which the concentrations of the four main active components, Pt, Rh, CeO_2 (or CeO_2-ZrO_2) and BaO were systematically varied. From the resulting data, catalyst activity-composition (and in some cases selectivity-composition) correlations were derived. An automated catalyst aging cycle has been implemented for the accelerated aging of model monolithic catalysts. Under lean-rich cycling conditions, ceria was found to exert significant effects on the intra-catalyst chemistry, as demonstrated by the analysis of rich phase intra-catalyst H_2 concentration profiles. (Crocker, University of Kentucky)
- Texas A&M University developed an engine cycle simulation to determine the effects of compression ratio and expansion ratio on engine performance and second law performance. The results showed that increases of compression ratio beyond about 10:1 do provide significant thermodynamic gains. The use of a greater expansion stroke compared to the compression stroke ("Atkinson cycle") was most effective for wide-open-throttle conditions. The use of a greater expansion stroke had modest effects on the second law parameters. The simulation was modified to be able to consider diesel engine operations. Preliminary results were obtained and compared to



University of Wisconsin-Madison Variable Geometry Spray (VGS) Arrangement with High and Low Pressure Injectors and Two-Stage Combustion Results experimental results for a 1.7-liter, direct-injection, Isuzu engine. (Caton, Texas A&M University)

- A fluidic rectifier with area ratio of 8, length of 5 mm and extension of 5 mm was fabricated and integrated into a forward/backward mass air flow sensor prototype and was characterized in the unsteady air intake flow facility and tested with robust, automotive hotwires at MSU. High-speed visualization of fuel air mixing and in-cylinder flame distribution was achieved to reveal the spray distribution, flame propagation, and fuel impingement in the optical engine. (Schock, MSU)
- A diesel engine and dynamometer rig for testing particulate matter sensors was designed and set up in the University of Texas (UT) Engine Combustion Laboratory. A particulate filter measurements system was designed and assembled to allow the sensors to be calibrated for non-volatile mass emissions of particulate matter. Using this system, the engine's PM emissions were determined as a function of engine operating condition. New sensor designs were developed, tested, and calibrated. (Hall, UT at Austin)



Effect of Expansion Ratio on Brake Thermal Efficiency at Different Compression Ratios as Determined by Texas A&M

FUTURE DIRECTIONS

Advanced Combustion and Emission Control Research for High-Efficiency Engines

A. Combustion and Related In-Cylinder Processes

The focus in FY 2008 for combustion and related in-cylinder processes will continue to be on advancing the fundamental understanding of combustion processes in support of achieving efficiency and emissions goals. This will be accomplished through modeling of combustion, in-cylinder observation using optical and other imaging techniques, and parametric studies of engine operating conditions. Several labs and universities plan to adopt a common engine research platform that will span optical single-cylinder through multi-cylinder experiments. Achievement of 43% peak efficiency for the 2008 FreedomCAR goal is expected to be validated at ORNL with this engine.

- ANL will increase the relevance of their measurements by studying sprays under conditions even closer to those of modern diesel engines. ANL plans to upgrade their fuel system to the latest generation of fuel injection equipment, and use full-production injectors that can also be run in the GM-Fiat 1.9-liter engine running in Argonne's Engine and Emissions group. ANL will also improve the measurement technique. While useful results are presented, improvements to the measurement technique will increase its applicability and accessibility in the future. Such improvements include faster data acquisition, processing, and analysis, improved X-ray detector systems, increased X-ray intensity, and greater automation. (Powell, ANL)
- SNL will develop an optical diagnostic technique for visualizing the in-cylinder spatial distribution of CO and apply optical techniques to investigate sources of UHC and CO emissions in highly dilute, LTC regimes. SNL will also evaluate the effect of engine boost on low-temperature

combustion systems and on the fuel conversion efficiency loss typically observed with high dilution levels. In addition, SNL will examine how trace components in simulated EGR influence the combustion and emissions formation processes. (Miles, SNL)

- SNL will apply optical diagnostics for other LTC conditions and maintain modeling collaboration with the University of Wisconsin to improve computer model performance for LTC conditions. SNL will develop a simple mixing model of end-of-injection mixing processes and continue to extend the conceptual model of diesel combustion to LTC conditions. (Musculus, SNL)
- SNL will investigate the location of evaporation for end of injection mixing near the nozzle and its impact on UHC. SNL will determine how multiple injections can be used to affect ignition timing and minimize UHC at LTC conditions. Direct measurements of mixing (equivalence ratio) at the time of the premixed burn in constant-injection-duration diesel fuel jets for various EGR levels and multiple injection strategies will be performed. This investigation will show how mixing between injections affects the equivalence ratio and location of the premixed burn. (Pickett, SNL)
- ORNL will explore advanced combustion operation on a GM 1.9-L engine including efficiency, emissions, noise, and stability with a high-pressure loop EGR system. The effect of intake mixture temperature and composition on advanced combustion operation will be characterized. ORNL will also investigate acoustic and vibration energy transmission paths for diagnostics and control of conventional combustion and advanced combustion modes. (Wagner, ORNL)
- SNL will continue development of high-fidelity simulations of the optical hydrogen internal combustion engine and systematically extend them to HCCI engine experiments. In addition, SNL will continue leveraging between DOE Office of Science and Energy Efficiency and Renewable Energy activities. (Oefelein, SNL)
- LLNL will validate KIVA3V-MZ-MPI against experimental data under partially stratified conditions by working with engine researchers at SNL to conduct validations of the code at PCCI conditions. LLNL will use KIVA3V-MZ-MPI as a predictive tool for engine geometry and fuel injection optimization and analyze spark-assisted HCCI experiments. (Aceves, LLNL)
- SNL will conduct an investigation of the potential of EGR/residuals for slowing the pressure-rise rate at high loads to further extend the upper-load limit of HCCI. The development of thermal stratification and its distribution in the bulk gases during the latter-compression and early-expansion strokes will be investigated. SNL will complete a detailed exhaust-speciation study over a range of fueling rates and for mixture stratification at low loads for iso-octane and gasoline and determine the effects of ethanol and/or ethanol-gasoline blends on HCCI performance for well-mixed and mixture-stratified operation. (Dec, SNL)
- SNL will complete the operating-range tests of recompression-HCCI combustion and investigate the use of alternative injection strategies, including injection during the recompression period, to accomplish advanced fuel-air mixing strategies. SNL will apply a PLIF diagnostic to characterize engine performance under these conditions and examine spark-assisted HCCI operation to understand its potential role for widening the HCCI operating range. (Steeper, SNL)
- ORNL will baseline and map SI-HCCI regions of operation on a multi-cylinder engine located at Delphi Automotive Systems. Detailed kinetics simulations will be performed of the SI-HCCI transition to improved physical understanding of multiple combustion modes and inter-mode switching. Simulations will be performed in-house as well as in collaboration with LLNL. ORNL will also improve the low-order combustion model for use in the development of fast diagnostics and control strategies. (Wagner, ORNL)
- LANL will continue with the validation of KIVA-4 in unstructured geometries and in parallel simulations of realistic engine geometries. LANL will implement LLNL's multi-zone combustion model into KIVA-4 and develop the capability to perform turbulent calculations with the large eddy simulation turbulence model in KIVA-4. (Torres, LANL)
- LLNL will extend model capabilities to additional new classes of fuel components, including hepta-methyl-nonane which is a primary reference fuel for diesel fuel and represents iso-alkanes in diesel fuel. LLNL will further validate their chemical kinetic model for n-hexadecane and continue the development of increasingly complex surrogate fuel mixtures to represent fuels for HCCI and diesel engines. (Pitz, LLNL)

- ORNL will characterize the thermodynamic availability of engine system components over the speed-load range of the engine and evaluate the potential efficiency benefits of bottoming cycles for waste heat recovery from the EGR system, exhaust system, etc. Low-temperature combustion approaches on the GM 1.9-L engine for reducing aftertreatment needs and improving overall system efficiency will be investigated. (Wagner, ORNL)
- SNL will fabricate and construct a two-stroke cycle, opposed piston research engine utilizing optimized coupling of Magnequench linear alternators as a proof-of-concept tool. The battery charging application will be optimized for higher power-to-weight ratio. Also, SNL will operate the research experiment fueled by hydrogen to measure indicated efficiency in a continuous operation regime and demonstrate flexibility and multi-fuel capability by operating on alternative fuels at various operating conditions (compression ratios, equivalence ratios). (Van Blarigan, SNL)
- ANL plans to expand engine testing to include central direct injection in addition to the current side injection location. ANL will evaluate newly designed injector nozzles for performance and emissions benefits and analyze the potential of water injection. Test runs at higher engine speed conditions will be conducted to evaluate the high-flow performance of the improved injectors. (Wallner, ANL)
- SNL will measure the velocity field in the vertical (axial) plane during the intake stroke to validate pre-injection accuracy of the companion simulation. Simultaneous two-dimensional measurements of velocity/equivalence ratio will be implemented. SNL will also install a new engine head, supplied by Ford R&D, featuring central injection and central ignition. Engine geometry will then be identical to that of collaborating labs at Ford and ANL. (Kaiser, SNL)
- Cummins will conduct multi-cylinder engine testing of advanced turbomachinery (electronic boosting, 2-stage turbocharging, and supercharging), advanced EGR cooling systems (EGR pump, 2-stage cooling, variable displacement pumps, etc.), and evaluate VVA including cylinder deactivation. (Stanton, Cummins)
- Caterpillar will continue optical engine tests to further develop fundamental understanding of low-temperature combustion and make improvements to further advanced fuel system capability and demonstration of those benefits. Additional fuels effects testing will be performed to discern fuel property effects. Control strategies will be refined and implemented on advanced multi-cylinder engines. (Milam, Caterpillar)
- International will complete the engine builds and benchmark the attributes of their variable compression ratio and VVA prototypes. KIVA3V combustion simulations will be conducted to further optimize combustion hardware. International will continue to conduct steady-state testing to optimize combustion hardware for U.S. 2010 heavy-duty emission regulations; special emphasis will be on fuel economy. Also, International will develop a prototype engine control unit to handle in-cylinder combustion diagnostics and feedback. (de Ojeda, International)
- GE Global Research will optimize the combination of post and pilot injections for the most favorable hardware combination, and expand the studies over the entire engine duty cycle. (Primus, GE Global Research)
- ORNL will shakedown and experimentally demonstrate low-irreversibility combustion in the CPER bench-top apparatus and continue analyses of data from CPER experiments to determine efficiency implications and appropriate ways to model exergy losses under different operating modes. Additionally, better ways for recuperating exhaust heat and utilizing compound cycles for extracting work will be explored. (Graves, ORNL)
- DDC will procure an advanced next generation fuel injection system including variable nozzles that can greatly enhance fuel injection flexibility. A master plan on consolidation of fuel injection strategy and dual combustion modes to minimize cylinder-out emissions will be developed. DDC will also continue steady-state advanced combustion development. (Zhang, DDC)
- GM will continue development and testing of their prototype gasoline and diesel engine hardware which enables operation of HCCI combustion for improved fuel efficiency and emissions performance. Both “two-step” and fully variable valve actuation systems will be further developed and tested.

B. Energy-Efficient Emission Controls

In FY 2008, work will continue on LNTs and selective catalytic reduction using urea (urea-SCR) to reduce NOx emissions. The focus of activities will be on making these devices more efficient, more durable, and less costly. For PM control, the focus will be on more efficient methods of filter regeneration to reduce impact on engine fuel consumption.

- PNNL will continue the studies of CO_2 and H_2O effects on BaO morphology changes and NOx storage properties. Characterization of the roles (especially with respect to deactivation) and material properties of promoter species will be detailed. PNNL will also initiate studies of interactions between multiple emission control devices (e.g., how to optimize LNT regeneration for NH_3 production if a downstream urea-SCR catalyst system is present). (Peden, PNNL)
- PNNL will further refine function-specific measures of 'aging' and validate the most-suitable function-specific measures on samples incrementally 'aged' under realistic conditions. PNNL will apply developed techniques to the commercial fresh and 'aged' samples in the monolith form and continue to improve mechanistic understanding of the sulfur removal processes. (Peden, PNNL)
- ORNL will conduct experiments to analyze the potential benefit of NH_3 emissions from LNT catalysts for downstream selective catalytic reduction, evaluate lower precious metal LNT catalysts to study possibilities for cost reduction (a key limitation to introduction of the technology), and examine LNT catalysts for lean gasoline engine applications. (Parks, ORNL)
- SNL will complete parameter optimization for the combined storage/regeneration mechanism, re-evaluating kinetic constants for the precious metal sites if necessary. SNL will also use the validated reaction mechanisms to investigate coupling between an LNT and other devices in the aftertreatment train. (Larson, SNL)
- ORNL will refocus efforts on the impacts of NH_3 storage on selective catalytic reduction catalyst performance, particularly at low temperatures and for aged catalysts. (Toops, ORNL)
- ORNL will investigate fast desulfation to potentially drive off weakly bound sulfates before they convert to strongly bound sulfates and determine sulfation/desulfation behavior of mixed model catalysts. Effects of doping storage phase with other alkali/alkaline components will be investigated to affect sulfate stability. (Toops, ORNL)
- ORNL will quantify engine-system non-uniformities and mitigation strategies as well as selected LNT sulfation effects. Selected nitrogen-selectivity issues related to LNT regeneration and hybrid catalyst systems will be investigated. (Partridge, ORNL)
- ORNL will continue engine-based studies to assess a combination of LNT catalysis for HECC and traditional modes. The ability of catalysts to control increased carbon monoxide and hydrocarbon emissions from advanced combustion modes will also be examined (Parks, ORNL)
- ORNL will continue co-leading the CLEERS planning committee and co-leading the LNT Focus Group, and support the DPF and SCR Focus Groups as needed. ORNL will also continue providing standard reference LNT materials and data for Focus Group evaluation and continue assisting in refinement of CLEERS technical priorities, especially in regard to the balance between LNT and urea-SCR R&D and synergies between these two technology areas. ORNL will organize the 11th CLEERS workshop in the spring of 2008 and continue maintenance and expansion of the CLEERS web site. (Daw, ORNL)
- ORNL will continue the expansion of the bench-flow and micro-reactor capabilities and continue the development and demonstration of methods for utilizing LNT protocol data to generate global reaction kinetics and simulate device-scale performance. ORNL will also continue the characterization of the Umicore LNT reference catalyst over a range of conditions relevant to both diesel and lean gasoline engine exhaust and transmit results to the LNT Focus Group as they become available. (Daw, ORNL)
- PNNL will conduct research into the design and optimization of 4-way devices which address soot, hydrocarbons, CO, and NOx in a single unit. Exploration of issues surrounding nano-particulate emissions, including nano-particle detection, identification by size and composition, and prediction of nano-particle formation and behavior in after-treatment systems will also be investigated. Filtration and regeneration experiments and simulations will be conducted to improve prediction

of global reaction rates during active and passive regeneration and estimation of device state from sensor data. (Stewart, PNNL)

C. Critical Enabling Technologies

The critical enabling technologies activities in FY 2008 include work on VVA, variable compression ratio systems, and combustion sensors.

- Delphi will refine their VVA system using finite element analysis and computational fluid dynamics (CFD). Accelerated durability testing of mechanism and dynamometer engine testing while monitoring exhaust emissions will verify the benefits predicted by CFD modeling. (Gutterman, Delphi)
- Envera LLC will optimize their variable compression ratio hydro-mechanical system for improved performance and manufacturability. The existing/optimized variable compression ratio engine will be installed and tested in a test vehicle. (Mendler, Envera LLC)
- The immediate future work for Streamline Automation, LLC is to take the engineering lessons learned from the design of the new stainless steel package, and of high-temperature interconnects, and complete the final construction of the new planar-type NOx sensor. During the next phase characterization, the differencing algorithm will be refined for real-time operation, and the identification and quantification portions of the signature processing will be integrated into that algorithm so that all processing is completed in real-time by an engine controller-type embedded computer. (Vogt, Streamline Automation, LLC)
- Testing will continue at TIAX LLC to generate further combustion sensor data at more speed and load points, and this data will be tested in the algorithms. Low-temperature combustion is planned to evaluate the sensor for HCCI engine operation (current data has been measured in diesel mode). The sensor package will also be tried on the second engine setup to determine the engine-to-engine repeatability of the algorithms. (Smutzer, TIAX LLC)
- Westport Power, Inc. will study sensor-to-sensor variation on two Cummins ISB engines as well as study the effectiveness of the current compensation methods in dealing with sensor-to-sensor variation. A charge amplifier for gain compensation will be investigated to further improve robustness using signals from non-adjacent bearing caps. (Mumford, Westport Power, Inc.)
- John Deere will perform vehicle testing to better define actual operating fuel savings. Emphasis will be primarily on the truck, since this is where there is most interest. Commercialization potential needs to be defined. More detailed cost analysis and projections are required. Volume projections will be important here, so knowing the nature of the benefits over a range of applications will be required. (Vuk, John Deere)
- Cummins will proceed to laboratory-based, engine-integrated system testing with an EGR-only WHR system and develop and tune the control system of the WHR system to provide optimum performance integrated with the engine and driveline systems. Cummins will also acquire, incorporate and test components necessary for main exhaust stream energy recovery and create specifications and initiate procurement of a second-generation hardware set appropriate for installation in-vehicle. (Nelson, Cummins)
- Volvo will test advanced compressors and turbines in special rigs and build a prototype of the high efficiency turbocompound device. Additional turbocompound device and turbocharger testing will be conducted in order to verify theoretical performance. Volvo will also demonstrate the engine and continuously variable transmission system in a test cell to determine system efficiency. (Habibzadeh, Volvo)
- Caterpillar plans an on-engine demonstration of a 4 to 4.5% improvement in thermal efficiency using advanced turbocharger technologies, intercooling, and insulated exhaust ports. Additionally, Caterpillar will conduct a bench demonstration of the performance of the Brayton bottoming cycle components, worth another 3 to 4% improvement in thermal efficiency. (Kruiswyk, Caterpillar)
- Volvo will conduct analysis of test results with simulation results and develop an advanced hybrid engine control strategy. (Kang, Volvo)

D. Health Impacts

The focus of the activities in Health Impacts is to identify and quantify the health hazards associated with exhaust from advanced combustion engines and put them in proper context with other air quality hazards, and to assess the relative hazards of emissions from different fuel, engine, and emission reduction technologies.

- ORNL will evaluate the impact of butanol fuel addition to ethanol-gasoline fuel mixtures on emissions and determine the efficiency of catalytic aftertreatment for reduction of mobile source air toxics from high efficiency clean combustion diesel operation. (Parks, ORNL)
- NREL will test a variety of light-, medium-, and heavy-duty vehicles over different driving test cycles at room temperature (72°F) and cold temperature (20°F) on chassis dynamometers in support of the Collaborative Lubricating Oil Study on Emissions (CLOSE) Program. (Lawson, NREL)
- The subproject of the Health Impacts activity will be completed by LRRI in early FY 2008. Wrap-up will include examining effects of nanoparticles and emission gases at lower concentrations, and publishing results. Future effort in this area will focus on evaluating emerging technologies. (Mauderly, LRRI)
- HEI will complete emissions characterization of the third and fourth 2007-compliant engines at SwRI and finalize the engine selection criteria described in the Initial Plan for Engine Selection with the ACES Oversight and Steering Committees. HEI will continue to work with LRRI, CRC, and the engine manufacturers to determine appropriate specifications for the LRRI engine facility. (Greenbaum HEI)

Solid State Energy Conversion

Research will continue in FY 2008 on thermoelectrics for capturing and utilizing waste heat from advanced combustion engines. Research will focus on development of practical systems that are suitable for future production.

- GM will finalize the TE waste heat recovery subsystem design and provide initial production-ready TE modules for application-based testing. GM will start TE exhaust waste heat recovery subsystem prototype construction and develop cost-effective thermoelectric materials and modules. (Yang, GM)
- BSST will complete the build of a full-scale high temperature TGM and perform a bench test including the primary heat exchanger and power conversion system subsystems. (LaGrandeur, BSST)
- MSU will conduct design and analysis of the power conditioning system to optimize thermoelectric system performance, including fault remediation and refine leg fabrication methods (e.g. wet milling/dry milling, hot pressing) for improving mechanical properties and microstructural characteristics. Additional refinement of fabrication techniques for scaleable couple/thermoelectric modules will also take place. Analytical studies will be finalized on the full engine system including coupling current simulations to the 3-D heat transfer studies to provide efficiency gains for the optimum thermoelectric generator-engine configurations. (Schock, MSU)

University Research

In FY 2008, our university partners will continue their fundamental research into combustion and the chemistry of emission control devices.

- UM will carry out single- and multi-cylinder experimental investigations of upper and lower load combustion limits with supercharging/turbocharging and fast thermal management of intake temperature. Valve actuation and supercharging/turbocharging implementations with the GT-Power® system model will be explored and performance and fuel economy benefits will be evaluated. UM will develop a model of spark-assisted HCCI and explore potential benefits of the technology from the point of view of control and range extension. (Assanis, UM)

- The University of Wisconsin-Madison will provide guidelines to the engine and energy industries for achieving optimal low-temperature combustion operation, and low emissions engine design concepts will be proposed and evaluated. (Reitz, University of Wisconsin-Madison)
- WVU will continue their activities in the following areas: (1) modeling to demonstrate the benefits of the "two fuels" approach in managing in-cylinder combustion, (2) determination of the optimal use of pre- and post-turbocharger heat from a system perspective, (3) design of the integrated heat exchanger and reformer, and (4) addressing the complete system design and control through modeling. (Clark, WVU)
- The University of Houston will conduct bench-scale experiments on the role of Rh and CeO_2 on the performance of their LNT. Focus will be placed on the effect of Pt/Ba interfacial coupling through bench-scale and temporal analysis of products (TAP) reactor experiments that quantify the effect of Pt/Ba interfacial perimeter on the activity and product distribution. Additionally, selected TAP experiments will be carried out using monolith catalysts, enabling a direct comparison of bench-scale and TAP data. (Harold, University of Houston)
- The University of Kentucky will complete accelerated aging of model monolithic catalysts (repeated sulfation/desulfation cycles). Aged catalysts will be characterized using standard physico-chemical techniques, in tandem with bench reactor tests, in order to correlate catalyst aging characteristics with washcoat composition. Additionally, *in situ* diffuse reflectance infrared Fourier transform spectroscopy and on-line mass spectrometry measurements will be performed on model powder catalysts in order to gain improved insights into the chemistry of catalyst desulfation. (Crocker, University of Kentucky)
- Texas A&M University will continue to use their engine cycle simulation to study diesel engines and initiate studies to examine novel engines such as the "iso-engine" (which uses an isothermal compression process). The on-going study of EGR for spark ignition engines will be completed. (Caton, Texas A&M University)
- MSU will correct the oscillation tracking deficiency in present automotive hotwire technology for improved frequency compensation methods through development of new, fast-response, yet robust sensor technology. The large eddy simulation model validation will be completed as well as performance testing of the HECC engine. (Schock, MSU)
- UT at Austin will evaluate new sensor designs to further improve sensor durability and complete the analysis of the effects of exhaust gas velocity on sensor output. Additionally, testing will begin on the sensor in a model-year 2007 6.7-liter Cummins diesel engine that will be installed in the UT Combustion Laboratory. (Hall, UT at Austin)

HONORS AND SPECIAL RECOGNITIONS

1. Paul Miles, Invited Lecture: *2007 SAE Homogeneous Charge Compression Ignition Combustion Symposium,* September 12–14, Lund.

2. 2006 SAE Russell S. Springer Award to Cherian Idicheria for best technical paper by author less than 36 years of age. (SAE 2006-01-3434).

3. Salvador M. Aceves invited to deliver a seminar at the SAE 2007 symposium on HCCI, September 2007, Lund, Sweden.

4. Daniel Flowers invited to deliver a seminar at the SAE 2007 symposium on HCCI, September 2007, Lund, Sweden.

5. Robert Wagner, Oak Ridge National Laboratory, FreedomCAR Technical Highlight in 2007.

6. John Dec, Plenary lecture at the SAE/NA 8th International Conference on Engines for Automobiles, Capri, Italy, September 2007.

7. John Dec, Invited presentation at the SAE HCCI Symposium, Lund, Sweden, September 2006.

8. Magnus Sjöberg, SAE Russell S. Springer Award, presented at 2007 SAE Congress.

9. John Dec, SAE Lloyd Withrow Distinguished Speaker Award, presented at 2007 SAE Congress.

10. 2007 Science & Technology highlight for the Energy & Engineering Sciences directorate at ORNL.

11. Robert Wagner, Oak Ridge National Laboratory, DOE EERE Weekly Report.

12. Robert Wagner, Oak Ridge National Laboratory, ACEC Technical Team summary to USCAR Board of Directors.

13. Robert Wagner, Oak Ridge National Laboratory, ACEC Technical Team highlight.

14. Robert Wagner, Oak Ridge National Laboratory, FreedomCAR Technical Highlight in 2007.

15. Letter from Dr. John C. Wall, Cummins Vice President and Chief Technical Officer: "The knowledge and tools developed in our CRADA were critical to the R&D efforts that culminated in the release of the aftertreatment technology that meets the 2010 environmental standards in 2007."

16. First Place Winner of the "DuBose-Crouse Award for Unique, Unusual and New Techniques in Microscopy"; 40th Annual IMS/ASM 2007 International Meeting, Fort Lauderdale, FL: Saenz, N., H.E. Dillon, S. Carlson and G.D. Maupin. *Advanced Meatallographic Techniques Applied to Diesel Particulate Filters*.

17. J. Yang, GM Research & Development Center - The John M. Campbell Award (outstanding contributions to pure or applied science).

18. Ron Graves, Oak Ridge National Laboratory, Fellow Grade of Membership, Society of Automotive Engineers, April 2007.

INVENTION AND PATENT DISCLOSURES

1. J. B. Green, C. S. Daw, R. M. Wagner, Oak Ridge National Laboratory, "Combustion Diagnostic for Active Engine Feedback Control"; United States patent number 7,277,790 B1.

2. Dec, J. E. and Sjöberg, M., U.S. Patent number 7,128,046 B1, "Fuel Mixture Stratification as a Method for Improving Homogeneous Charge Compression Ignition Operation," issued October 31, 2006.

3. Oak Ridge National Laboratory, "A method for diagnosing and controlling combustion instabilities in internal combustion engines operating in or transitioning to homogeneous charge compression ignition modes", IDEAS 05-156, patent pending.

4. Streamline Automation, LLC, Provisional Patent filed – Voltammetry-Enhanced Multiple Gas Emissions Sensing, application number 60944156.

5. Streamline Automation, LLC, Provisional Patent filed – Aerodynamically-Efficient High-Performance Adapter for Exhaust Gas Sensors, application number 60944272.

6. Streamline Automation, LLC, Provisional Patent filed – Miniature Multi-Channel Potentiostat for Gas Voltammetry, application number 60950336.

7. Streamline Automation, LLC, Provisional Patent Application pending – Gas-Selective Filter for Automotive Exhaust Gas Sensors.

8. The University of Texas at Austin, Patent Pending: 2443 - A Sensor to Measure Time-Resolved Particulate (soot) Exhaust Emissions from Internal Combustion Engines has been patented with coverage in the US in the form of a PCT that was nationalized in the US. Provisional: 7/19/2002, PCT conversion: 7/18/2003, Nationalization in the US: 1/19/2005.

9. Westport Power, Inc., Patent application in progress for algorithm developed during this period.

10. Cummins Inc., Patent No. US7,211,793 B2; Date of Patent May 1, 2007; Neal W. Currier and Aleksey Yezerets, Mass spectrometry system and method.

11. Caterpillar, Ignition Timing Control with Fast and Slow Control Loops (IVP and EGR).

12. Caterpillar, Mixed High and Low Pressure EGR in HCCI Engine.

13. Caterpillar, Strategy for Extending the HCCI Operation Range using Low Cetane Number Diesel Fuel and Cylinder Deactivation.

14. Caterpillar, Recipe for High Load HCCI Operation.

15. Caterpillar, Power Balancing Cylinders in HCCI Engine.

16. Marc Allain and Min Sun, Detroit Diesel Corporation, "Method and System of Diesel Engine Setpoint Compensation for Transient Operation of a Heavy-Duty Diesel Engine", U.S. Patent No. 7,281,518, October 16, 2007.

17. Guangsheng Zhu and Houshun Zhang, Detroit Diesel Corporation, "Invention of Squish-Induced Mixing-Intensified Low Emission Combustion (SIMILECOM)." Record of invention was submitted on August 16, 2007.

18. John Deere, 17307, Turbo Generator Control with Variable Valve Actuation

19. John Deere, 18117, Circumferential Dual-Vane Turbine Inlet

20. Mike Kass and Bill Partridge, Oak Ridge National Lab, US Patent "Integrated Self-Cleaning Window Assembly for Optical Transmission in Combustion Environments," Patent No. U.S. 7,247,383 B1, Date of Patent July 24, 2007.

21. Delphi Variable Valve Actuation Provisional Patents submitted:

1. System for Continuously Varying Engine Valve Duration.
2. Continuously Variable Valve Actuation System.
3. Electro-hydraulically actuated Variable Valve Duration System.

22. GM has submitted over forty invention disclosures related to their externally heated particulate filter regeneration device. Numerous patent applications are in process.

The remainder of this report highlights progress achieved during FY 2007 under the Advanced Combustion Engine R&D Sub-Program. The following 63 abstracts of industry, university, and national laboratory projects provide an overview of the exciting work being conducted to tackle tough technical challenges associated with R&D of higher efficiency, advanced internal combustion engines for light-duty, medium-duty, and heavy-duty vehicles. We are encouraged by the technical progress realized under this dynamic Sub-Program in FY 2007, but we also remain cognizant of the significant technical hurdles that lay ahead, especially those to further improve efficiency while meeting the EPA Tier 2 emission standards and heavy-duty engine standards for the full useful life of the vehicles.

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