VII Abstracts of Newly Awarded Projects

VII.A High-Efficiency Clean Combustion

VII.A.1 Low-Temperature Combustion Using Pre-Mixed Charge Compression Ignition

Cummins Inc.

Cummins will develop state-of-the-art diesel combustion technology into commercially viable light- and heavy-duty engines which are capable of providing significantly improved thermal efficiency while achieving ultra-low NOx and particulate emissions. The engines developed will be fully compliant with the EPA 2010 heavy-duty on-highway emissions standard of 0.2 g/hp-hr NOx and 0.01 g/hp-hr particulate or the EPA Tier II Bin 5 light-duty automotive emissions standard of 0.07 g/mile NOx and 0.01 g/mile particulate. Cummins will utilize new low-temperature combustion modes which are capable of reaching much lower emissions levels than conventional diffusion-controlled diesel combustion. The efficiency of the engine will be optimized by precisely controlling the combustion event and by minimizing losses. The engine's thermal efficiency will be improved by 10% or more through the use of this new combustion technology.

Implementation of this novel combustion approach will require development and optimization work on several subsystems within the engine. Modifications to the fuel system, the air handling and exhaust gas recirculation (EGR) system, the engine control system and other systems will probably be required. Some of the key technologies which may be employed to achieve these goals include higher flow cooled EGR and advanced air handling and control strategies.

The proposed activities include concepts for use on both heavy-duty and light-duty engine platforms. Both engine platforms will utilize the ultra-low emissions combustion technology, but each platform will be optimized to meet its specific requirements. By using this approach, the initial analysis and exploratory development work will be common for the two platforms. The system will be compatible with current diesel fuel, but the technology will be tunable to take advantage of the unique properties of renewable fuels. In this way, the engine developed under this proposal will aid in reducing dependence on imported petroleum. The proposed engine concept also lends itself to integration with an exhaust energy recovery system since a large portion of the system's waste heat is available for recovery from the EGR cooler and the exhaust system.

This project will yield several benefits for the engine owner. First, the low-emissions combustion mode employed here will eliminate or significantly reduce the exhaust aftertreatment system on the engine. This will result in a simpler, more robust engine design. Another benefit is in the reduction of fuel consumption. For a heavy-duty engine, fuel can be the single largest cost in owning and operating the engine. The improved efficiency will reduce these costs. This project will have a significant benefit for the U.S. environment and society while making U.S. industry more competitive.

VII.A.2 Development of High-Efficiency Clean Combustion Engine Designs for Spark Ignition and Compression Ignition Internal Combustion Engines

General Motors Corporation

General Motors (GM) Corporation has formed a multi-disciplinary team of research and industrial experts, consisting of GM Powertrain and Sturman Industries, to develop high-efficiency clean combustion engine hardware for spark ignition and compression ignition internal combustion engines. The proposed project will address a wide range of crucial economic, engineering and scientific questions that must be answered to bring this technology from the laboratory scale to the marketplace. This team effort will focus on utilizing the latest materials research breakthroughs, incorporating these innovations into an existing internal combustion engine system and other subsystems, and integrating them into vehicles. The goal of this project is to develop and evaluate hardware and controls solutions that enable homogeneous charge compression ignition (HCCI) combustion and, in turn, to reduce or eliminate the hardware and controls risks of implementation that exist today.

This project is aimed at complementing and enabling the basic HCCI research of numerous projects already in existence at numerous organizations in the U.S. and elsewhere.

The successful implementation of a mechanical drivetrain that will enable HCCI technology will impact a broad range of vehicle applications. As the largest manufacturer of motor vehicles in the world, GM is in a unique position to quickly bring the benefits of any newly developed technology into the U.S. and global marketplace, thereby realizing economic and environmental benefits. GM will make the benefits of any environmentally friendly technology available to other manufacturers in order to maximize the associated benefits.

VII.A.3 Development of Enabling Technologies for High-Efficiency, Low-Emissions Homogeneous Charge Compression Ignition Engines

Caterpillar Inc

Subcontractors:
ExxonMobil
Sandia National Laboratories
IAV Automotive Engineering

Caterpillar has made significant progress in developing the basic combustion system for an engine using a form of homogeneous charge compression ignition (HCCI). To date, high load performance has been achieved on both single- and multi-cylinder engines with near-zero emissions of NOx and particulates, reasonable hydrocarbon and carbon monoxide levels, and competitive thermal efficiency. The objective of this project is to identify and/or advance the required technologies to enable a low-temperature, high-efficiency combustion solution for commercial 2010 on-highway truck or 2014 non-road machine applications. These enabling technologies include fuel properties, advanced fuel and air systems, cooling systems, and advanced controls methods. Some of these technologies are in the prototype test stage while others are in the concept stage and will require further resources to develop.

In the area of fuel effects, a partnering relationship with ExxonMobil has yielded valuable insight on how fuel properties affect HCCI combustion and the ability to reach high power. The goal is to develop an understanding of the engine/fuel interactions to provide HCCI engines and fuels with enhanced efficiency and performance and to ensure satisfactory operation over the range of commercial in-use conditions. This project will utilize 3-D combustion modeling and system simulation tools to refine the combustion process. This will entail advanced optical diagnostic techniques to provide in-cylinder imaging of fuel/air mixing, equivalence ratio contours, emissions formation/oxidation, and wall wetting. Once the models are well validated, they will be used to optimize the fuel-air mixing and combustion processes with conventional and genetic algorithm approaches.

Engine control of HCCI is an area that needs significant development to realize a practical, production-feasible system. This project will also focus on developing and/or evaluating low-cost, durable combustion phasing sensors, refining existing controls approaches and developing production-intent controls architecture for eventual application in a Class 8 truck. Analysis will be conducted to ensure the robustness of engine hardware, including pistons, head/block, connecting rods, bearings, etc. Cold-starting aids to enable real-world starting in ambient conditions as low as –20°F will also be developed and validated in the laboratory and in a vehicle.

VII.A.4 Low-Temperature Combustion Demonstrator for High-Efficiency Clean Combustion

International Truck and Engine

The goal of this project is to develop a production-capable diesel engine using homogeneous charge compression ignition (HCCI) combustion capable of achieving the 2010 U.S. Environmental Protection Agency heavy-duty engine emissions standards at conventional power density with improved fuel consumption and emissions control technology compatibility. International Truck and Engine Corporation (ITEC) has assembled a team with all the facilities, skills, and tools necessary to successfully complete this project. The team includes Siemens, Ricardo, Jacobs, BorgWarner, Mahle, Lawrence Livermore National Laboratory, University of California Berkeley and Argonne National Laboratory.

ITEC will use a new 6-liter V8 diesel engine as the basic platform for the project. This state-of-the-art engine is in its original configuration equipped with 4 valves per cylinder, common rail fuel injection system, variable geometry turbine (VGT) turbocharger, and cooled exhaust gas recirculation (EGR). The project targets will be achieved through engine modifications, technology additions, fuels developed for HCCI, and statistical optimization techniques. The engine technologies employed will include a multiple injection capable piezo common rail fuel system, variable valve timing (VVT), variable compression ratio (VCR), and modified combustion and charge air systems.

The overall approach consists of four main phases:

- Concept validation
- Subsystem design and development
- Steady-state engine development
- Transient engine development and demonstration

Combustion will be based on the use of non-wall wetting early injection of fuel forming a pre-mixed charge, combined with a pilot injection for ignition purposes and a novel passive ignition system. The phasing of the combustion events will be controlled mainly via the VVT and fuel injection events. To enable operation across the full range of operating loads, a VCR system will be added to expand the range of the VVT's effective compression ratio. Fuel consumption will be minimized by control of air-fuel ratio and EGR for optimum heat release rate, implementation of a quiescent combustion system, insulated exhaust ports, optimized air system and high expansion ratio. The steady-state operation calibration in combination with the cylinder pressure based control system forms the basis for the development and optimization of transient operations.

The engine developed in this project is anticipated to demonstrate achievement of 2010 U.S. Environmental Protection Agency heavy-duty engine emissions standards without NOx or particulate aftertreatment.

VII.A.5 Heavy-Duty Stoichiometric Compression Ignition Engine with Improved Fuel Economy over Alternative Technologies for Meeting 2010 On-Highway Emissions Standards

John Deere Product Engineering Center

This project proposes a novel concept of a compression ignition engine with cooled exhaust gas recirculation (EGR), a diesel particulate filter, and a three-way catalyst. In order for the three-way catalyst to be effective, the engine must be operated under stoichiometric conditions. Combustion will be similar to conventional diesel combustion, although the peak temperatures will be lower due to the presence of EGR, which will reduce the engine-out NOx. At the same time, the high level of EGR will suppress smoke due to the lower combustion temperature and the presence of water and carbon dioxide, which will react with fuel to make hydrogen and carbon monoxide as intermediate products rather than smoke.

The fuel efficiency of the proposed concept is expected to exceed that of other proposed future diesel engines meeting the 2010 standards because optimum injection timing can be used without producing excessive NOx and no excess fuel will be needed for regeneration of the particulate filter or the NOx control device. Also, the moderately high and relatively steady exhaust temperature will allow exhaust energy recovery using turbo-compounding or a thermoelectric device.

The proposed engine concept will have improved fuel economy over a gasoline stoichiometric engine for the following reasons:

- Higher compression ratio for greater cycle efficiency
- Turbocharging and aftercooling to improve cycle efficiency
- Higher brake mean effective pressure to reduce relative friction losses
- Faster combustion will result in increased expansion work near top dead center
- More EGR can be used than with spark ignition
- Makes use of the higher energy content (and safety) of diesel fuel

The overall goal of this project is to develop an engine system that meets the 2010 on-highway emissions standards and has over 10% better fuel economy than a typical 2010 engine. The project objectives are to 1) prove the concept of the stoichiometric diesel, 2) prove that the 2010 emissions standards can be met, 3) prove that acceptable transient response can be obtained, and 4) demonstrate the improved vehicle fuel economy with the complete system.

VII.A.6 Demonstration of Air-Power-Assist (APA) Engine Technology for Clean Combustion and Direct Energy Recovery in Heavy-Duty Applications

Mack Trucks, Inc.

The objective of this project is to demonstrate a minimum of 15% fuel economy improvement with emissions meeting the 2010 Environmental Protection Agency (EPA) regulations. The concept is to use the engine to convert braking energy into compressed air stored in an on-board tank (SAE Paper 2000-01-1025). Later, during acceleration, the engine is powered by the stored compressed air with or without burning diesel fuel to get up to speed or until the compressed air is depleted. Once the vehicle has attained a cruising speed, the engine converts back to a conventional diesel engine. The positive pumping work performed by compressed air during the intake stroke is added to the work performed by combustion gas during the gas-expansion stroke. The additional work performed by the compressed air permits a reduction in the quantity of fuel needed to achieve the required engine power. In this way, the engine efficiency is increased, and the vehicle fuel economy is improved (SAE Paper 1999-01-0623). The high boost pressure during engine acceleration helps reduce the emission of particular matter. In addition, smaller quantities of fuel burned in each cylinder during each cycle lead to lower peak temperatures, which result in lower nitrogen oxide emissions. The noise from the sudden exhaust gas blow-down process during engine braking is reduced by minimizing the pressure difference across the engine valves, and the reduced noise is further muffled by the air tank. This provides a solution to the noise issue that a conventional engine brake has. Therefore, regenerative compression braking can be utilized in the areas where conventional engine braking is prohibited due to its noise pollution. This facilitates greater usage of the engine brake, which in turn helps save fuel and reduces the frequency of brake service with its associated costs.

In summary, an APA engine absorbs the vehicle kinetic energy during braking, puts it into storage in the form of compressed air, and reuses it to assist in subsequent vehicle acceleration. The energy saving principle of this technology is similar to that of the electric hybrid technology, except that the high capital cost for an electric hybrid drivetrain is avoided.

In a previous engine modeling and driving simulation study, this concept was applied to a gasoline engine for a passenger car, and improvement in fuel economy over the EPA city and highway driving cycles was projected to be 60% and 10%, respectively (SAE Paper 2003-01-0038). It is proposed here to use the same concept to develop high-efficiency clean combustion heavy-duty engines. It is anticipated that a minimum of 15% fuel economy improvement will be achieved over the EPA City driving cycle with substantial emissions reduction. In actual driving cycles for the refuse vehicles to which Mack Trucks is the largest supplier, more savings is expected since the application involves more low-speed operation with many stops. Once this APA engine technology is proven to be feasible, it can also be transferred to medium- and light-duty diesel engines as well as gasoline-powered engines.

VII.B Waste Heat Recovery

VII.B.1 Exhaust Energy Recovery

Caterpillar Inc.

Caterpillar's Technology and Solutions Division will develop a new air management and exhaust energy recovery system that will enable a minimum 10% improvement in thermal efficiency over the base engine (e.g., 40% brake efficiency to 44%), with no emissions increase. The overall project objective is to demonstrate the efficiency gain with complete engine system prototypes by 2008. Emphasis will be placed on developing and incorporating cutting edge technologies that meet demanding cost, packaging, and driveability (response) requirements. The Caterpillar project will evaluate concepts within the context of an advanced low-emissions engine system leveraging Caterpillar's system-level understanding and analysis capability. The Caterpillar project will include multiple phases that will begin with a detailed system-level analysis to validate the technical direction. Subsequent phases are dependent upon the results of the preliminary analysis; however, it is envisioned that electric turbocompounding and high-efficiency air system technology will be key technology building blocks developed under this project.

VII.B.2 Electrically Coupled Exhaust Energy Recovery System Using a Series Power Turbine Approach

John Deere Product Engineering Center

Pending diesel engine emissions regulations for 2007-2010 are projected to adversely impact engine efficiency and brake mean effective pressure. Technologies that negate these losses are of strong interest in the current environment where economic drivers seem to be converging to produce higher fuel costs and decreased energy security.

Thermodynamic analysis suggests that the energy in the exhaust gasses of typical diesel engines is approximately equivalent to shaft output. Turbo compounding has been in use for over 60 years and has been proven to provide both increased system power output and improved fuel economy. Market acceptance of hybrid vehicles is providing the incentive for development of the high-capacity power electronics needed to cost-effectively couple a power turbine to the engine or vehicle drivetrain. The series turbine approach provides potential emissions advantages and offers higher output and efficiency than other arrangements studied.

This project targets a 10% improvement in system fuel economy and a 20% increase in net engine power output. The project is based on detailed performance modeling to determine turbo machinery pressure ratios and the net impact on the pumping work of the engine. System architecture includes dynamic system control algorithms that provide optimal performance and system safety in case of component failures. Components with very high efficiencies have been designed, and first-generation experimental hardware is being built. The hardware will be applied to both on-highway and off-highway vehicles in an effort to accurately quantify performance benefits. Initial engine dyno testing will focus on turbo machinery matching and emissions mapping. Additional modeling will be completed to help define optimum power outputs and controls. A second-generation system will be developed if the concept shows sufficient promise which will focus on improved packaging, manufacturability, and broad application. A multi-phase commercialization study is planned to expedite application and to produce cost-effective architectures and component designs. Eaton is teaming with Deere to develop a turbo compounding system that integrates with their hybrid drivetrain systems for on-highway trucks. Rockwell Automation will provide the electric coupling system to join the engine and power turbine.

VII.B.3 Waste Heat Recovery for Internal Combustion Engines

Cummins Inc.

Project Objectives

- Demonstrate an improvement in fuel efficiency of 10% or more by recovering waste heat energy.
- Reduce overall vehicle cost by eliminating the need for additional heat rejection capacity.
- Increase cooling capacity for optimum combustion efficiency and performance.

The stringency of the U.S. Environmental Protection Agency 2010 emissions standards requires diesel engine manufacturers to develop new combustion methodologies and employ new systems such as dual-stage turbocharging, cooled exhaust gas recirculation, and Miller-Cycle air handling. Although these systems demonstrate promise to meet future emissions requirements, customers purchasing these diesel engines are saddled with increased complexity and reduced fuel efficiency. Furthermore, the end result is that the U.S. must increase fuel imports, since the diesel engine provides prime propulsion and power generation for agriculture, construction and truck transportation.

Adding cooled exhaust gas recirculation and/or incorporating Miller-Cycle air handling to develop future emissions-capable combustion also increases heat rejection. Vehicle manufacturers are now increasing radiator and cooling fan capacity, further increasing vehicle costs. By 2007, it is anticipated that vehicle manufacturers will have reached a practical heat rejection limit. Combustion technology trends to achieve 2010 emissions are expected to increase heat rejection in excess of established limits.

This project addresses the critical needs of heat rejection while improving fuel economy through the intelligent application of existing technology solutions. The integration of Cummins' waste heat recovery (WHR) system supports clean and efficient combustion while reducing engine heat rejection for 2010 vehicles. Through modification and replacement of current heat transfer components, an efficient WHR system is envisioned. Recovered energy improves the overall diesel engine efficiency and thereby reduces tail pipe emissions. The result is a doubling of benefits - both to the end-user and to the environment.

VII.B.4 Very High Fuel Economy, Heavy Duty, Constant Speed, Truck Engine Optimized via Unique Energy Recovery Turbines and Facilitated by a High Efficiency Continuously Variable Drivetrain

Mack Powertrain Division of Volvo Powertrain Corporation

Diesel truck transport is the mode favored for nearly 95% of distribution of all types of products in the U.S. The diesel engine industry accepts the public need for increasingly cleaner air and improved efficiency of delivery of these products. Improved delivery fuel efficiency is achievable even with the demanding EPA 2010 emissions standards for truck engines. This can be achieved by a new emphasis on recovering exhaust energy that is currently wasted in conventional engines.

While the diesel engine provides the highest efficiency of conventional prime movers, compromises to the design occur when developing the engine to operate over a relatively wide speed range. These compromises result from the demands of the typical drivetrains available today. There are several drivetrain configurations now emerging for heavy truck applications that can enable the diesel engine to operate at a constant speed. Constant engine speed operation provides significant opportunity to improve thermal efficiency. It also provides benefits to improved engine turbocharger efficiency and the addition of an exhaust turbine to extract additional work. Both turbocharger and turbine designs for high efficiency are significantly facilitated by coupling the devices with an engine with a constant speed or very limited operating speed range. Furthermore, constant engine speed facilitates optimization of fuel injection, valve timing, EGR, and inlet/exhaust manifold design to better satisfy the turbine energy recovery characteristics.

The project will include an engine and continuously variable transmission powertrain demonstration in a state-of-the-art transient emissions test cell where fuel economy gains can be compared to conventional engine and transmission powertrains. Overall, on a highway operating cycle, an engine thermal efficiency improvement of 13-15% and an overall powertrain efficiency improvement of 10-11% are expected. The base powertrain for this comparison will consist of an engine calibrated to meet the Environmental Protection Agency 2007 emissions standards for heavy-duty engines coupled with a typical production transmission.

VII.C Enabling Technologies

VII.C.1 EGR Control for Emissions Reduction Using Fast-Response Sensors

Honeywell International

Exhaust gas recirculation (EGR) has become an integral part of diesel engine technology because of emissions control requirements. Unfortunately, EGR systems in current use negate the historical improvements in exhaust energy recovery made by turbochargers. This project will develop fast-response particle mass (PM) and oxides of nitrogen (NOx) sensors that can enable improved EGR systems through better control of cylinder-by-cylinder trimming. The fast-response particle mass sensor can also provide on-board diagnostics for particle trap loading as well as a potential particle trap failure sensor.

This project will implement fast-response PM and NOx sensors to perform cylinder trimming and particle trap operational diagnostics, and integrate these sensors with a low-pressure EGR system to enhance efficiency and reduce emissions. This project will also develop intelligent control of air/EGR flow and temperature compatible with aftertreatment and exhaust energy recovery requirements. The objective will be to test, validate, and optimize NOx and PM sensors for engine control and diagnostics. A further objective will be to optimize engine response to EGR at various operating conditions. This information will be used to assist Honeywell in the development of a lumped parameter control model that can determine an optimized strategy for using these fast-response sensors.

In order to optimize the sensor response, the PM sensor will need to be validated for the use of cylinder-to-cylinder trimming. In addition, the fast-response PM sensor will be evaluated for use with on-board diagnostics such as determining particle trap failure and particle trap loading. The PM and NOx sensors will be used for the optimization of the low-pressure EGR system and the development of a cylinder-by-cylinder monitoring system for fuel/boost trim.

Development of a modified lumped parameter model will determine the control strategies for EGR and turbo control to minimize NOx and PM emissions. This model will be used in the proof-of-concept for using the PM and NOx sensors to control the low-pressure EGR system.

VII.C.2 Low-Cost Fast-Response Actuator for Variable Compression Ratio Engines

Envera LLC

A fast-response actuator is being developed for adjusting compression ratio in variable compression ratio engines. The fast cycle-resolved response of the actuator system will improve real-time efficiency of spark ignition and compression ignition direct injection diesel engines and will provide improved control of homogenous charge compression ignition combustion. Key attributes of the actuator system include low cost, reliable design, and operation with virtually no accessory power loss. A compression ratio range of 8.5:1 to 18:1 is anticipated. An actuator system will be built and tested in a demonstrator vehicle having a variable compression ratio engine. Objectives include demonstration of fast cycle-resolved response, reliable system design, low cost, and virtually no accessory power loss. Envera LLC will be responsible for engineering development. Bench testing of the system will be conducted at Automotive Specialists in Phase I. Magna-Steyr, a Tier 1 engineering and automotive manufacturing company, will be responsible for vehicle installation and testing of the developed hardware in Phase II. Commercial value is derived from the system's low cost, production reliability, fast response, and minimal parasitic power consumption.

VII.C.3 Variable Valve Actuation

Delphi Automotive Systems, LLC

The objective of this project is to develop and demonstrate an optimal, cost-effective systems approach to diesel engine variable valve actuation (VVA) to facilitate advanced, low-temperature combustion processes. VVA is expected to be a major enabler for expanding the operating range of homogeneous charge compression ignition (HCCI) combustion and regulation of the temperature of aftertreatment catalysts. These are critical functions in terms of the ability to meet future, extremely low emissions requirements. The use of VVA is expected to reduce or eliminate the penalty in fuel consumption related to extremely low emissions standards. The system benefits would also include reduced emissions, reduced aftertreatment catalyst precious metal loading, and the potential to reduce engine displacement through increases in engine power.

The project will be conducted in two phases:

<u>Phase 1 - Feasibility Study/Proof of Principle</u>

Recent advances in diesel and HCCI-like combustion have outlined the general system requirements for a VVA system. A diesel engine will be selected that would be the most universally appropriate for attracting interest from high-volume original equipment manufacturers (OEMs). A first-generation, continuously VVA system will be developed to fit that engine, based on engine control strategies that appear to have the most potential, while staying within the limitations of such a system.

<u>Phase 2 - Development and Scale-Up</u>

The design will be revisited based on the results of Phase 1. A candidate single-cylinder research engine/ OEM partnership will be identified for a system demonstration. Initial validation will be performed on a motored cylinder head stand prior to applying the hardware to a firing engine.

This project will develop and demonstrate a credible set of hardware for diesel VVA applications - which could be quickly adopted by a number of OEM customers in support of their HCCI or other low-temperature combustion initiatives. While the project is focused on diesel HCCI applications, the technology could be adapted to gasoline HCCI applications as well as hydrogen-assisted combustion.

VII.D University Research

VII.D.1 A University Consortium on Low-Temperature Combustion for High-Efficiency, Ultra-Low Emission Engines

University of Michigan (lead university), Massachusetts Institute of Technology, Stanford University, and the University of California at Berkeley

The objective of this project is to determine the practical boundaries of low-temperature combustion (LTC) engines and develop methods to extend those boundaries to improve fuel economy of these engines while operating with ultra-low emissions. The work will involve studies of thermal effects, thermal transients and temperature control, internal mixing and stratification, and direct injection strategies for improving combustion stability. The new fundamental knowledge will enable development of solutions for thermal management and balancing of cylinders in multi-cylinder engines, enhancing power density through turbocharging and control of the engine to maximize the range of homogeneous charge compression ignition (HCCI) operation, and optimization of overall drive cycle performance. Vehicle system-level simulations will be used to characterize realistic in-vehicle transients. In addition, the efficiency and emissions benefits of HCCI, partially premixed compression ignition (PPCI) and other advanced engine strategies for automotive applications will be further improved through exhaust gas treatment devices and novel ignition concepts. Further aspects of the work will examine fuel pre-treatment and its potential to extend the range of HCCI/PPCI operation and the replacement of petroleum-based fuels with bio-renewable fuels, reformed fuels, and fuel blends.

To meet the project objectives, this multi-university consortium will launch this three-year research effort combining computational and experimental approaches, while striking the appropriate balance between fundamental and applied research tasks, in order to deliver the understanding and technology necessary to extend the range of practical HCCI/PPCI operation, dramatically improve automotive engine efficiencies, and yield ultra-low emission technologies.

The proposed project will include the following tasks: 1) wall heat transfer, precision temperature control and thermal management of LTC engine for extended range of operation; 2) improving combustion stability and reducing emissions at low load; 3) engine control for extended HCCI operation; 4) increased power density by turbo/supercharging and temperature control; 5) direct injection studies to enhance combustion stability at low load; 6) emission control devices for PPCI engines; 7) spark-assisted HCCI; 8) fuel pre-treatment strategies, non-petroleum-based fuels and fuel blends for use in advanced low-temperature engine strategies.

VII.D.2 Optimization of Low-Temperature Diesel Combustion

University of Wisconsin

The goal of this project is to develop methods to optimize and control low-temperature combustion diesel technologies (LTC-D) that offer the potential of nearly eliminating engine NOx and particulate emissions at reduced cost compared to traditional technologies by controlling pollutant emissions in-cylinder. LTC involves developing lean or dilute mixtures in-cylinder using direct fuel injection, using compression ignition and maintaining low peak combustion temperatures to minimize NOx formation in-cylinder.

The work is divided into 5 tasks, featuring experimental and modeling components:

- Fundamental understanding of LTC-D and advanced model development,
- Experimental investigation of LTC-D combustion control concepts,
- Application of detailed models for optimization of LTC-D combustion and emissions,
- Determination of impact of heat transfer and spray impingement on LTC-D combustion, and
- Transient engine control with mixed-mode combustion.

The research will use a production 4-cylinder high-speed diesel engine coupled to a fast-response engine dynamometer for studying transient engine performance, and 2 high-speed, light-duty and 1 heavy-duty fully instrumented single-cylinder diesel engines with prototype fuel injection systems to define LTC-D combustion regimes and operational characteristics. Modeling tools will be developed, validated and used to propose design concepts and methods to optimize and control low-emissions diesel engine operation for both light- and heavy-duty engine classes. The engine experiments and detailed modeling will be applied to study fundamental and practical issues that influence combustion phasing (fuel efficiency) and pollutant emissions. In addition, the research will develop criteria for transition from LTC-D to other engine operation regimes (e.g., standard diesel combustion).

Expected outcomes from the research include providing guidelines to the engine and energy industries for achieving optimal low-temperature combustion operation through use of advanced fuel injection strategies, and determining the potential to extend low-temperature operation through manipulation of fuel characteristics. In addition, recommendations will be made for improved combustion chamber geometries that are matched to injection sprays that minimize wall fuel films. The role of fuel-air mixing, fuel characteristics, fuel spray/wall impingement and heat transfer on LTC-D engine control will be revealed. Methods will be proposed for transient engine operation during load and speed changes to extend LTC-D engine operating limits, power density and fuel economy. Low-emissions engine design concepts will be proposed and evaluated.

VII.D.3 Low-Temperature Combustion with Thermo-Chemical Recuperation to Maximize In-Use Engine Efficiency

West Virginia University Research Corporation

West Virginia University's Center for Alternative Fuels, Engines & Emissions, in collaboration with the Gas Technology Institute (GTI) and Atkinson LLC, will study and develop practical means by which thermo-chemical recuperation (TCR) can be integrated with low-temperature combustion (LTC). The major objective of this project is to improve substantially (10% fuel use reduction) the efficiency of compression ignition engines for both light-duty and heavy-duty use, while meeting the ultra-low NOx requirements for the 2010 engine model year. The tools to be used are alternative combustion modes coupled with thermo-chemical reforming of fuel to recover exhaust waste heat, with an optimization of the LTC mean effective pressure versus displacement tradeoff. It is a further objective and requirement that an engine arising from this design philosophy could be created by 2012.

TCR for reciprocating internal combustion engines employs high-efficiency heat exchangers to recover sensible heat from the engine coolant and exhaust gases and uses this energy to transform fuel composition. This is accomplished through catalytic and endothermic reactions in a specially designed reforming reactor. GTI, its Ukrainian TCR research partner Ecotherm, and Ricardo, Inc. have been studying and developing TCR for stationary gas engines used in power generation. These studies indicate that gas engine efficiency can be increased between 8-20% with TCR depending upon engine/system design and operating conditions. At the same time, the reforming reactions lead to somewhere between 15-25% hydrogen (volume) in the product stream. This hydrogen-enriched fuel provides several combustion benefits and is an invaluable additional "lever" for transient control in the application of LTC for ultra-low emissions operation of engines. LTC offers further opportunities to enhance engine efficiency.

First, modeling will be used to examine the tradeoff between engine displacement and indicated mean effective pressure to maximize shaft efficiency under LTC operation. The models, which build upon a prior West Virginia University (WVU) dual fuel project, must take cooling load into account. The TCR will build upon the expertise of GTI in reforming of gaseous fuels and will be configured to make use of available heat from the engine exhaust. The TCR will be enabled through both modeling and experimental research at GTI. For the experimental research at the WVU Engine and Emissions Research Laboratory, the TCR stream (rich in hydrogen) and an untreated fuel stream (diesel, or compression ignition fuel blend) will be employed as two variables to facilitate broad and rapid load control of the LTC using a well-instrumented cylinder with a displacement of two liters. Other control parameters that will be varied include boost, exhaust gas recirculation and manifold temperature, under constraint of compression ratio. Optimization will take place using a neural net model based on the experimental data, and this will allow compensation for confounding factors such as cylinder wall temperature as well as an assessment of cylinder deactivation benefits.
Two pre-competitive (basic) engine designs and control strategies will be developed as a final product.

VII.D.4 Kinetic and Performance Studies of the Regeneration Phase of Model Pt/Rh/Ba NOx Traps for Design and Optimization

University of Houston

Long-term growth in the use of more fuel-efficient and durable diesel/lean burn vehicles requires significant reductions in emissions of nitrogen oxides (NOx) and particulate matter. NOx storage and reduction (NSR) is emerging as a viable NOx emission abatement technology for lean burn and diesel vehicles. The 'lean NOx trap' (LNT) is an adsorptive catalytic monolith reactor requiring periodic regeneration. In the first step, exhaust NOx is adsorbed onto the alkali earth site of a bifunctional supported precious metal based catalyst. In the second step, the nitrate is released and reduced by exhaust hydrocarbons, achieved by intermittent rich engine operation or fuel injection into the exhaust. Several studies of NSR have demonstrated NOx conversion exceeding 80% with a sequence of a ca. 30-60 second lean storage period followed by a ca. 3-10 second rich period on model supported Pt/Ba catalysts.

Optimization of the LNT requires fundamental studies that elucidate the transient cycle to direct improvements in LNT catalyst formulations. While progress has been made in understanding the performance features of the NOx trap, more work needs to be done to advance the technology to commercial readiness. In particular, there is a need for detailed analysis of the role of the reductant and the process of regeneration. The main objectives of this project are (i) to carry out fundamental studies of the transient kinetics of lean NOx trap regeneration on model Pt/Rh/Ba catalysts, (ii) to evaluate and compare the effects of different reductants spanning H_2, CO, CO/H_2 mixtures and a model diesel compound (n-tetradecane) on the LNT performance, (iii) to incorporate the kinetics findings and develop and analyze a first-principles based predictive LNT model for design and optimization, and (iv) to test LNT designs in a heavy-duty diesel vehicle dynamometer facility.

VII.D.5 Investigation of Aging Mechanisms in Lean NO_x Traps

University of Kentucky Center for Applied Energy Research

Subcontractors:
Oak Ridge National Laboratory
Ford Motor Co.
Umicore Autocat USA

Lean NOx traps (LNTs) represent a promising technology for the abatement of NOx under lean conditions. While LNTs have found application on lean-burn gasoline vehicles in Europe, the issue of catalyst durability remains problematic. LNT susceptibility to sulfur poisoning is the single most important factor determining effective catalyst lifetime. The NOx storage element of the catalyst has a greater affinity for SO_2 than it does for NO_2, and the resulting sulfate is more stable than the stored nitrate. Although this sulfate can be removed from the catalyst by means of high-temperature treatment under rich conditions, the required conditions give rise to deactivation mechanisms such as precious metal sintering, total surface area loss, and solid-state reactions between the various oxides present.

Given that there is little incentive to employ lean-burn gasoline vehicles in the U.S. market (in view of the development of hybrid gasoline-electric vehicles), this project focuses on lean NOx traps of the sort used on diesel vehicles. While numerous academic studies have been performed using model catalysts of the Pt/(Rh)/BaO/alumina type, few studies have been reported for catalysts aged to any significant degree, and details pertaining to the evolution of catalyst composition and structure with aging (and hence performance deterioration) are lacking. The approach utilized in this project will make use of detailed characterization of model catalysts prior to and after aging, in tandem with measurement of catalyst performance in NOx storage and reduction. In this manner, the evolution of catalyst microstructure upon aging will be related to NOx storage and reduction characteristics. Rather than using poorly characterized proprietary catalysts, or model catalysts of the Pt/Rh/BaO/Al_2O_3 type (which represent the first generation of LNTs), we will focus on Pt/Rh/CeO_2(-ZrO_2)/BaO/Al_2O_3 catalysts, representing a model system which more accurately reflects current diesel LNT formulations.

The effect of washcoat composition on catalyst aging characteristics will be examined by systematic variation of the concentration of the four main active components, Pt, Rh, CeO_2 (or CeO_2-ZrO_2) and BaO. Catalyst aging will be performed on a synthetic gas bench using repeated sulfation-desulfation cycles with periodic measurement of NOx storage capacity and NOx reduction activity. Subsequently, the aged catalysts will be subjected to detailed chemical and physical analysis in order to correlate NOx adsorption/reduction performance with catalyst composition and structure. The kinetic data will be incorporated in a model with the objective of describing, in quantitative terms, the kinetics of catalyst deactivation. In so doing, the project will address the short-term need for reliable data describing the kinetics of LNT deactivation and the longer-term requirement for improved understanding of the chemistry of LNT aging so as to facilitate the design of more durable catalysts.

VII.D.6 Improved Engine Design Concepts Using the Second Law of Thermodynamics: Reducing Irreversibilities and Increasing Efficiencies

Texas A&M University

The overall objective of this project is to apply both the first and second laws of thermodynamics to develop improved engine design concepts by reducing irreversibilities (irreversible processes) and thereby increasing efficiency. Most engine development work in the past has neglected the use of the second law of thermodynamics even though the second law provides an exciting avenue toward developing more efficient engines. Most previous engine research has focused on the use of the first law of thermodynamics and has only been able to consider the "quantity" of energy, focusing on items such as cylinder heat loss and exhaust gas energy. These analyses have not included the "quality" of the energy associated with the engine processes. Availability (or exergy) is the property that has been developed to complete this quantification. Availability can be computed for any thermodynamic state and for any working substance. Availability (unlike energy) can be destroyed by irreversibilities.

This project will provide more complete understanding of engine operation from the perspective of the second law. In particular, the objectives of the project are to better understand engine irreversibilities and to explore avenues for reducing them. Examples of irreversibilities include mechanical friction, fluid friction, mixing, combustion, unconstrained expansion, and heat transfer across a finite temperature difference. In practice, an availability balance is constructed for the engine processes, and the destruction of availability is determined as the result of this balance.

The proposed work has been divided into three phases: (1) analyses of fundamental processes (such as adiabatic, constant volume combustion), (2) development and use of thermodynamic engine cycle simulations to investigate new concepts to reduce irreversibilities, and (3) use of the simulations to investigate actual engine data for new modes of combustion (such as low-temperature engine combustion with high exhaust gas recirculation).

The analyses of fundamental processes will include a comprehensive investigation of a wide range of parameters such as initial temperature and pressure, equivalence ratio and fuel type. In addition, these types of analyses may be used to explore ultra-high temperature (>3500 K), where some work has indicated that the Gibbs energy of the reactants and products is equal (thus resulting in reversible combustion). Although such temperatures are not practical, this study may provide useful insights into mechanisms for reducing the irreversibility of actual combustion systems.

The development and use of engine cycle simulations will explore more extreme operating conditions and examine the use of "negative" catalysts to provide some control to the combustion process. Again, although not necessarily practical, this type of study may lead to more useful directions for reducing the irreversibilities of actual engines and increasing their efficiency.

VII.D.7 High-Compression-Ratio, Atkinson-Cycle Engine Using Low-Pressure Direct Injection and Pneumatic-Electronic Valve Actuation Enabled by Ionization Current and Forward-Backward Mass Air Flow Sensor Feedback

Michigan State University

This project plans to maximize the in-vehicle fuel economy of light-duty vehicles by improving Otto-cycle engine efficiency by reducing thermal, dynamic, volumetric, and system losses. The choice of the Otto-cycle engine has its roots in commercial, as well as consumer, value. Not only are Otto-cycle engines inherently less expensive to manufacture, but also billions of dollars have already been invested in the facilities to manufacture these engines in the United States. The objective of this project is to produce a gasoline engine that will have near-diesel-like efficiencies when diesel engines are modified to meet the Environmental Protection Agency 2010 Tier 2 Bin 5 emissions regulations while being significantly less costly.

Historically, diesel engines have delivered about 30% better fuel economy than conventional port fuel injection (PFI) spark ignition engines. This efficiency was achieved with a manufacturer's cost premium of anywhere from $1,000 for a 4-cylinder engine to about $1,800 for an 8-cylinder engine. The cost difference is mainly attributable to high-pressure, common rail fuel systems; complex turbocharger systems; advanced exhaust gas recirculation (EGR) systems; and vehicle noise, vibration, and harshness enhancements. The addition of advanced aftertreatment, such as diesel particulate filters and lean NOx traps, could add $500–$800 to the powertrain cost and reduce vehicle fuel economy by as much as 5–7%. There are also secondary vehicle impacts associated with the increased weight, packaging, and associated durability/warranty of such diesel aftertreatment systems that further improve the attractiveness of an advanced spark ignition engine with improved efficiencies and the demonstrated ability to achieve Tier 2 Bin 3 exhaust emissions standards.

The high-efficiency clean combustion (HECC) engine that we propose is targeted to achieve an in-vehicle fuel economy improvement of 20% over the baseline PFI gasoline-fueled engines currently in production. The proposed engine concept employs a high-compression-ratio, modified Atkinson combustion cycle that uses a novel low-pressure, direct-injection fuel system and electronic-pneumatic valve actuation. These features are enhanced and enabled by combustion sensing that we call ionization feedback control (IFC) and a forward-backward mass air flow sensor which will allow direct measurement of air mass entering the cylinder. IFC uses the ions created by the products of combustion to extract critical combustion information in real time. The engine concept also employs stoichiometric and high residual gas recirculation mixtures that allow the use of a three-way catalytic converter, which has proven effective in current engines and will facilitate rapid commercialization of this HECC concept. In addition, the project includes investigating the commercialization feasibility of low-temperature combustion enabled by the same technological building blocks as employed for the HECC engine.

VII.E Health Impacts

VII.E.1 The Advanced Collaborative Emissions Study (ACES)

Health Effects Institute

The objective of the Advanced Collaborative Emissions Study (ACES) project is to determine before widespread commercial deployment whether or not the new heavy-duty diesel engines (compliant with 2007 and 2010 EPA emissions standards) may generate toxic emissions which could adversely affect the environment and human health. ACES is planned to take place in three phases. In Phase I, extensive emissions characterization (at an existing laboratory) of up to four production-intent prototype engine and control systems designed to meet 2007 standards for NOx and PM will be conducted. In Phase II, extensive emissions characterization of a group of production-intent prototype engine and control systems meeting the 2010 standards (including more advanced NOx controls to meet the more stringent 2010 NOx standards) will be the basis for selecting one heavy-duty diesel engine/aftertreatment system for health testing. In Phase III, the engines selected from Phases I and II will be further characterized during health effects studies to form the basis of the ACES safety assessment. The results of the study will identify if any toxic emissions are generated that might adversely affect the environment and human health.