3.3 Advanced Combustion Engine R&D and Fuels Technology

The Advanced Combustion Engine R&D and Fuels Technology subprograms support the mission of FCVT to develop more energy-efficient and environmentally friendly highway transportation technologies that enable the United States to use less petroleum. They will contribute to the FCVT Program goals by dramatically improving the efficiency of internal combustion engines (ICEs) and by identifying fuel properties that improve the system efficiency or can displace petroleum based fuels. Improved efficiency and petroleum displacement fuels both can directly reduce petroleum consumption.

The Advanced Combustion Engine R&D subprogram is focused on removing critical technical barriers to the commercialization of higher-efficiency, advanced combustion engines in light-duty vehicles (passenger cars and light trucks) and commercial medium- and heavy-duty vehicles. R&D focus is on improving engine efficiency while meeting future federal and state emissions regulations through a combination of combustion and fuels technologies that increase efficiency and minimize in-cylinder formation of emissions, and aftertreatment technologies that further reduce exhaust emissions. Activities under the Advanced Combustion Engine R&D subprogram include Combustion and Emission Control R&D, Heavy Truck Engine R&D, Waste Heat Recovery, and Health Impacts.

The Fuels Technology subprogram supports R&D to provide vehicle users with fuel options that enable high fuel economy, deliver lower emissions, contribute to petroleum displacement, and are cost competitive. This subprogram's Fuels for Advanced Combustion Engines activity is closely coordinated with the Combustion and Emission Control R&D activities since different fuel characteristics and reduced property variability may be needed to meet the efficiency and emissions goals. Without the suitable fuels, high-efficiency advanced combustion engines may not be introduced into the market and oil savings will not be realized.

The Advanced Combustion Engine and Fuels Technology R&D activities are undertaken in collaboration with industry, national laboratories, and universities and in conjunction with the FreedomCAR and Fuel Partnership and the 21st Century Truck Partnership (21st CTP).

The following activities are discussed in this section:

- Combustion and Emission Control R&D;
- Heavy Truck Engine R&D;
- Fuels for Advanced Combustion Engines;
- Waste Heat Recovery; and

- Health Impacts.

3.3.1 Combustion and Emission Control R&D

The Combustion and Emission Control R&D activity focuses on enabling energy-efficient, clean vehicles, powered by advanced combustion engines that use clean, petroleum- and non-petroleum-based fuels, and hydrogen. This research activity focuses on developing technologies for light-, medium-, and heavy-duty engines operating in advanced combustion regimes, including homogeneous charge compression ignition (HCCI) and other modes of low-temperature combustion, which will increase efficiency beyond current advanced diesel engines and reduce engine-out emissions of Nitrogen Oxides (NO_x) and particulate matter (PM) to near-zero levels.

Advanced combustion engines are a key element in the pathway to achieving the goals of the FreedomCAR and Fuel Partnership. Advanced engine technologies being researched and developed will 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.

3.3.1.1 External Assessment and Market Overview

Although the achievement of EPA Tier 2 emissions performance has been demonstrated by advanced light-duty diesel engine technology, the rate of market penetration will still be limited by the energy consumption, cost, and durability of the emission control system. The National Academy of Sciences' Committee on the Effectiveness and Impact of Corporate Average Fuel Economy Standards "believes that the Tier 2 NO_x and PM standards will inhibit, or possibly preclude, the introduction of diesels into vehicles under 8500 lb." [a] Research in this activity has transitioned to the development of technologies that will enable advanced engines to operate in low temperature combustion (LTC) regimes with diesel-like efficiency and near-zero emissions. The lower engine-out emissions are expected to enable the use of lower-cost emission control systems with little or no energy consumption and greater durability, making these more efficient combustion engines cost-competitive with current gasoline engines and gaining greater market penetration in passenger vehicles.

3.3.1.2 Internal Assessment and Activity History

The compression ignition direct injection (CIDI) engine, an advanced version of commonly known diesel engines, is the most promising technology for achieving dramatic energy-efficiency improvements in light-duty vehicle applications, where it is suited to both conventional and hybrid-electric powertrain configurations. High efficiency and durability are the attributes that made the diesel the primary engine for commercial heavy-duty applications. Although it is more efficient than conventional gasoline engines, if the CIDI engine is to become widely used in light-duty passenger

[a] National Research Council, Effectiveness and Impact of Corporate Average Fuel Economy (CAFÉ) Standards, 2002, p. 35

vehicle applications, advancements will be required in the mid-term to further improve efficiency while meeting more stringent future emissions standards. The CIDI engine offers a propulsion platform with the potential for further significant efficiency improvements beyond its current capabilities. Advancements will be required in clean combustion, emission control technology, and clean diesel fuels. The Combustion and Emission Control R&D activity initially focused on technologies that enabled the CIDI engine for all applications, from light- to heavy-duty vehicles. Work has since transitioned into engines operating in advanced LTC regimes that offer substantial improvements in efficiency and near-zero emissions.

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 starting in 2006 will greatly benefit the effectiveness, durability, and life of emission control devices. There is close coordination with the Fuels for Advanced Combustion Engines activity because operation in combustion regimes such as HCCI and LTC is enabled by, and heavily dependent on, especially tailored fuel properties. In addition, the subprogram is in the process of securing unanimous concurrence from current participants in the Sandia Advanced Combustion Engine Memorandum of Understanding (MOU) to add FreedomCAR and Fuel Partnership energy companies as full participants.

Work is also undertaken in hydrogen-fueled ICE research that will provide an interim hydrogen-based powertrain technology that promotes the longer-range FreedomCAR and Fuel Partnership goal of transitioning to a hydrogen-fueled transportation system. This goal is shared by FCVT and HFCIT. Hydrogen engine technologies being pursued have the potential to provide diesel-like engine efficiencies with near-zero emissions.

3.3.1.3 Federal Role

Bringing together expertise from both the public and private sectors through collaborative efforts to expand the knowledge base in high-risk, pre-competitive technology areas is a proper Federal Government role. The experimental research and modeling tasks conducted by participating DOE national laboratories will allow a more effective evaluation of potential advanced combustion engine technologies and validation of technology selection. Working at the forefront of these new technologies enhances the knowledge base that can be used by industry partners and suppliers (e.g., original equipment manufacturers, engine manufacturers, emission control device manufacturers, catalyst suppliers) to develop energy-efficient, cost-effective advanced engine and emission control systems. Cooperative research conducted with universities and industry partners accelerates the introduction of these high-risk, mid-term technologies into the marketplace.

3.3.1.4 Approach

The Combustion and Emission Control activity will address in-cylinder combustion and emission control, exhaust aftertreatment technologies, and fuel formulation strategies simultaneously for the most cost-effective approach for optimizing advanced combustion engine efficiency, emissions, and performance. Experimental data and validated computer simulation models will be developed to provide a more definitive understanding of the in-cylinder fuel injection, combustion, and emissions formation processes, as well as the evolution of emissions in the aftertreatment systems. The models to be developed will enable rapid and effective optimization of the fuel injection and combustion systems and the aftertreatment devices for maximum overall system efficiency, compliance with emissions standards, and cost-effectiveness.

3.3.1.5 Performance Goals

The following goals are intended to enable FCVT to meet energy-efficiency improvement targets for advanced combustion engines suitable for passenger cars and light trucks, as well as to address technology barriers and R&D needs that are common between light- and heavy-duty vehicle applications of advanced combustion engines:

- By 2007, achieve engine efficiency of at least 42 percent and, combined with some emission control devices, meet EPA Tier 2, Bin 5 in a light-duty vehicle using diesel fuel (specified by the Fuels Technology subprogram) with a fuel efficiency penalty of not more than 2 percent.
- By 2010, 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.

Presented in the following table are the technical targets (consistent with the goals) for the Combustion and Emission Control activity. The FreedomCAR and Fuel Partnership goals for both hydrocarbon- and hydrogen-fueled ICEs are also shown. These apply to light-duty vehicles (passenger cars and light trucks).

3.3.1.6 Strategic Goals

The Combustion and Emission Control R&D activity supports DOE's Energy Security Strategic goal to "improve energy security by … exploring advanced technologies that make a fundamental improvement in our mix of energy options, and improving energy efficiency."

3.3.1.7 Market Challenges and Barriers

The primary market challenge is as follows:

A. ***Cost.*** Engines that use LTC are more expensive than conventional, port fuel-injected, spark-ignited engines; the engine structures must be stronger to accommodate the inherently higher combustion pressures. Also, the high-pressure fuel injection systems must be correspondingly more robust, and an air boosting system is required to increase power density. The emission control devices required by engines to meet emission targets add to the cost of the system.

Table 3.3-1. *Technical Targets for the Combustion and Emission Control Activity*

Characteristics	Units	FY 2007	FY 2009	FY 2010
FreedomCAR and Fuel Partnership Goals				
ICE Powertrain				
Peak brake thermal eff. (CIDI/H_2–ICE) (H_2–ICE)	%			45/45 45 (2015)
Cost (CIDI/H_2–ICE) (H_2–ICE)	$/kW			30/45 30 (2015)
Reference peak brake thermal efficiency[a]	%	32	34	35
Target peak brake thermal efficiency/part-load brake thermal efficiency (2 bar BMEP[b] @1500 rpm)	%	42/29	44/30	45/31
Powertrain cost[c,d]	$/kW	35	30	30
Emissions[e]	(g/mile)	Tier 2, Bin 5	Tier 2, Bin 5	Tier 2, Bin 5
Durability[e]	Hrs.	5000	5000	5000
Thermal efficiency penalty due to emission control devices[f]	(%)	<3	<1	<1

[a] Current production, EPA-compliant engine.
[b] Brake mean effective pressure.
[c] High-volume production: 500,000 units per year.
[d] Constant out-year cost targets reflect the objective of maintaining powertrain (engine, transmission, and emission control system) system cost while increasing complexity.
[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.

Better use of advanced LTC modes to reduce the formation of emissions in-cylinder will reduce aftertreatment system requirements and associated costs.

3.3.1.8 Technical Challenges and Barriers

The technical challenges and barriers to achieving the technical targets are as follows:

B. ***Fundamental knowledge of engine combustion.*** Engine efficiency improvement, engine-out emissions reduction, and minimization of engine technology development risk are inhibited by an inadequate understanding of the fundamentals of fuel injection, fuel-air mixing, thermodynamic combustion losses, and in-cylinder combustion/emission formation processes over a range of combustion temperature regimes of interest, as well as by an inadequate capability to accurately simulate these processes. An insufficient knowledge base will inhibit the development of advanced LTC or mixed-mode combustion systems that operate effectively over the full load range of an engine. These advanced combustion systems offer significant potential for providing engines that operate with CIDI-like engine efficiencies over the full load range while meeting EPA Tier 2 emissions standards with greatly reduced aftertreatment system requirements.

C. ***Emission control.*** Meeting EPA requirements for oxides of nitrogen and particulate matter emissions standards with little or no fuel economy penalty will be a key factor for market entry of advanced combustion engines. NO_x adsorbers appear to be the most viable NO_x reduction devices for light-duty vehicles, but they are very sulfur-sensitive, resulting in an increasingly greater energy penalty over time to compensate for loss of activity. Other technologies under consideration have their own technical barriers as well. Particulate trap technology is costly, and certain regeneration technologies are energy-intensive. The most effective particulate trap technologies cause reductions in engine efficiency through increases in backpressure. While there is more experience with PM emission control devices than with NO_x control devices, PM control technology will likely be pushed to its limits in favor of controlling NO_x emissions, which currently is the more intractable of the two problems.

D. ***Engine controls.*** Effective sensing and control of various parameters will be required to optimize operation of engines in advanced LTC regimes over a full load-speed map similar to that of the CIDI engine. Parameters and operations that need improved controls include 1) ignition timing across the load-speed map, 2) the rate of heat release, and 3) transients and cold starts.

E. ***Durability.*** The emission control system has to perform effectively for 120,000-miles of light-duty vehicle (cars and light trucks) operation.

3.3.1.9 Strategies for Overcoming Barriers/Challenges

Fundamental combustion R&D will focus on developing greater understanding of the combustion and emissions processes and their dependence on fuel spray characteristics, in-cylinder air motion, and fuel selection so that pathways to higher engine efficiencies and lower NO_x and PM from the engine can be identified. R&D tasks will include:

- Identification of advanced combustion system concepts that enable high efficiencies and fuel injection strategies for the implementation of advanced combustion systems;
- Research on combustion systems for advanced fuels;
- Investigation of mechanisms and strategies to reduce thermodynamic combustion losses;
- Investigation of NO_x and PM formation mechanisms in the engine; and
- Identification of potential fuel-derived reductants.

Numerical and chemical kinetics models will be developed to guide the experimental combustion research.

Advanced combustion engine technologies that will be pursued are those that operate in LTC regimes that can provide high, diesel-like efficiencies and have ultra-low engine-out NO_x and particulate levels. Engines to be investigated include engines operating purely on LTC modes such as HCCI; and engines that use conventional

CIDI or spark-ignited (SI) combustion modes for starting and at higher loads, and use LTC modes at moderate to light loads, referred to as mixed-mode operation. In the case of mixed-mode operation with CIDI at high loads, the high-efficiency, high-load capabilities of CIDI are coupled with the high-efficiency, low-emission capabilities of the LTC modes, overcoming the deficiencies in CIDI aftertreatment systems at light loads and the limited high-load capabilities of LTC modes. In the case of mixed-mode operation with SI at high loads, CIDI-like engine efficiencies can be achieved by using LTC at moderate to light loads to eliminate part-load throttling losses and to control emissions, while maintaining the high-load capabilities of conventional port-fuel-injected engines.

Research will also be undertaken to develop a fundamental knowledge base on very lean, low-temperature hydrogen combustion under high-pressure in-cylinder conditions. This will support both the development of advanced hydrogen-fueled engines and the simulation tools used to aid the development of the knowledge base and the optimization of engines. This will require improved understanding of hydrogen injection and fuel-air mixing processes; combustion stability, combustion duration and pre-ignition phenomena; emissions formation; and the effects of engine speed and load, combustion chamber geometry, and in-cylinder air motion (e.g., swirl) on hydrogen combustion and emissions processes.

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. These phenomena are being researched using X-ray and optical diagnostics with the experimental results used to develop spray models. In-cylinder emissions reduction can also be achieved with very careful control of injection timing, duration, and rate shape. Recent developments have shown that the application of multiple injections in a cycle can result in much lower engine-out emissions.

Engine control systems R&D will focus 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 (EGR) to allow advanced combustion engines to operate over a wider range of engine speed/load conditions. In addition, control strategies will be developed to enable the effective transition from low-temperature, low-emission modes of combustion used at lighter loads to conventional CIDI or SI combustion at higher loads (e.g., control strategies for mixed-mode operation).

Complex, precise engine and emission controls will require sophisticated feedback systems employing new types of sensors. NO_x and PM sensors are in the early stages of development and will require additional advances to be cost-effective and reliable.

However, these technologies are essential to control systems for these advanced engine/aftertreatment systems.

Development of technologies enabling LTC will be undertaken to achieve the best combination that enables meeting maximum fuel economy and performance requirements. These include variable compression ratio (VCR), variable valve timing, variable boost, advanced sensors, and exhaust emission control devices (to control hydrocarbon emissions at idle-type conditions) in an integrated system. Variable valve control, independent valve control, and VCR offer the potential for operating with the highest efficiency and for providing ignition timing control through control of in-cylinder temperature or internal EGR. These technologies can reduce engine-out NO_x emissions and thus reduce the need for ancillary systems such as external EGR.

Emission control system R&D tasks will focus on reducing the energy penalty of emission control systems through development of more-effective emission control devices for reducing NO_x and PM in exhaust systems.

Research on improving the effectiveness of NO_x adsorbers for diesel engine exhaust aftertreatment will focus on 1) defining the optimum regeneration schedule with a lean-burn engine, 2) improving NO_x reduction at the lower exhaust temperatures of the duty cycle for light vehicles, and 3) determining long-term degradation mechanisms and susceptibility to sulfur poisoning. As lower engine-out emissions are achieved, continuous lean-NO_x catalysis again becomes a viable alternative. High-throughput combinatorial chemistry will be employed to develop lean-NO_x catalyst materials with higher conversion rates and greater durability. Several common issues—such as sulfur tolerance, reductant optimization, and long-term degradation mechanisms—crosscut among all the NO_x-reducing technologies and will be investigated.

PM-reduction devices face challenges in the areas of long-term degradation and the ability to effectively regenerate despite the relatively cool exhaust temperatures typical of light-duty engines. The focus will be on the refinement of existing technologies and development of novel and innovative PM control technologies. Three different PM-reducing technologies—the catalyzed diesel particulate filter, the continuously regenerating diesel particulate filter, and the microwave-regenerable filter—will continue to be pursued. Research will focus on evaluations of their potential to meet the PM emissions targets, especially in conjunction with NO_x-reducing technologies. To help improve the understanding of PM formation and in-cylinder control, especially during engine transients, new high-energy, laser-based diagnostics with real-time capabilities for measuring and characterizing PM emissions at low concentrations will be used. Other enabling technologies that will be investigated include sulfur traps, sulfur-tolerant catalysts, and low temperature oxidation catalysts for control of HC and CO.

3.3.1.10 Tasks

A description of each task, along with the estimated duration and the associated barriers, is provided in the following table. These tasks support the mid-term goals of the FreedomCAR and Fuels Partnership. They were initiated in January 2002 with the inception of the Partnership and will continue through 2015.

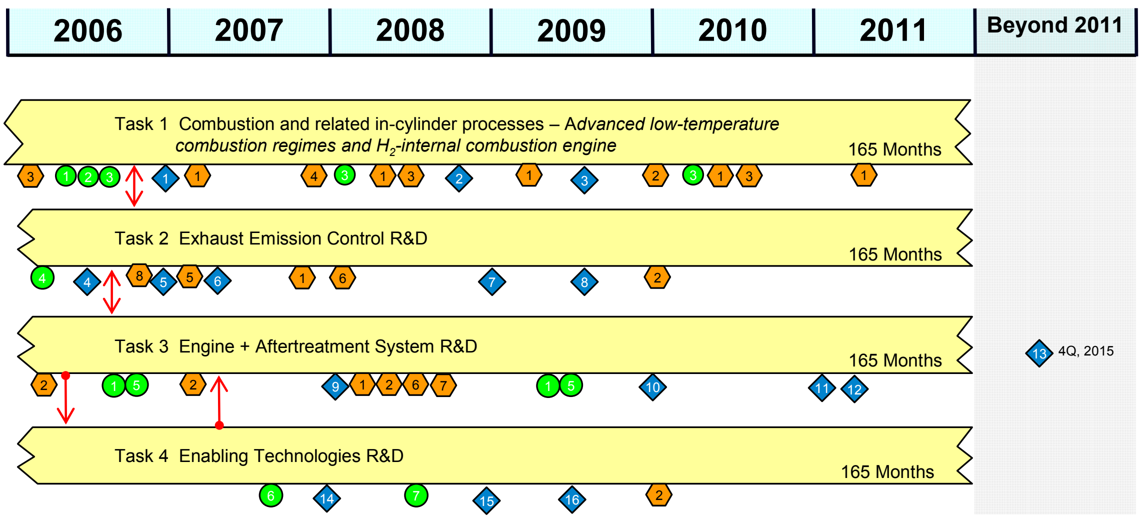
Table 3.3-2. *Tasks for Combustion and Emission Control R&D*

Task	Title	Duration & Barriers
1	***Combustion and related in-cylinder processes - Advanced low-temperature, low emission combustion regimes and H_2-ICE*** • Develop fundamental understanding of low-temperature combustion regimes and their control over a range of engine loads and speeds through experimental and modeling/simulation approaches • Exploit emissions characteristics of LTC regimes and methods of coupling to aftertreatment systems to achieve maximum efficiency • Establish relationships between new combustion regimes and potential efficiency gains and develop paths to efficiency targets • Develop understanding and methods for mixed-mode approaches that must alternate between conventional and new combustion regimes • Develop fundamental understanding of H_2-ICE combustion processes	165 months Barriers A, B, C, E
2	***Exhaust Emission Control R&D*** • Improve the scientific foundation of NO_x adsorber–catalyst performance and degradation mechanisms to mitigate the trend of greater efficiency loss as catalyst ages • Develop strategies for mitigating sulfur effects on aftertreatment, including catalyst tolerance, regeneration methods, and further reduction of sulfur sources (lubricants) • Improve the catalyst materials and systems for lean NO_x catalysis with urea and alternative reductants for performance over wider temperature range. • Improve the simulation capability for exhaust aftertreatment devices to accelerate the design of the most efficient and effective emission control systems • Improve the technologies and strategies for PM filters to achieve reliable regeneration at low exhaust temperatures	165 months Barriers A, C, E
3	***Engine + Aftertreatment System R&D*** • Develop and demonstrate integrated controls and strategies for engine and aftertreatment systems with maximum fuel economy at the necessary emissions levels	165 months Barriers A, B, C, D, E
4	***Enabling Technologies R&D*** • Develop and validate NO_x and PM sensors for engine and aftertreatment control and diagnostics • Develop advanced engine control methods and strategies for operation over a range of loads and speeds	165 months Barriers A, C, D, E

3.3.1.11 Milestones and Decision Points

Combustion and Emission Control R&D activity milestones and decision points are provided in the following chart:

Combustion and Emission Control R&D Network Chart



Legend

Milestone

1. Complete assessment of two-stage ignition fuels for extending to high-load LTC
2. Complete characterization of engine-out HC, CO, PM, and NOx emissions from LTC engine
3. Complete development and construction of 30kW prototype hydrogen free-piston engine
4. Complete evaluation of catalyst materials using combinatorial chemistry
5. Validate NO_x and PM control device efficiencies (sufficient to limit NO_x to 0.07 g/mile and PM to 0.01 g/mile, respectively) using 15-ppm sulfur-content fuel with durability to projected full-useful-life requirements
6. Complete microwave regeneration of PM filter
7. Complete protocols for emission control simulation tools
8. Complete demonstration of emission control strategy compatible with LTC
9. Validate 42% thermal efficiency with <2% fuel efficiency penalty for meeting standards with emission control devices using a fuel formulation recommended by the Fuels Technology sub-program

Milestone

10. Validate 44% thermal efficiency with <1% fuel efficiency penalty for meeting standards with emission control devices using a fuel formulation recommended by the Fuels Technology sub-program
11. Validate 45% peak thermal efficiency H2-IC engine
12. Validate 45% thermal efficiency with <1% fuel efficiency penalty for meeting standards with emission control devices using a fuel formulation recommended by the Fuels Technology sub-program
13. Validate 45% peak thermal efficiency H2-IC engine at $30/kW
14. Evaluate sensors to control HCCI combustion
15. Validate efficiency improvement with variable valve timing
16. Validate at least 5% fuel economy improvement with variable compression ratio

Technology Program Output

1. Transfer of technical data/information to industry
2. Technical results to Heavy Truck Engine R&D
3. Fuel Property requirements for HCCI, to Fuels Technology R&D
4. Technical results on H_2-ICE to Hydrogen, Fuel Cells, and Infrastructure Technologies Program
5. Rapid aging protocol for NO_x adsorber system, to Fuels Technology R&D
6. Technical results and feedback to Fuels Technology
7. Technical results to Vehicle Systems R&D
8. Engine/emission control system model that predicts fuel effects on the system (to Fuels for Advanced Combustion Engines)

Supporting Input

1. Fuel formulation that enables emission control system to meet useful life requirements, from Fuels Technologies R&D
2. Input from Hydrogen, Fuel Cells, and Infrastructure Technologies Program
3. Fuels composition that meets requirements of HCCI, from Fuels Technology R&D
4. Technical data on sulfur trap, from Fuels Technology
5. Fuel-derived reductant for emission control use, from Fuels Technology
6. Validated small orifice fuel injector from Heavy Vehicle Propulsion Materials
7. Validated emission control devices (sensors, PM filter), from Automotive Propulsion Materials

Figure 3.3-1. Network Chart for Combustion and Emission Control R&D

3.3.2 Heavy Truck Engine R&D

Heavy Truck Engine R&D is focused on increasing heavy-duty diesel engine efficiency significantly above current levels, as well as addressing efficiency penalties resulting from technologies required to meet increasingly stringent emissions standards. The engine efficiency losses would result in higher operating costs to truck owners and operators and, ultimately, higher costs to consumers. On a national scale, increased heavy truck fuel efficiency would result in reduced petroleum demand.

3.3.2.1 External Assessment and Market Overview

The truck industry and government partners in the 21st CTP have developed a common vision–"that our Nation's trucks and buses will safely and cost-effectively move larger volumes of freight and greater numbers of passengers while emitting little or no pollution and dramatically reducing the dependency on foreign oil."[b] Ultimately, the partnership seeks safe, secure, and environmentally friendly trucks and buses that use sustainable and self-sufficient energy sources, thereby helping enhance America's global competitiveness. Primarily due to the requirements of long-haul commercial vehicles for long driving range and cargo carrying capacity, the heavy-duty diesel engine is seen as the only viable option to power trucks of the 21st Century. R&D is needed to continue to improve the heavy-duty diesel engine system efficiency while meeting applicable EPA emissions standards.

3.3.2.2 Internal Assessment and Activity History

The Heavy Truck Engine activity supports the development of technologies needed to significantly improve the efficiency of heavy-duty diesel engines beyond present levels while meeting the 2007/2010 heavy-duty engine emissions standards. This activity was initiated in FY 1999 to address the energy efficiency impact of the anticipated more stringent 2007 and 2010 EPA heavy-duty diesel engine emissions standards. An efficiency penalty of as much as 10 percent in heavy-duty diesel engines was anticipated with the use of emission control technologies available at that time. Also, the high sulfur content of available diesel fuel has deleterious effects on the performance of emission control devices.

In December 2000, EPA enacted the 2007 Heavy-Duty Diesel Engine Emissions Standards. EPA also issued a rule in January 2001 requiring that 80 percent of all on-road diesel fuel have less than 15 ppm sulfur, starting in 2006. This rule is in conjunction with the phase-in of emissions standards in the 2007–2010 timeframe. The rule on sulfur content of diesel fuel is expected to greatly benefit the performance and durability of emission control technologies under development.

3.3.2.3 Federal Role

Freight transport provided by heavy trucks has continued to increase with the expansion in economic activity and has resulted in a significant contribution to the increase in U.S. highway transportation energy use. Heavy truck engine technologies

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[b] Secretary Spencer Abraham, Unveiling of the 21st Century Truck Partnership, Dearborn, Michigan, November 12, 2002.

R&D undertaken to meet this growing energy demand more efficiently while meeting future emissions standards is an appropriate Federal role because heavy trucks are critical to economic growth due to their extensive use in trade and commerce and in providing essential services. Targeted investment in technology research and development in strategic partnerships with commercial heavy-duty engine and vehicle manufacturers and national laboratories will produce leveraged benefits for the American taxpayer.

3.3.2.4 Approach

An integrated systems approach involving advancements in engine design, fuels, and aftertreatment technologies is required to simultaneously address fuel efficiency and emissions. R&D in combustion, materials, fuels, and aftertreatment devices provides the foundation for technology advancement, including simulations (virtual labs) in concert with controls development and experimentation.

3.3.2.5 Performance Goals

The long-term (2013) goal of this activity is to develop the technologies that will increase the thermal efficiency of heavy-duty diesel engines to at least 55 percent while reducing emissions to near-zero levels. More specifically,

- By 2006, increase the thermal efficiency of heavy-duty engines to 50 percent while meeting EPA 2010 emission standards.
- By 2013, increase the thermal efficiency of heavy truck engines to 55 percent while meeting prevailing EPA emissions standards.

The technical targets for Heavy Truck Engine R&D are provided below:

Table 3.3-3. *Technical Targets for Heavy Truck Diesel Engine R&D*

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

[a] Using 15-ppm sulfur diesel fuel

3.3.2.6 Strategic Goals

The Heavy Truck Engine R&D activity supports the Department's Energy Security Strategic goal to "improve energy security by … exploring advanced technologies that make a fundamental improvement in our mix of energy options, and improving energy efficiency" – and also the 21st Century Truck Partnership goal to develop and validate a commercially viable, 50 percent efficient, emissions-compliant engine system for Class 7 and 8 highway trucks by 2010.

3.3.2.7 Market Challenges and Barriers

The market challenge is as follows:

A. ***Cost.*** The emission control devices required by engines to meet emission targets add costs to the heavy truck engine system. Increased cost is a critical consideration to truck operators who need to be fully competitive in the prevailing markets.

3.3.2.8 Technical Challenges and Barriers

The technical challenges and barriers to achieving dramatically improved efficiency and near-zero emissions in heavy truck engines are as follows:

B. ***Efficiency.*** There are several barriers to improving engine efficiency. In-cylinder NO_x reduction methods in conventional diesels, using traditional combustion modes, limits efficiency by limiting peak in-cylinder temperatures and the time spent at peak temperatures. Aftertreatment systems have energy penalties that reduce the overall engine/aftertreatment system efficiency. Current commercially viable materials and lubricants limit engine efficiency by limiting peak cylinder temperatures and pressures at which critical engine components can operate.

C. ***Emissions.*** The key barriers to achieving the emissions reduction targets for heavy truck diesel engines include (1) maintaining efficiency and low NO_x while keeping PM down; (2) incomplete development of aftertreatment technology, especially for NO_X; and (3) immature simulation and control systems integration capabilities, as well as a lack of static and dynamic optimization of multiple emission reduction systems. Common to each barrier is a lack of adequate simulation capabilities and 'ready to implement' sensing and process control systems. Improved simulation capabilities are needed to optimize both the combustion and aftertreatment systems so as to transform a "statically" integrated system into an optimized overall engine/aftertreatment package that results in maximum efficiency and performance and minimum emissions. In turn, a mature and robust sensing and control system will monitor and navigate these multiple systems over the complex "dynamics" of normal over-the-road vehicle operation, while yielding the best vehicle fuel economy, performance, and emissions.

D. Durability. The barrier to achieving 435,000-mile durability for heavy-duty engines and their emission control systems is the premature degradation of the emission control devices due to operation under high-temperature and high-flow-rate conditions.

3.3.2.9 Strategies for Overcoming Barriers/Challenges

Improving Engine Efficiency. R&D to improve the understanding of energy losses in engine operation such as the combustion process, mechanical friction, heat transfer, air handling, and exhaust losses. All are important in improving engine efficiency. Major elements of the technical approach include the following:

- Define baseline engine designs in sufficient detail to delineate the areas of required technology advancement. This will be a guide for enabling technology tasks. Conduct, on a continuing basis, analysis and supporting validation tests to assess progress toward goals.

- Optimize the mechanical design and combustion system for increased expansion ratio and thermodynamic efficiency.
- Develop and integrate cost-effective exhaust-heat-recovery technologies into the engine system.
- Improve the fundamental understanding of diesel combustion and emissions formation processes and exhaust aftertreatment systems, and the predictive simulation capabilities for these processes and systems needed to more effectively optimize performance.
- Develop and exploit advanced fuel injection and engine control strategies and new LTC regimes for their potential efficiency gains. Use modeling and simulation as an integral component of the system design strategy.
- Improve turbocharger and/or air handling systems and controls, and trade-offs between turbocharger efficiency and transient response. Develop new low-inertia materials and response-enhancing technologies.
- Continue the refinement of piston/cylinder designs, valve trains, and other mechanical components for reduced friction losses.
- Develop accurate, robust sensors for control systems.

Close coordination between the Heavy Truck Engine R&D and the Heavy Vehicle Propulsion Materials R&D, discussed in the Materials Technology, Section 3.4, ensures that materials issues important to engines are addressed.

Reducing Emissions. Simultaneous attainment of thermal efficiency targets and future emission standards requires unprecedented attention to the effective integration of multiple, new system technologies. At the historical and most fundamental level, systems optimization and component performance has been and continues to be accelerated through the application of computer simulations. The emphasis is on high-order "off-line" calculations that are crucial to understanding and defining the basic engine configuration and its performance and emission signature. Simulation and control techniques are active companions in the diesel engine development and operational process. A high-priority need is the advancement of computational simulation capabilities for all systems, especially for aftertreatment systems, which are currently in an immature state of development. Major elements of the technical approach to meet emissions targets also include:

- Further develop flexible fuel-injection systems and engine control strategies and new combustion regimes for their emissions reduction potential, integrating modeling and simulation with engine controls development.
- Optimize cooled exhaust gas recirculation (EGR) for maximum NO_x reduction and minimum PM emission, mitigating durability concerns with EGR through materials engineering and operational controls.
- Improve the fundamental understanding of diesel combustion/emissions formation processes and exhaust aftertreatment systems, and the predictive

simulation capabilities for these processes and systems needed to minimize emissions.

- Develop strategies for mitigating the effects of sulfur on aftertreatment, including catalyst tolerance, regeneration, and further reduction of sulfur sources (lubricants).
- Improve the scientific foundation of NO_x adsorber-catalyst performance and degradation mechanisms. Improve the catalyst materials and systems for lean NO_x catalysis using reductants, so that performance can be maintained over a wider temperature range.
- Improve methods for generating and introducing NO_x reductants to catalysts.
- Develop and apply sensors in controls and diagnostics of engine and emission control processes.
- In the development of emission control devices, include features necessary to make the devices suitable for retrofit on existing trucks.

Fuel properties, particularly sulfur content, are pivotal to the success of NO_x adsorber catalyst technology. Work involving fuels is coordinated with the Fuels for Advanced Combustion Engines activity as discussed in Section 3.3.3.

3.3.2.10 Tasks

A description of each technical task, along with the estimated duration and technical barriers associated with the task, is provided in the following table. Tasks 2, 3, and 4 began with the reinstitution of 21st CTP in November 2002 and will continue through 2013.

Table 3.3-4. *Tasks for Heavy Truck Engine R&D*

Task	Title	Duration & Barriers
1	***Integrated enabling combustion and emission control technologies***	131 months Barriers B, C, D
2	***Research on advanced combustion regimes and enabling technologies (sensors and controls) to increase efficiency for heavy-duty vehicle application:*** • Exhaust heat utilization • Mitigating thermodynamic combustion losses • Reduced parasitic losses • Reduced air handling losses • Improved thermal management sensors • Sulfur traps • Catalyst and filter fundamentals	120 months Barriers B, C, D

3.3.2.11 Milestones and Decision Points

The Heavy Truck Engine R&D activity milestones and decision points are provided in the following chart:

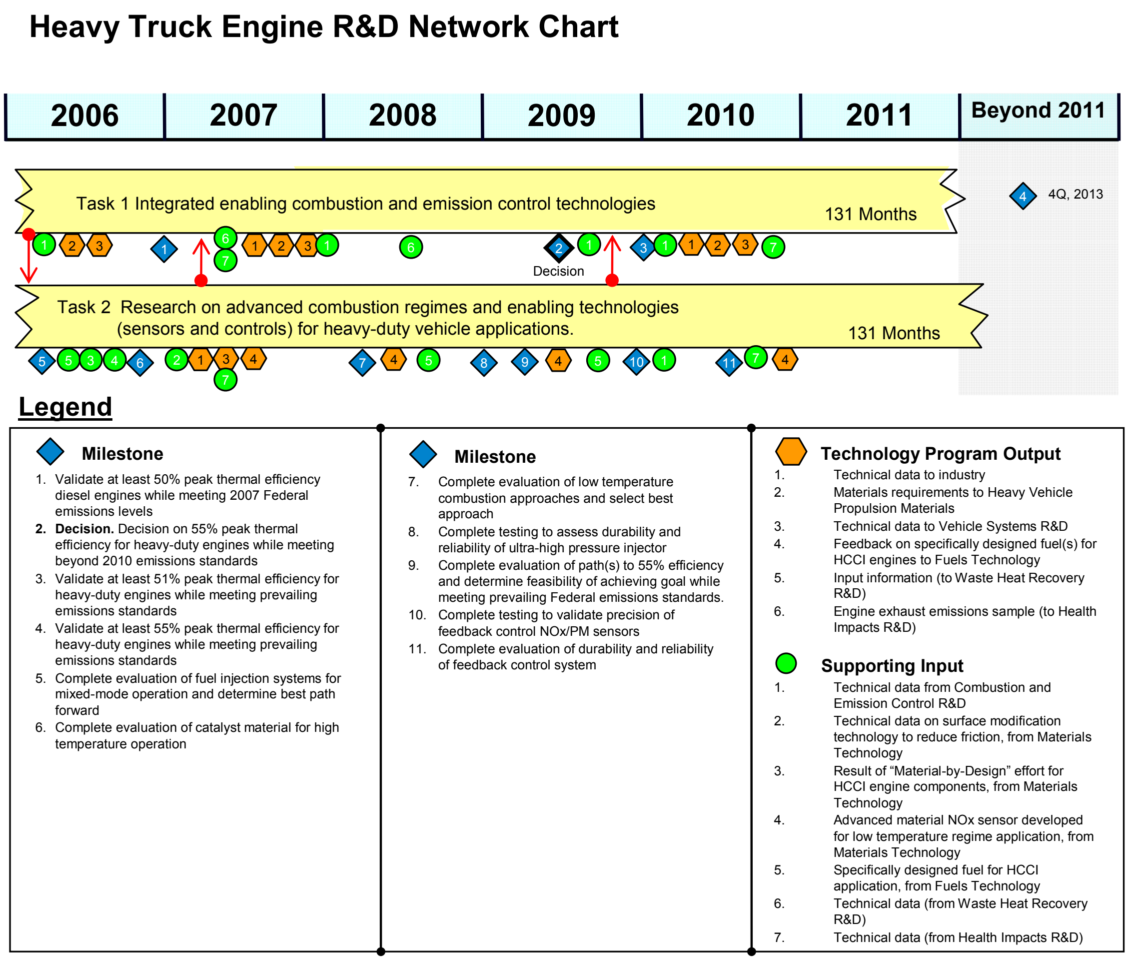


Figure 3.3-2. Network Chart for Heavy Truck Engine R&D

3.3.3 Fuels for Advanced Combustion Engines

The Fuels for Advanced Combustion Engines activity is undertaken 1) to enable current and emerging advanced combustion engines and emission control systems to be as efficient as possible while meeting future emission standards and 2) to reduce reliance on petroleum-based fuels. This activity will enable advanced combustion regime engine technology as well as identify practical, economic fuels and fuel-blending components with the potential to directly displace significant amounts of petroleum. These fuels and fuel-components are anticipated to be derived from non-fossil renewable resources such as biomass, vegetable oils, and waste animal fats, as well as from fossil sources other than light, sweet crude oil (e.g., natural gas, heavy crude, oil sands, oil shale, and coal). The production of diesel fuel from these sources is technically feasible, yet none is in significant use in the United States because of lack of adequate data on fuel properties, their quality, and/or cost. The Fuels Technology subprogram activities focus on the properties and quality of the finished fuels derived from these sources, not primarily on their production. Fuel production and processing issues are considered in coordination with the appropriate DOE entities through the Fuels Crosscut Team.

3.3.3.1 External Assessment and Market Overview

World crude oil is becoming heavier (lower API gravity) and more sour (including greater amounts of sulfur) over time. This trend is well-established and not expected to change. Moreover, much domestic crude is heavy (e.g., California crude from the San Joaquin Valley) and many potential future sources of energy are heavier still (e.g., bituminous coal, oil sands). In addition to presenting different refining issues than light crude, the fuels produced from such feedstocks may differ from those for which the U.S. domestic refining industry is optimized.

Venezuelan and domestic heavy crude use in U.S. refineries is well-established. Refining of synthetic crude derived from oil sands is growing in use in Canada, and expansion into U.S. petroleum pools is beginning. Fischer-Tropsch diesel fuels, synthesized from natural gas or coal, have been studied in numerous engine tests to determine their impact on emissions and have been used as a blending material in California diesel fuels since 1993. Use of similar fuels derived from biomass – Biomass-to-Liquid (BTL) fuels – may increase in the future. Biodiesel (fatty acid methyl esters), produced from vegetable oils and waste fats, has been used extensively as a blending component in Europe and its use in the United States is increasing. The Fuels Technology subprogram will track and exploit some of these developments for applicability to the United States as a significant potential source of displacement of foreign petroleum.

Desirable attributes for advanced combustion engine fuels include compatibility with all aspects of the existing fueling infrastructure, and thus the capability to be used as replacements for current fuels and a general lack of undesirable components, such as sulfur and aromatics. Fuels with these characteristics are intended to enable the implementation of advanced-combustion-regime technologies. In addition, these fuels will enable more-effective, more-durable, yet less-expensive emission control systems that require less energy for operation and therefore reduce the negative impact of those devices on vehicle efficiency.

3.3.3.2 Internal Assessment and Activity History

Advanced fuels are critical for enabling diesel engines – currently the highest-efficiency engines available – to meet future emission standards. Future diesel-powered vehicles will be dependent on exhaust emission control devices to control NO_x and particulate emissions. Even the most attractive NO_x emission control devices are deactivated by sulfur in currently-available fuels. An important objective of the Fuels Technology subprogram has been the determination of the diesel fuel sulfur level that can be tolerated by effective and durable NO_x emission control devices.

Testing and analysis conducted by the Fuels Technology subprogram in collaboration with EPA, the engine manufacturers, emission control device manufacturers, and fuel producers conclusively demonstrated that fuel sulfur content had immediate adverse effects on the effectiveness of fresh emission control devices. This information was used by EPA in issuing a final rule on January 18, 2001 that established a single comprehensive national control program to regulate both heavy-duty vehicle emissions and diesel fuel. The diesel sulfur rule limits the amount of sulfur in on-highway diesel fuel to 15 ppm, beginning in 2006. This is in preparation for the implementation of the EPA 2007-2010 heavy-duty diesel engine emissions standards. These emission standards are the first for heavy-duty diesel engines that are expected to require exhaust emission control devices.

In 2001, the Clean Diesel Independent Review Panel was created to conduct a review of the 2007 heavy-duty diesel engine emissions standards and the diesel fuel sulfur content standard and provide "advice to the EPA on technology issues associated with the introduction of technology to reduce engine exhaust emissions and technology to lower the sulfur level of highway diesel fuel in accordance with the dates incorporated in the highway diesel program promulgated in 2001." The panel was composed of leading experts from the public health community, petroleum refiners, fuel distributors and marketers, engine manufacturers, emission control systems manufacturers, and state governments. The specific objectives of the panel's charter were to: 1) assess the progress of manufacturers of diesel engines and emission control systems in developing technology to reduce engine exhaust pollutants; and 2) assess the progress of the fuels industry in developing and demonstrating technologies to cost-effectively lower the sulfur level of highway diesel fuel. In its final report, the panel found that NO_x adsorbers and catalyzed particulate filter systems are the two leading emission control technologies for diesel engines. The panel also identified improving the durability of the NO_x adsorber, especially as it relates to desulfation (removing accumulated sulfur), as the most significant fundamental challenge that is being addressed currently.

The panel's findings directly support the research priorities of the Fuels activity. Although EPA has set a sulfur limit of 15 ppm, it is still unclear whether this is an adequately low sulfur level for advanced diesel engines with advanced emission control systems. The durability of these systems at this level of fuel sulfur has not been established. Also, with these emission control devices, the optimum fuel formulation for advanced diesel engines has yet to be defined. The current base of knowledge suggests that NO_x-adsorbers may not be sufficiently durable and/or energy efficient when exposed to fuel containing 15 ppm sulfur allowed under the 2006 standard. The Fuels activity is funding work to expand technological, non-regulatory approaches to solving any remaining sulfur and fuel-contaminant problems. Blends of petroleum-based fuels and non-petroleum fuels can be effective in reducing sulfur content and, in some cases, improving performance. In previous work, Fischer-Tropsch distillate has shown potential for synergistic emission reductions when paired with existing emission control devices. There is some evidence that biodiesel may also exhibit synergistic effects.

3.3.3.3 Federal Role

At present, little detailed information is available on the chemistry of fuels. While such investigations are inherently complex, DOE's national laboratories have the expertise and facilities to begin an investigation into what physical and chemical properties are of most significance to advanced combustion regime engines. Such investigations are typically beyond the scope of business interest of the energy industry. Even if such information is sought by the energy industry, in most cases the companies do not have the specialized capabilities equivalent to those available at the national laboratories. Also, information obtained by private industry is generally not available to the public. Activities of the Fuels Technology subprogram, therefore, play an important role in the pre-competitive arena addressing these issues in partnership with the energy, engine and automotive industries.

3.3.3.4 Approach

A major focus of the Fuels Technology activities is to determine the impacts of fuel properties on the efficiency, performance, and emissions of advanced combustion engines. In the near term, these are expected for the most part to be direct-injection diesel engines and their associated emission control systems. There exists little understanding of the compatibility of the engine-emission control system with renewable fuels such as biodiesel or BTL. Additional information is also required on performance and durability with fuels derived from heavy-crude, oil sands, oil shale, and coal.

For the long term, focus is on fuels optimized for advanced combustion regimes, which include a variety of technologies that have the potential to provide diesel-like (or greater) efficiency with extremely low engine-out emissions. HCCI and LTC are examples of such combustion regimes. Work is not expected to remain confined to the parameter space of pure HCCI or, indeed, even to the general area of low-temperature combustion in investigating the limits of advanced combustion engine efficiency. Consideration will be given to the potential of fuel-related factors for fostering or hindering the expansion of operating conditions of HCCI and related technologies. Work will be constrained to pre-competitive areas with potential for commercial viability.

While anecdotal evidence points to variations in performance and emissions in near-term (e.g., prototype model year 2007) engines related to fuel-property variations, it is almost certain that future, advanced combustion engine technologies will show a greater sensitivity to such variations. As such, co-development of fuels and engines will be essential to ensure availability of fuels optimized for operation in advanced combustion regime engines in the post-2010 timeframe; this necessitates a much-improved state of fundamental knowledge about fuel properties and composition and their impact on combustion phenomena. If fuel specifications need tighter definition for engine operation in advanced combustion regimes, close coordination between the Advanced Combustion Engine R&D and Fuels Technology subprograms will be essential.

The expertise of the national laboratories is used for in-house research and development efforts, in "working group"–level interactions in government-industry consortia, and in technical management. In the near term, fuel issues associated with 2007–2010 engines and emission control systems are of immediate concern. Included in this near-term focus are tasks that support removing sulfur from the fuel at fueling stations or on-board the vehicle prior to combustion in order to provide a near-zero sulfur level, if necessary. An additional focus is on assessing the impact of renewable and non-petroleum blending components such as biodiesel and BTL, along with an examination of the impacts of use of fuels derived from heavy-crude. For the long term, the challenge is development of a fuel specification optimized for operation of advanced combustion regime engines up to full load and during transients. Other challenges include assessing the implications of the properties of newly developed fuels on engine performance and emissions, and identifying compatible lubricants for use with newly developed fuels.

3.3.3.5 Performance Goals

The primary goal of the Fuels Technology subprogram is to identify fuel formulations with increasingly significant use of non-petroleum fuel components that will enable emerging advanced ICEs to be more energy-efficient while meeting future emissions standards. More specific goals are as follows:

- By 2007, identify fuel formulations optimized for use in 2007-2010 technology diesel engines that incorporate use of non-petroleum-based blending components with the potential to achieve at least a 5 percent replacement of petroleum fuels by 2015.
- By 2010, identify fuel formulations optimized for use in 2010-2020 advanced combustion regime engines providing high efficiency and very low emissions, which incorporate use of non-petroleum-based blending components with the potential to achieve at least a 10 percent replacement of petroleum fuels by 2025.

Fuels, engines, and emission control devices are being addressed, in collaboration with the Advanced Combustion Engine R&D subprogram, in the context of complete, integrated engine power systems. The following table lists the fuels-specific technical targets that support crosscut targets with the Advanced Combustion Engine R&D subprogram (shown in italics), as well as direct petroleum fuel replacement targets.

Table 3.3-5. *Technical Targets for Advanced Combustion Engine Fuels*

Characteristic	Unit	2007 Targets	2010 Targets
Crosscut Targets with Advanced Combustion Engine R&D			
Engine efficiency	*%*	*>50 (heavy-duty engine)*	*30–45 (light-duty engine)*
NO_x emissions	*g/bhp-h*	*<0.20 (50% phase-in)*	*<0.20*
PM emissions	*g/bhp-hr*	*<0.01*	*<0.01*
Durability	*Miles (equivalent)*	*120,000 light duty) 435,000 (heavy duty)*	*120,000 (light duty) 435,000 (heavy duty)*
Fuels Targets			
Fuel sulfur level (available fuel)	Ppm	15	15
Fuel sulfur level (w/on-board or fuel-station based removal)	Ppm	<5	<3
Emission control penalty reduction	%	50	>50
Fuel price differential	% of retail diesel	<5	<5
Potential for replacement of petroleum	%	At least 5	>5
Compatibility with infrastructure	NA	Validated	Validated
Health effects Unregulated toxics and ultra-fine PM Health and safety of fuel	(by analysis)	No significant increase in composite risk compared with conventional fuels	No significant increase in composite risk compared with conventional fuels
Life-cycle greenhouse and criteria emissions	(by analysis)	No increase	

3.3.3.6 Strategic Goals

The Fuels Technology subprogram supports DOE's Energy Security Strategic goal to "improve energy security by … exploring advanced technologies that make a fundamental improvement in our mix of energy options, and improving energy efficiency" – and also the goal of 21st CTP to develop and validate a commercially viable, 50 percent efficient, emissions-compliant engine system for Class 7 and 8 highway trucks by 2010.

3.3.3.7 Market Challenges and Barriers

The market challenges and barriers are as follows:

A. ***Infrastructure.*** The lack of a fuel quality specifications, as well as distribution and fueling infrastructure, is a major barrier for any non-petroleum-based liquid fuel component that is not compatible with all current systems. This barrier must be addressed to have a significant impact on reducing the transportation sector's dependence on petroleum-based fuels.

B. ***Cost.*** There are insufficient public data on refinery economics and processing strategies to enable comparison of options for advanced combustion engine fuels. Also inadequate are the databases on the health, safety, and regulatory issues associated with most non-petroleum fuel components that might be used to replace petroleum-based fuels, as well as the knowledge base on the technical and economic impacts of non-petroleum fuel components on the distribution, storage, and fueling infrastructure.

3.3.3.8 Technical Challenges and Barriers

In order to fully exploit the full potential of high-efficiency, clean advanced combustion regime engines, co-development of the engines and fuels is a necessity. Nearer term, the understanding of the compatibility of non-petroleum based fuels with 2007-2010 engines is critical to increasing use of these fuels. The technical barriers to achieving this are as follows:

C. ***Inadequate data and predictive tools for fuel property effects on combustion and engine optimization.*** Existing data and models for engine efficiency, emissions, and performance based on fuel properties and fuel-enabled engine designs or operating strategies are inadequate. They are limited in scope, have unexplained differences among various engine types, and do not adequately account for the effects that the physical properties and molecular structures of fuels have on the dynamic operation of the fuel injection system and on the ability to operate in low-emission, low-temperature combustion regimes. Also, the variability of refinery stream (blendstock) composition on the efficiency, performance, and emissions of engines appears to be significant but is poorly understood.

D. ***Inadequate data and predictive tools for fuel effects on emissions and emission control system impacts.*** The database on the extent to which petroleum fuel and non-petroleum fuel components contribute to toxic emissions is inadequate and must be improved in order to optimize engine and aftertreatment systems from a fuel economy standpoint. The relationship between fuel properties and the formation of ultra-fine particles (i.e., particles of <0.1 nm in diameter) is not well established. Also inadequate are data on the effects of fuel properties (other than sulfur) on exhaust emission control systems, and widely-accepted test procedures to measure these effects do not exist. Furthermore, suitable test equipment and universally-recognized test procedures to generate this knowledge base are not available.

E. ***Long-term impact of fuel and lubricants on engines and emission control systems.*** The knowledge base is inadequate on the effect of fuel properties on the deterioration rates and durability of engine fuel system and emission control system devices and components. The effects of lubricating oil on engine emissions and emission control devices are not clearly understood, nor are the effects of non-petroleum based fuels on lubricating oil performance. Improved understanding is needed in developing approaches that mitigate any deleterious effects caused by fuel and lube oil components. Furthermore, new fuel formulations could require corresponding new lube oil formulations.

3.3.3.9 Strategies for Overcoming Barriers/Challenges

Activities of the Fuels Technology subprogram will test and evaluate a wide variety of fuels to develop a better understanding of the relationships between fuel properties, engine efficiency, system durability, and emissions. Exhaust emission control devices are expected to be necessary to meet future emissions standards for diesel-powered vehicles. Fuels-compatibility testing will include such devices as they become available (through close collaboration with the Advanced Combustion Engine R&D subprogram).

Key deliverables from these activities will be test data and test-data–based analyses of the sensitivity of the performance and emissions of engines and emission control devices to fuel and lubricant properties. As data accumulate in the database, it will become increasingly feasible to predict fuel formulations with favorable properties to reduce emissions of NO_x and PM. In addition, some emission control strategies rely on reductants derived from the fuel to operate effectively, a fact that will be taken into account as required reductant properties are identified by the Advanced Combustion Engine R&D subprogram.

Guidance on the fuels to be tested and other tasks will be provided by representatives from the automotive, energy, and engine companies; renewable and non-petroleum based fuel manufacturers; industry associations; and national laboratories. Government/industry technical and supporting groups will make specific recommendations for tasks, data analyses, and overall direction.

Through the use of roundtable discussions, government-industry workshops, peer reviews, participation in the Coordinating Research Council (CRC), and through other forums, this activity has obtained what is believed to be a good understanding of the inadequacies of predictive tools and fuel property data necessary to identify fuel property requirements for fuels for advanced combustion engines.

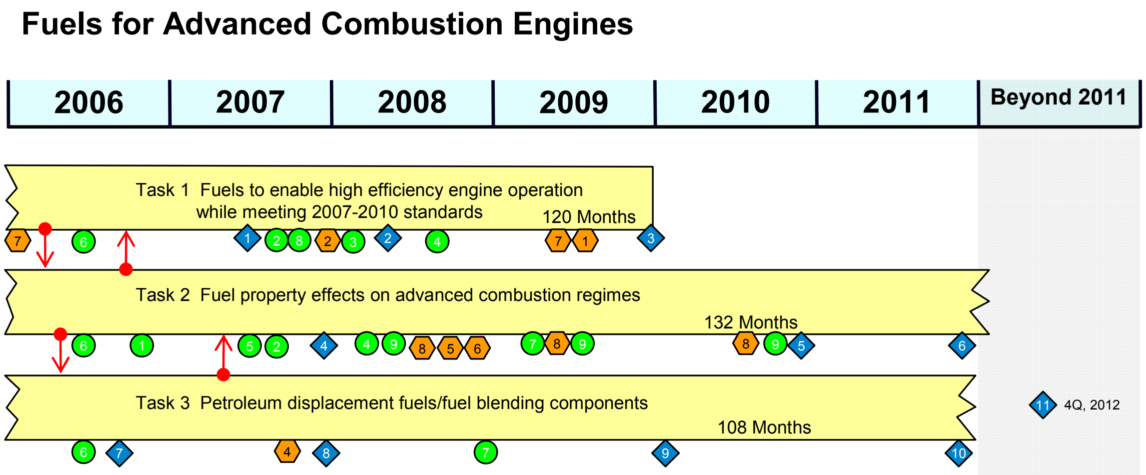
3.3.3.10 Tasks

The technical task descriptions are provided in the following table:

Table 3.3-6. R&D Tasks for Fuels for Advanced Combustion Engines		
Task	**Title**	**Duration / Barriers**
1	***Fuels and Lubricants to Enable High Efficiency Engine Operation while Meeting 2007–2010 Standards*** • Evaluate long-term degradation and loss of effectiveness of light- and heavy-duty engines equipped with 2007–2010 technology emission control devices and using 15-ppm-sulfur diesel fuel and renewable blending components such as biodiesel • Improve fundamental understanding of the effect of fuel and lubricant composition on aftertreatment systems by applying experimental and modeling approaches • Investigate options for optimizing engine and emission control systems for both emissions and performance when switching between conventional fuel and non-petroleum based fuels • Identify fuel properties other than sulfur that are critical to improving the efficiency, performance, and emissions of diesel engine and aftertreatment systems • Develop measurement techniques and characterize unregulated emissions from 2007–2010 engines and aftertreatment systems • Study fuels-based in-cylinder strategies to achieve high-efficiency, low-emissions operation at high power density and to improve understanding of hydrocarbon molecular structure effects on the sooting tendency of diesel fuel constituents	120 months Barriers A, B, C, D, E
2	***Fuel Properties Effects on Advanced Combustion Regimes*** • Develop fundamental understanding of fuel effects on in-cylinder combustion and emissions formation processes in advanced combustion regimes through experimental and modeling approaches • Develop predictive tools that relate molecular structure to ignition behavior and heat release for fuels used in advanced combustion engines • Evaluate new fuels and fuel blends for efficiency, emissions, and operating stability with advanced combustion regimes • Evaluate the potential of reforming small amounts of fuel to generate additives that can be used to achieve fast control in low-temperature combustion modes • Evaluate the performance of traditional lubricant formulations in engines using advanced combustion regimes and identify any performance deficiencies	132 months Barriers B, C, D, E
3	***Petroleum Displacement Fuels/Fuel Blending Components*** • Study combustion and emissions-formation processes of non-petroleum based fuels and blending components using experimental and modeling approaches • Identify renewable and synthetic fuel blending components that provide enhanced efficiency, performance, and emissions characteristics • Quantify the potential for improving engine and/or vehicle fuel economy through the use of renewable biolubricants • Enhance the use of petroleum displacement fuels and non-petroleum based fuels infrastructure development through technical forums and by providing specialized technical support to early adopters of these advanced non-petroleum based fuels • Perform R&D to support appropriate codes and standards to increase the availability of petroleum displacement fuels	108 months Barriers A, C, D, E

3.3.3.11 Milestones and Decision Points

The milestones and decision points for Fuels for Advanced Combustion Engines are provided in the following chart:



Legend

Milestone

1. Complete determination of maximum tolerable level of sulfur and other contaminants in fuels and lubricants for emission control systems to meet full useful life with reduced emission control fuel penalty
2. Complete identification of fuel formulation that provides >50% reduction in energy penalty due to meeting 2007 –2010 emission requirements (using 7% penalty as baseline)
3. Validate that fuel formulation use in advanced combustion regime engine results in reducing emissions energy penalty by 50% and meets useful life requirement.
4. Complete identification of fuel and lubricant characteristics that are critical to engine operation in advanced combustion regimes
5. Complete identification of fuel and lubricant formulation for advanced combustion regime engines needed to achieve >50% efficiency, emissions compliance, and power density >20 bar bmep
6. Validate that advanced fuel formulation can enable > 50% engine efficiency with full in-cylinder emissions reduction and eliminates the need for exhaust gas aftertreatment
7. Complete evaluation of adequacy of existing codes and standards to fuels with non-petroleum and synthetic blending components
8. Complete optimization of fuel formulation for 2007 – 2010 engines to incorporate use of non-petroleum based blending components with the potential to achieve at least 5% replacement of petroleum fuels by 2015

Milestone

9. Complete R&D to eliminate technical barriers to achieving a 5% petroleum displacement in 2007 – 2010 engines
10. Complete identification of fuel formulations optimized for use in advanced combustion engines (2010-2020) that provide high efficiency and very low emissions
11. Validate that at least 10% replacement of petroleum fuels can be achieved by 2025

Technology Program Output

1. Fuel formulation that allows emission control system to meet useful life requirements, to Combustion and Emission Control R&D
2. Fuel formulation for materials compatibility evaluation, to Materials Technologies/Heavy Vehicle Propulsion Materials
3. Fuel-derived reductant for emission control use, to Combustion and Emission Control R&D
4. Fuels composition that meets requirements of HCCI, to Combustion and Emission Control R&D
5. Fuel formulation for full scale vehicle system testing, to Vehicle Systems R&D
6. Fuels formulation for health impacts testing to Health Impacts Research
7. Technical data on sulfur trap, to Combustion and Emissions Control R&D
8. Specifically designed fuel for HCCI application, to Heavy Truck Engine R&D

Supporting Input

1. Engine/emission control system model that predicts fuel effects on the system, from Combustion and Emission Control
2. Fuel formulation constraints for APUs, from Vehicle Systems R&D
3. Rapid aging protocol from Combustion and Emission Control R&D
4. Technical data on materials compatibility of fuel formulations, from Materials Technologies/ Heavy Vehicle Propulsion Materials
5. Fuel physical property requirements for HCCI, from Combustion and Emission Control R&D
6. Technical data and information from industry
7. Technical data and information from Health Impacts Research activity
8. Technical results and feedback, from Combustion and Emissions Control R&D
9. Feedback on specifically designed fuel(s) for HCCI engines, from Heavy Truck Engine R&D

Figure 3.3-3. Network Chart for Fuels for Advanced Combustion Engines

3.3.4 Waste Heat Recovery

The Waste Heat Recovery activity develops technologies for converting waste heat from engines into useful energy (e.g., electrical energy) to improve overall thermal efficiency and reduce emissions.

3.3.4.1 External Assessment and Market Overview

Effective use of waste heat from ICEs would significantly increase vehicle fuel economy. Only about 30-35 percent of the fuel's energy currently is used for vehicle propulsion. Approximately 35-40 percent is lost in the exhaust gases and another 30-35 percent is lost to the coolant. Recovery of energy from engine exhaust and/or engine cooling system represents a potential for 10 percent or more improvement in overall engine efficiency. Technologies for engine waste heat recovery include direct thermal-to-electric conversion and turbocharging/turbocompounding.

The temperature differences between the ambient air and the radiator, lubricating oil sump, exhaust gas, exhaust gas recirculation loop, turbocharger compressed air discharge (engine intake air), and brakes present opportunities for direct conversion of heat to electricity known as the Seebeck effect (an electric current is generated when a temperature differential is applied across a thermoelectric material).

Thermoelectrics were used as thermocouples and thought of as an "academic curiosity" through a major part of the 19th century and the first half of the 20th century. In the later half of the 20th century, bulk semiconductors appeared that provided 5 to 6 percent conversion efficiency when operating between 50°C and 250°C. They were labor-intensive to make due to small volumes and typical applications were for niche markets. Thermoelectrics, mated with radioisotope power sources, have worked continuously in space for over 30 years with less than 10 percent degradation.

The same devices used to convert heat to electricity can be used to heat or cool, depending on the polarity of the direct current passed through the thermoelectric device. This is known as the Peltier effect. The largest use of thermoelectrics for this application is the climate control of car seats; it takes 40 watts to cool a person while air conditioning uses over 1,000 watts to cool the front passengers' seat space. GM, Ford, and Toyota purchased one million of these units in 2004.

In the early 1990s, a new theory based on advances in nanostructured devices[c] made by Mildred Dresselhaus and her research group at Massachusetts Institute of Technology, envisioned thermoelectric materials of 20 percent and higher efficiencies. Since then, several organizations have experimentally validated, at the laboratory bench level, that nanostructured thermoelectrics can achieve efficiencies that are 3 times those obtained with the bulk semiconductor thermoelectrics.

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[c] Hicks, L.D., Harman, T.C., Dresselhaus, M.S., "Use of Quantum-Well Superlattices to Obtain a High Figure of Merit from Nonconventional Thermoelectric-Materials," Applied Physics Letters, 63, 3230-3232, 1993.

Recovery of engine exhaust energy is also possible with turbocharging or turbocompounding. Current turbocharger efficiencies are around 50 to 58 percent; these could be increased to 72 to 76 percent with enhancements such as variable geometry. An electrically driven turbocharger with increased transient response would be another approach. Integrating an electro-turbocompound unit with the engine control system has the potential to enable production of about 3 to 5 kW from light-duty engine waste heat for passenger vehicles, and up to 20 kW from heavy-duty engine waste heat for commercial vehicles.

3.3.4.2 Internal Assessment and Activity History

The FCVT Program initiated a project with Hi-Z Technology in the mid-1990s to determine if thermoelectric generators were viable for heavy truck applications. Hi-Z developed a 1 kW(e) thermoelectric generator that was integrated with the muffler but restricted to a tap on the radiator cooling water for the cold side. This device installed in a Class 8 heavy truck which was run fully loaded by PACCAR Incorporated on their test track for the equivalent of 550,000 miles. The only failure was in the cooling water line which was easily repaired. Hi-Z also supplied a 350 watt unit to Clarkson University for installation in a GM lift truck for a joint program with the New York State Energy Research and Development Agency (NYSERDA). A similar device was provided to Ohio State for test on a Ford vehicle. These test provided satisfactory results.

Bulk semiconductor thermoelectric devices are currently 6 percent efficient. Recent developments in quantum well thermoelectrics suggest a potential improvement to over 20 percent is possible. These can provide a 10 percent efficiency improvement to a diesel or gasoline vehicle propulsion engine efficiency. But the technology must be advanced from the laboratory to commercially viable production and installed as a thermoelectric generator using the engine's waste heat to be competitive.

Focusing the thermoelectric generator market on transportation vehicles provides the most probable major improvement in fuel economy in the next 15 years, which would be accompanied by the bonus of CO_2 reduction. The potential volume of thermoelectric devices in the transportation sector could provide the base for low cost, low grade energy recovery thermoelectrics with opportunities for application in industrial processes, geothermal energy recovery, ocean thermal energy recovery, and energy storage battery temperature control.

The FCVT Program initiated collaborative work with industry in FY 2001 on the development of electrically driven turbochargers for recovering light-duty engine waste heat to improve passenger car fuel economy. Work was also initiated on electric turbocompounding combined with starter motor-alternator and damper technology to eliminate turbo-lag and improve heavy-duty engine overall thermal efficiency by up to 10 percent.

3.3.4.3 Federal Role

Bringing unique expertise and capabilities of the national laboratories, to assist industry and conducting collaborative research that bridges the gap between science and the marketplace, is an appropriate role for DOE. Stimulating the development and adoption of high efficiency thermoelectric technologies for vehicle applications is high-risk and would not be undertaken by industry on its own.

3.3.4.4 Approach

A competitive solicitation was conducted for waste heat recovery R&D and awards were made to eight teams (four teams for thermoelectrics and four for turbocompounding) for five-year cooperative agreements to develop the technologies for automobile and commercial diesel engines.

The selected teams for thermoelectrics include: a) manufacturers of thermoelectric devices who could develop high efficiency thermoelectric modules that can convert engine waste heat to power levels suitable for vehicle applications; and b) vehicle and engine manufacturers who could undertake integration of commercially viable engine waste heat recovery devices into their products; and c) national laboratories or R&D laboratories with expertise in applied thermoelectrics R&D. Work is done through cost-shared cooperative agreements. Two of the teams are focusing on Class 7 and 8 heavy-duty truck diesel engines and the other two are developing thermoelectric generators for light trucks (pickups, vans, and sport utility vehicles) and for automobiles.

Success with the single thermoelectric project would lead to a follow on project wherein 5 thermoelectric generators would be used to maximize engine waste heat recovery to achieve a 55 percent efficient heavy duty diesel engine or a nominally 45 percent efficient light truck/auto diesel engine with potential for even higher efficiencies. Achieving these efficiencies would require the thermoelectric generated electricity to go into power conditioning and then be integrated with the "beltless engine" or "more electric engine" concept where all the engine accessories are electric motor driven (e.g., the 2005 BMW 5 series car has an electric water pump).

Thermoelectric generators could also be used with the integrated motor/alternator/starter which could absorb the electrical energy and reduce engine drag. It is estimated that on a per vehicle basis, compared with an equivalent 2005 gasoline engine, there could be as much as a 50 percent fuel economy gain and a 42 percent reduction in CO_2 (greenhouse gas) emissions.

3.3.4.5 Performance Goals

The longer-term goal of this activity is to develop the technologies for recovering engine waste heat and converting it to useful energy that will improve overall diesel 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, enable commercially viable turbocompound units that can produce up to 40 kW of additional power from heavy-duty engine waste heat recovery.
- By 2012, achieve at least 25 percent efficiency in quantum well thermoelectric devices for waste heat recovery.

This activity also supports the overall engine efficiency goals of the FreedomCAR and Fuel Partnership and 21st CTP.

The technical targets for Waste Heat Recovery are shown in following table:

Table 3.3-7. *Technical Targets for Waste Heat Recovery*

Characteristics	Units	Year		
		2003 Status	2008	2010
Thermoelectric Devices				
Efficiency				
• bulk semiconductor	%	5–7	--	--
• quantum well			>15	>20
Projected cost/output (250,000 production volume)	$/kW	--	500	180
Turbocompound System				
Class 7–8 trucks				
Fuel economy improvement	%	<1	>5	>10
Power	kW	<10	>20	>40
Projected component life	hours	<10	>5,000	>10,000

3.3.4.6 Strategic Goals

The Waste Heat Recovery R&D activity supports DOE's Energy Security Strategic goal to "improve energy security by … exploring advanced technologies that make a fundamental improvement in our mix of energy options, and improving energy efficiency."

3.3.4.7 Market Challenges and Barriers

A. ***Cost.*** The electro-compound system capital cost to the owner and operator should be repaid in 24 months or less. This payback period will depend on the cost of the fuel or a tax incentive. For nano-thermoelectrics, achieving the large-scale production goal of devices for direct conversion of heat to electricity would require large-scale sputtering equipment that could cost-effectively deposit the layers in an automated high throughput manner. There are two very large companies that are interested in the production of thermoelectric modules who are participating in this activity at no cost to the Government.

3.3.4.8 Technical Challenges and Barriers

B. ***Scale-up to a practical thermoelectric device.*** High efficiency thermoelectrics are a turn-of-the-century technological development. Several types of high efficiency thermoelectrics are emerging. They are based on increasing electrical conductivity while reducing thermal conductivity. This only works in the nano-scale. The primary thermoelectrics being evaluated are the two-dimensional quantum well, quantum dots, segmented, and skutterudites. As an example, the two-dimensional system is essentially a nanostructure consisting of alternate N and P layers about 100 Angstroms thick deposited on an extremely thin low thermal conductivity substrate. The challenge is to develop coating techniques that can deposit a sufficient number of layers to achieve the efficiency goal. This entails dramatically increasing the size of the laboratory developed specimens and doing so cost effectively. In addition, new technologies for heat transfer in these nanostructure films need to be explored and techniques for measuring key parameters in these nano-films need to be further developed.

C. ***Turbocompound device/system packaging.*** The electro-turbocompound system, including its power electronics and overall system controller, must fit under the vehicle hood with adequate space for cooling. All of the power must be absorbed by the integrated motor/starter/generator or by accessories converted from belt-driven to electric-motor-driven. The turbocharger that has the motor/alternator attached between the turbine and compressor operates at a nominal 55,000 rpm for Class 7 and 8 heavy trucks and 120,000 rpm for light trucks. This is pushing the state of the art for the light truck application. This system will increase exhaust gas backpressure and adversely affect fuel economy, The turbocompound system must not cause drivability or noise, vibration and harshness (NVH) problems.

D. ***Component/system durability.*** Specific durability requirements must be met by the waste heat recovery systems. The electric turbocompound system must perform for 250,000 miles and 500,000 miles in light and heavy truck applications, respectively. High efficiency thermoelectric devices will have to survive vibrations encountered in vehicle applications. Although lessons learned with the thermoelectric generator developed with bulk semiconductors will be useful, quantum well thermoelectric devices present a more difficult challenge due to their more complex fabrication.

3.3.4.9 Strategies for Overcoming Barriers/Challenges

The technical approach to developing commercially competitive thermoelectric devices[d] for transportation applications is first to validate the bulk semiconductor-based 2-kW thermoelectric generator. The emphasis will be to develop thermoelectrics (or “nano-thermoelectrics”) that can perform power generation (using the Seebeck effect) or heating/cooling (using the Peltier effect) for vehicular applications within the cost criteria for commercial production. A measurement

[d] A detailed discussion of past efforts in thermoelectrics, the current state of the art for quantum well thermoelectrics, available approaches for improved thermoelectric device performance, present and past R&D tasks by DOE and other entities, as well as detailed steps of the technical approach appears in the document *R&D Approaches to Exploit Recent Major Breakthroughs in Thermoelectrics, for FY 2003–2007*, Office of FreedomCAR and Vehicle Technologies, U.S. Department of Energy, 1000 Independence Avenue, SW, Washington DC 20585, September 2003 draft.

technique for these ultra-thin devices will be developed. Multilayer devices will be made by sputtering with alternate N and P layers (on the order of 1000 layers). Multilayer systems that will initially be investigated include Si/Si0.8Ge0.2 and B4C/B9C deposited on 0.5-mm-thick kapton or other low thermal conductivity substrates. Coating parameters will be optimized, and heat transfer issues will be addressed.

Iterative test and redesign efforts will be conducted for electric turbocompound systems to validate the electric power produced and the resulting overall engine efficiency gains. In addition, turbochargers can improve the low-speed torque which can result in reduced engine size for the same performance. Validation will be undertaken by motoring the turbocharger during acceleration to reduce turbo-lag and improve emissions. Testing will also be conducted in the Heavy Truck Engine activity with EGR-equipped engines to validate NO_x reduction achieved due to increased exhaust back pressure.

3.3.4.10 Tasks

A description of each technical task, along with the estimated duration and technical barriers associated with the task, is provided in following table:

Table 3.3-8. *Tasks for Waste Heat Recovery R&D*

Task	Title	Duration & Barriers
1	***Thermoelectrics for Transportation Application*** • Produce a 10% fuel economy improvement from both heavy truck (Class 7 and 8) and autos and light trucks with a thermoelectric generator • Fabricate high efficiency thermoelectric device with at least 21% efficiency • Based on a successful 10% thermoelectric generator, extend to 6 thermoelectric generators on radiator, lube oil sump, exhaust, EGR loop, turbocharger discharge air, and brakes, which when integrated with the beltless engine would produce a nominal 55% efficient diesel engine. • Develop vehicular air conditioning system based on the high efficiency thermoelectrics developed for the generator which would provide a 20% improvement in efficiency while eliminating the R-134a refrigerant	120 months Barriers A, B, D
2	***Turbocompound System for Heavy Trucks*** • Develop a system to provide an additional 40 kW of electric power • Integrate an electric turbocompound system with heavy truck engine controls and validate through laboratory tests that 40 kW can be produced for over 10,000 h for a 10% fuel economy improvement • Redesign the system using laboratory test results, install the modified electric turbocompound system in a Class 7/8 heavy-duty truck engine, and validate a 10% fuel economy improvement over 10,000 h	120 months Barriers A, C, D

3.3.4.11 Milestones and Decision Points

The Waste Heat Recovery R&D activity milestones and decision points are provided in the following chart:

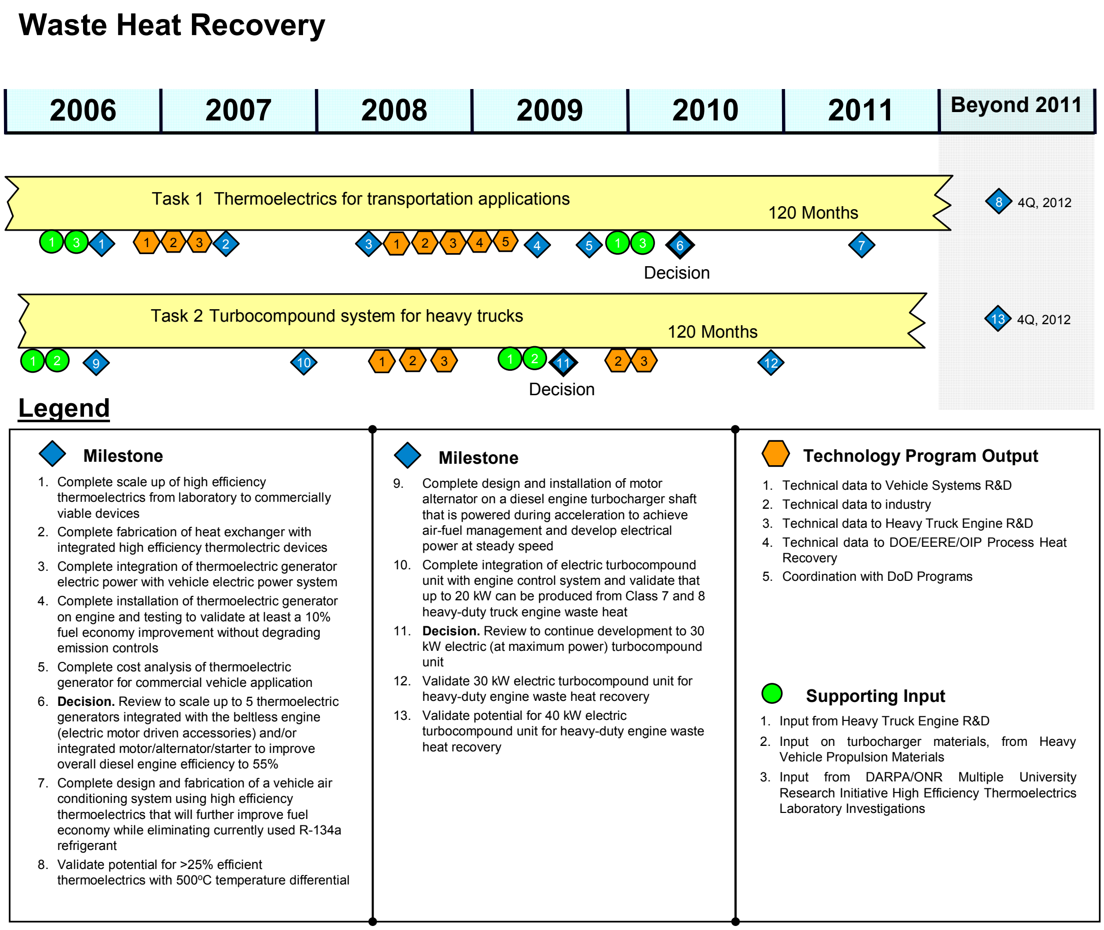


Figure 3.3-4. Network Chart for Waste Heat Recovery

3.3.5 Health Impacts

The FCVT Program and its industry partners are on the leading edge in the development of future light- and heavy-duty vehicle technologies to improve fuel economy and enable the use of non-petroleum based fuels. The Health Impacts research activity performs the critical role of elevating potential health issues related to these future vehicle technologies to the attention of industry partners and DOE/FCVT management. By proactively evaluating the potential air quality and human health impacts of changes in fuel, engine, lubricant, and aftertreatment technologies before they are widely implemented in transportation vehicles, this activity ensures that development of new vehicle technologies considers the possibility of causing negative health impacts, rather than just complying with existing standards.

3.3.5.1 External Assessment and Market Overview

At times in the past it has been assumed that new fuels and vehicle technologies would have no negative health related side effects. One such instance occurred with the installation of the automotive catalytic converter in 1975, which has led to the assumption that emissions from gasoline engines have been rendered totally benign. While catalytic aftertreatment of automobile exhaust has been extremely successful, degradation of catalyst effectiveness over time often due to lack of proper vehicle maintenance has led to "high emitters' which are now becoming recognized as the source of the bulk of toxic emissions from motor vehicles. In addition, ultra-clean, new gasoline vehicles might still emit ultra-fine particles, the health impacts of which have never been documented. Studies have only recently been initiated to look into the potential health impacts of fine particle emissions emanating from these new vehicles.

In another instance, use of methyl tert-butyl ether (MTBE) as a gasoline additive was mandated by EPA to reduce carbon monoxide emissions and to clean urban air, but since then it has been found to result in serious groundwater contamination[1]. Even more recently, high levels of toxic compounds such as formaldehyde and 1,3-butadiene have been measured in natural gas vehicle emissions[2].

As the U.S. continues to address the energy security issue due to the growing dependence of transportation on imported oil, there are major health concerns that cannot be overlooked in the rush to commercialize alternatives.

[1] Health and Environmental Assessment of MTBE, Report to the Governor and Legislature of the State of California, prepared by U.C. Toxic Substances Research and Teaching Program, November 12, 1998.

[2] Ahlvik, P. and A. Brandberg, "Relative Impact on Environment and Health from the Introduction of Low Emission City Buses in Sweden," SAE Technical Paper 2000-01-1882, presented at the International Spring Fuels and Lubricants Meeting and Exposition, Paris, France, June 19-22, 2000.

3.3.5.2 Internal Assessment and Activity History

One technology that offers the potential to achieve significant reduction in transportation petroleum use is the diesel engine. Diesel engines have a fuel efficiency advantage over gasoline engines and hence, will require less fuel and produce lower emissions of the greenhouse gas carbon dioxide. However, despite this advantage, use of the diesel engine to improve transportation fuel economy has been slow to gain favor in the U.S. because of the highly visible emissions experienced with the old generation diesel engines. Although diesel engine emissions have been reduced considerably in recent years, the negative image continues to persist.

When FCVT adopted a "dieselization" strategy for reducing transportation fuel use, in addition to carrying out research to eliminate noxious emissions from diesel engines, it also initiated a comprehensive Health Impacts effort to develop a better understanding of the health issues related to the cleaner new diesel engines and aftertreatment technologies. Results from the Health Impacts research, which have been widely disseminated in technical meetings, workshops, other conferences, and peer-reviewed journals, have shown greatly lessened emissions levels from the new clean diesel technologies and disproportionately large contributions to air pollution made by high emitting vehicles (both gasoline and diesel).

3.3.5.3 Federal Role

It is incumbent upon FCVT and in the public interest that no new technologies are deployed that could unintentionally cause adverse human health impacts. The FCVT research on advanced vehicle and fuel technologies is in the exploratory and developmental stages and therefore is not yet sufficiently commercial for EPA regulatory oversight. In addition, this research investigates the health impacts of complex mixtures (e.g., engine exhaust) where toxic synergisms are enhanced and develops information that puts the health impacts of advanced technologies in context with respect to the relative risk from alternative means of providing transportation. R&D into these technologies would necessarily have to include approaches to mitigate any impacts.

3.3.5.4 Approach

Assessment of the health impacts of specific vehicle technologies is accomplished through the development of more accurate measurements of deleterious emissions components and validated models that can differentiate the contribution of these new technologies relative to current technologies. Although PM and NO_x are known to present health hazards at high concentrations, much less is known about the hazards presented by other emission components, or the relative importance of other components to PM and NO_x. Emissions from advanced technologies will be screened for toxicity and in selected cases where possible, components responsible for toxicity will be determined to ascertain if engineering solutions can reduce the toxic components. Of special interest to FCVT are emissions from advanced combustion engines using fuels optimized for new combustion regimes such as HCCI.

FCVT is not primarily a health research program, but it does direct some resources toward a limited scope of well-focused, technology-specific health impacts research activities to ensure that there are no unintended consequences from emerging technologies. Other agencies addressing health issues related to exposure to emissions from the current technologies in the vehicle population will have interest in future technologies as they begin entering the commercial market. To leverage resources, FCVT Health Impacts research is done in collaboration and communication with others (EPA, California Air Resources Board [CARB], Sacramento California Air Quality Management District [SCAQMD], industry, Combustion Research Council [CRC], Health Effects Institute [HEI], etc.) who have found the FCVT results to be unique and important in guiding the development of more accurate models and standards.

3.3.5.5 Goals

The goals of FCVT Health Impacts activity are as follows:

- To provide a sound scientific basis underlying any unanticipated potential health hazards associated with the use of new power train technologies, fuels and lubricants in transportation vehicles.
- To ensure that vehicle technologies being developed by FCVT 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.

3.3.5.6 Strategic Goals

The Health Impacts Research activity supports the Department's Energy Strategic Goal: To protect our national and economic security by reducing imports and promoting a diverse supply of reliable, affordable, and *environmentally sound* energy.

3.3.5.7 Market Challenges and Barriers

A. ***Market Perception.*** There is increasing public awareness of adverse health impacts related to vehicle emissions. As a result market acceptance is contingent upon improved understanding and knowledge that these new technologies have considered mitigation of known health impacts and will have no unknown potential health impacts.

3.3.5.8 Technical Challenges and Barriers

The technical challenges to be addressed are:

B. ***Lack of actual emissions data on pre-commercial and future combustion engines.*** The health impacts of future technologies (e.g., 2007/2010 compliant production engines) have to be evaluated well in advance of their market introduction and, therefore, lack actual real-world emissions data, not to mention the difficulty of measuring very low level emissions that are expected from them.

C. ***Lack of analytical tools (rapid assay techniques) relevant to human toxicity.*** This includes lack of standardized "baseline case" inhalation exposure atmospheres and collected samples with which to compare *in vivo* and *in vitro* responses; the need for confirmation that *in vitro* toxicity test systems accurately mirror relative response of lungs to different exposures, and the poor ability to separate different components from "whole" emissions; or to selectively eliminate components for inhalation exposures.

D. ***Lack of credible validated models for emissions source apportionment.*** There are no universally recognized molecular markers to distinguish between gasoline and diesel exhaust, as well as other fuel types, and little data from various source types to adequately apportion air toxics to their respective sources (cars vs. trucks). There is an inadequate understanding regarding engine operating conditions (and ambient conditions) that influence emissions from mobile sources and a lack of standardized "baseline" collected real-world emissions samples with which to compare the health response.

3.3.5.9 Strategies for Overcoming Barriers/Challenges

The most accurate measurement methods and tools will be applied to characterize the physical and chemical properties of vehicle emissions and possibly to differentiate emissions from various mobile sources (e.g., gasoline-, diesel-, natural gas-fueled and other alternative fuel vehicles). The contribution of emissions from these sources to the total emissions inventory will be established. Emissions from new and in-use technologies and non-petroleum-based fuels will be evaluated. Impacts of diesel and gasoline PM emissions in air quality will be investigated, compared, and contrasted. The atmospheric reactivity of exhaust emissions from alternative-fuel engines will be evaluated to assess the impact on urban air quality relative to conventional fuels. Work will also contrast primary and secondary particulates associated with the use of different fuel formulations. More specifically, it is necessary to achieve the following:

- Characterize the chemical and physical properties of diesel exhaust at the low emissions 2007/2010 certification standards required by EPA to evaluate if there are potential adverse health impacts.
- Evaluate the impact of unregulated emissions and toxic compound components from the 2007/2010 compliant engines on human health at some exposure levels.
- Measure, characterize the chemical and physical properties of, and possibly differentiate, emissions from various mobile sources (e.g., gasoline-, diesel-, natural gas-fueled vehicles) highway vehicles (and/or farm and construction equipment and locomotives, as needed) as a function of fuel composition, lubrication technology, and duty cycle.
- Establish the proper apportionment of emissions among the various mobile sources, e.g., cars vs. heavy trucks, and conventional fuel (gasoline and/or diesel fuel) versus alternative fuels (e.g., non-petroleum based fuels).
- Establish a scientific basis for determining the impacts of emissions on human health.

3.3.5.10 Tasks

A description of each technical task, along with the estimated duration and technical barriers associated with the task, is provided in the following table:

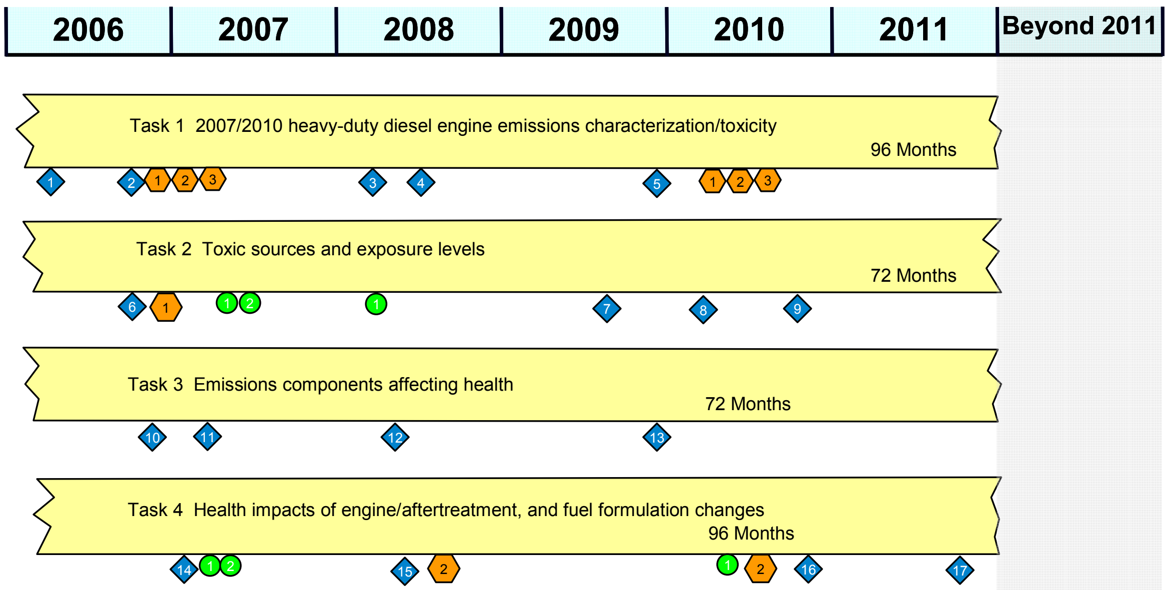
Table 3.3-9. *Tasks for Health Impacts Research*

Task	Title	Duration & Barriers
1	***Characterization of 2007/2010 emissions-compliant heavy-duty diesel engines and evaluation for toxicity and health impacts*** • Collection and chemical characterization of emissions samples from at least 4 representative 2007 emission compliant heavy duty diesel engines; selection of representative emissions profile • Exposure over specified time periods, of animals (rats, mice), bacteria (Ames test) and cultured mammalian lung cells to emissions from representative engine • Identification and statistical interpretation of observed biological responses to specified exposure levels • Replicate protocol for 2010 compliant heavy duty diesel engines	96 months Barriers B, C, D
2	***Characterization of toxic emissions from mobile sources and evaluation of the relative contribution to exposure levels; establish relative health hazards of diesel, gasoline, and natural gas engine system(s) emissions*** • Identify molecular markers that differentiate emissions from various sources • Establish apportionment of emissions among various among various sources	48 months Barriers B, C, D
3	***Emissions components affecting health*** • Identify components of complex "whole" emissions responsible for health hazard • Establish protocol for determining toxicity of various emissions components and corresponding health hazard	72 months Barriers B, C, D
4	***Health impacts of engine/aftertreatment and fuel formulation changes*** • Testing and evaluation of non-petroleum-based fuels for toxic emissions	96 months Barriers B, C, D

3.3.5.11 Milestones and Decision Points

Health Impacts Research activity milestones and decision points are provided in the following chart:

Health Impacts



Legend

Milestone

1. Complete evaluation of production-intent prototype 2007 EPA-compliant heavy-duty diesel engines; one representative engine/aftertreatment system selected for exhaust emissions characterization and toxicity assessment.
2. Complete collection of emissions sample from representative 2007 compliant diesel engines for toxicity studies.
3. Complete evaluation of production-intent prototype 2010 EPA-compliant heavy-duty diesel engine; one representative engine/aftertreatment system selected for emissions characterization and toxicity assessment.
4. Complete installation of representative engine for emissions generation at health facility.
5. Complete chronic inhalation bioassay on two rodent species (2010 EPA-compliant diesel engines).
6. Complete characterization of oil-derived and conventional diesel nanoparticles.
7. Complete collaborative government/ industry evaluation of effects of lubricating oil composition on gasoline and diesel vehicle exhaust.
8. Complete evaluation of evaluation of sources of in-cabin vehicle pollutant exposure during on-road driving conditions

Milestone

9. Complete apportionment study of contributors to ambient ozone levels in the Los Angeles basin.
10. Complete validation comparison of *in vitro* and *in vivo* responses to diesel and gasoline emissions.
11. Complete evaluation of chemical determinants of toxicity of natural gas engine emissions.
12. Complete multivariate analysis of toxic agents in conventional diesel, gasoline, and natural gas vehicle emissions from roadside samples.
13. Complete comparison of toxicity emissions from gas-to-liquids, kerogen-derived, heavy-oil derived, and biodiesel in conventional diesel engine.
14. Complete initial sample collection for subsequent toxicity testing of metallic compounds in engine emissions originating from fuels and lubricants.
15. Complete evaluation of effect of lube oil composition and usage on toxicity of diesel emissions.
16. Complete initial evaluation of potential health hazards from HCCI engines and fuels.
17. Complete evaluation of potential health hazards from hybrid-electric duty cycles and fuels.

Technology Program Output

1. Technical data/information to refereed journals for wide public dissemination.
2. Technical data/information to Fuels Technology.
3. Technical data/information to Heavy Truck Engine R&D

Supporting Input

1. Input from industry.
2. Fuel specifications from Fuels Technology.
3. Engine exhaust emissions sample from Heavy Truck Engine R&D.

Figure 3.3-5. Network Chart for Health Impacts