DOE/CE-0300P

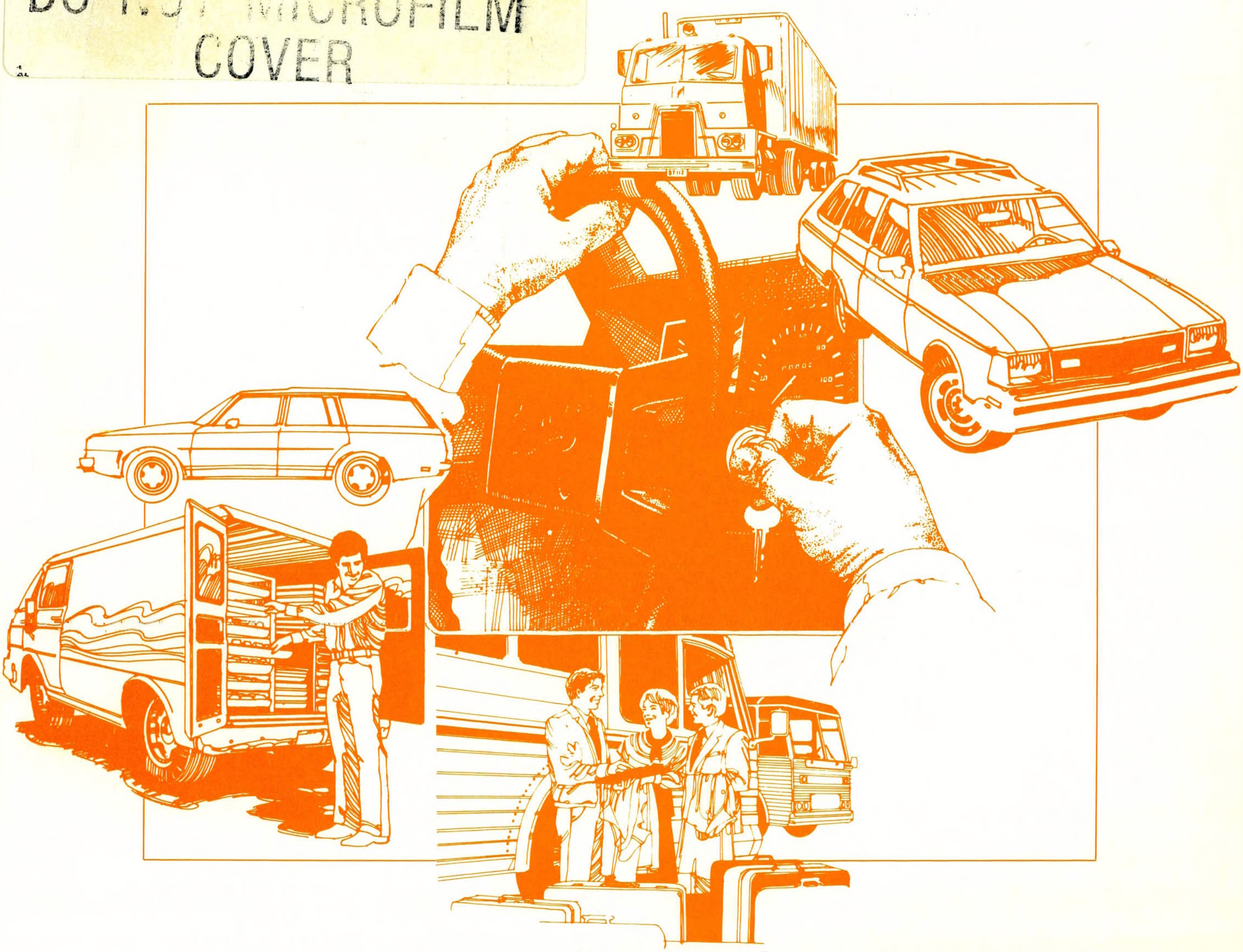
U.S. Department of Energy

NOVEMBER 1990

Assistant Secretary for Conservation and
Renewable Energy
Transportation Technologies
Propulsion Division

on, DC 20585

Twelfth Annual Report to Congress on the Automotive Technology Development Program



NOVEMBER 1990

U.S. Department of Energy

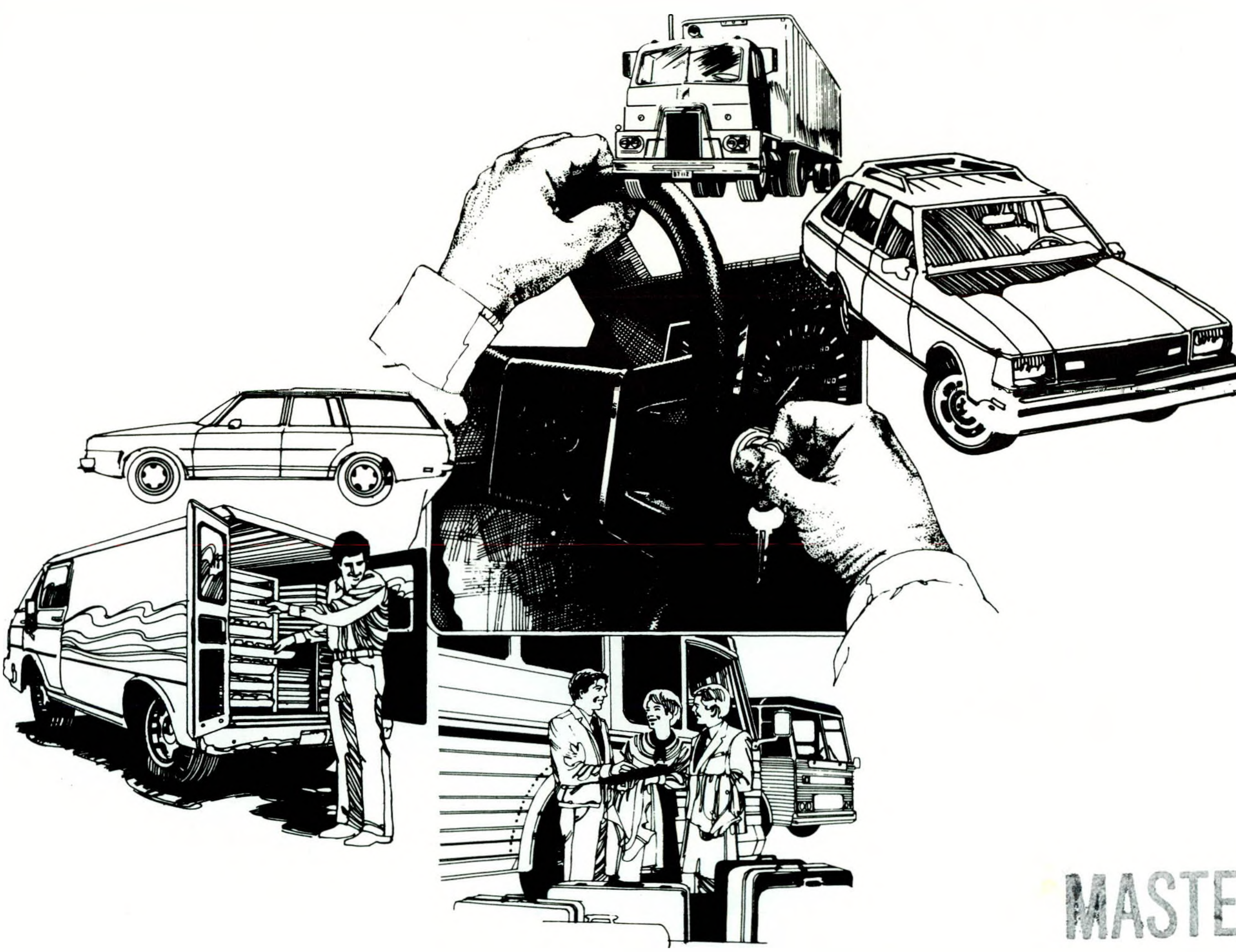
Assistant Secretary for Conservation and
Renewable Energy
Office of Transportation Technologies
Advanced Propulsion Division

Washington, DC 20585

DOE/CE--0300P

DE91 008995

Twelfth Annual Report to Congress on the Automotive Technology Development Program



NOTE: This report, which is Annex No. 2 of the DOE Annual Report to Congress, is required by Section 310(a) of the Automotive Propulsion Research and Development Act of 1978 (Title III of Public Law 95-238).

Table of Contents

Page

PREFACE iii

EXECUTIVE SUMMARY 1

1 INTRODUCTION AND OVERVIEW 3

2 STATUS OF CONVENTIONAL POWERTRAIN TECHNOLOGY 5

3 AUTOMOTIVE TECHNOLOGY DEVELOPMENT PROGRAM 15

3.1 Advanced Turbine Technology Applications Project 15
3.2 Heavy Duty Transport Technology Project 18
3.3 Advanced Materials Development Project 24
3.4 Alternative Fuels Utilization Program 32
3.5 CFC Reduction Project 36

4 RECOMMENDATIONS 39

5 APPENDICES 41

5.1 Appendix A - Procurement Summary — Advanced Turbine Technology Applications Project 42

5.2 Appendix B - Procurement Summary — Heavy Duty Transport Technology Project 43

5.3 Appendix C - Procurement Summary — Advanced Materials Development Project 44

5.4 Appendix D - Procurement Summary — Alternative Fuels Utilization Program 47

5.5 Appendix E - Procurement Summary — CFC Reduction Project 48

5.6 Appendix F - Certification of New R&D Contracts, Grants, and Cooperative Agreements 49

Table of Contents (Concluded)

LIST OF FIGURES

Figure 1 Change in Market Share, 1976-1990 ... 13

Figure 2 Radial and Axial Ceramic Turbine Rotors Designed for 2500°F Operation ... 17

Figure 3 Engine Concept Using One Fluid for Lubrication and Cooling as Adopted by Caterpillar and Cummins ... 21

Figure 4 Cutaway of Turbocharger and Turbocompound System on Caterpillar Diesel Engine ... 22

Figure 5 Comparison of Spherical Joint and Conventional Piston Design ... 23

Figure 6 Development of Gelcasting Technology for Forming Complex Shapes of Silicon Nitride and Other Structural Ceramics ... 27

Figure 7 Determining High Temperature Mechanical Properties of Silicon Nitride Using Button-Head Specimens ... 28

Figure 8 HTML Users from Institute of Defense Analyses, Alexandria, Virginia, Preparing to Perform Measurements on a Tensile Test Instrument in the Mechanical Properties User Center ... 32

LIST OF TABLES

Table 1 Fuel Consumption Related Characteristics ... 11

Preface

This is the Twelfth Annual Report to Congress on the implementation of the Automotive Propulsion Research and Development Act of 1978 (title III of Public Law 95-238), covering FY 1990. It is intended to fulfill the reporting requirements of sections 310(a) and 304(f) and is based on work currently in progress. In addition, it serves as a communication link between the Department of Energy's Automotive Technology Development Program and all of the interests involved in this Program.

Specific requirements of sections 310(a) and 304(f) of title III of Public Law 95-238 that are addressed in this report are:

Section	Title III Requirement	Section of Twelfth Annual Report to Congress
310(a), (1)	Current comprehensive program definition for implementing title III.	Executive Summary and Section 3
310(a), (2)	Evaluation of the state of automobile propulsion systems research and development in the United States.	Sections 2 and 3
310(a), (3)	Number and amount of contracts and grants awarded under title III.	Section 5
310(a), (4)	Analysis of the progress made in developing advanced automobile propulsion system technology.	Executive Summary and Section 3
310(a), (5)	Suggestions for improvements in advanced automobile propulsion system research and development, including recommendations for legislation.	Section 4
304(f), (4)	Discussion of how each research and development contract, grant, or project funded under the authority of this Act satisfies the requirement of this subsection.	Appendix F

Executive Summary

Introduction

The Automotive Propulsion Research and Development Act of 1978 was enacted on 25 February 1978 as title III of Public Law 95-238. It directs the Department of Energy (DOE) to undertake expanded research and development (R&D) of new automotive propulsion systems to achieve improved fuel economy and multi-fuel capability.

Program Implementation

DOE's Automotive Technology Development Program formulated in response to the Act consisted of three major engine-related projects: (1) the Automotive Gas Turbine Engine Development Project, (2) the Automotive Stirling Engine Development Project, and (3) the Heavy Duty Transport Technology Project. In addition, basic ceramic materials and alternative fuels utilization technologies for all engine projects are being developed under the Advanced Materials Development Project and the Alternative Fuels Utilization Program, respectively. The Automotive Stirling Engine Development Project was completed in 1989, demonstrating a ten percent fuel economy improvement over a comparable spark ignition powered vehicle.

Major Accomplishments

Major Automotive Technology Development Program accomplishments in FY 1990 include the following:

Advanced Turbine Technology Applications Project

Completed the prototype component development phase to establish fabrication process parameters based on the improved 2500°F ceramic materials; fabricated the first axial turbine ceramic components suitable for running in an engine; initiated rig testing of ceramic components near 2500°F; and completed the design of an impact-resistant radial turbine rotor.

In addition to these major accomplishments, the assessment and characterization of laboratory-developed ceramic materials continued to identify improved silicon carbide and silicon nitride materials with higher temperature capability, strength, toughness, or reduced cost potential.

Heavy Duty Transport Technology Project

Initiated major contracts with the Cummins Engine Company and Caterpillar Inc. to develop in-cylinder components and applied tribology for the low heat rejection (LHR) diesel engine concept. Thus, through competitive procurements, three of the four U.S. heavy duty diesel engine manufacturers are supported for the development of major elements of the LHR diesel engine concepts. The new Environmental Protection Agency (EPA) regulations on emissions are having a major impact on the program. The significant emission problem is the particulates; 30 to 50 percent of these are attributable to lube oil. The molecular engineering phase of the High Temperature Liquid Lubrication Program holds the promise of making a major contribution to particulate emissions reduction. It will also enhance the viability of the LHR diesel engine concept.

Advanced Materials Development Project

Initiated collaborative research agreement with the Allied-Signal Company to transfer gelcasting technology to industry for forming complex silicon nitride shapes; developed ceramic joint design methodology and joining technology; developed environmentally sound powder processing technology; completed program to develop improved ceramic composites; developed layered composites and fabricated automotive cam roller followers for engine rig tests; established in-process NDE inspection procedures needed to develop highly reliable ceramics for gas turbine rotors and stators; evaluated friction and wear in prototype piston ring-cylinder liner material couples for diesel engines; continued progress in international cooperative research program with Germany and Sweden; and expanded High Temperature Materials Laboratory user program by serving increased numbers of industry, university, and government researchers.

Chlorofluorocarbon Program

Because CFCs as used in automotive air conditioners (A/C) are harmful to the environment, a study of non-inert refrigerants such as propane and butane is being undertaken. These simple hydrocarbons have the potential to provide thermodynamic performance superior to currently used chlorofluorocarbon-12 (CFC-12), and have zero ozone depleting potential. Thirty-seven percent of the CFC-12 produced is used in automotive air conditioners.

An investigation has been initiated into the feasibility of developing CFC/non-CFC blends as substitute fluids in order to ease the transition from the use of CFC-12 and also prevent the premature obsolescence of the approximately 170 million car and light truck air conditioners now in use.

Prototype coatings and glazing for improved solar heating control have been developed by the Lawrence Berkeley Laboratory and the Dow Chemical Corporation. These can limit solar heat gain into the passenger compartment, thereby reducing the peak load on the air conditioner and permitting the evaluation of alternative refrigeration cycles and systems.

A technology assessment is in progress in which a wide variety of non-CFC mobile air conditioning options will be examined. Promising options will be identified, mathematical models developed, and technology development accomplished.

Alternative Fuels Utilization Program

Identified technical approaches to reducing unburned fuel emissions in heavy duty methanol engines; completed emissions tests of high-mileage vehicles from the Federal Methanol Fleet; published transient emissions data on methanol and natural gas heavy duty engines; and initiated central activities on the Alternative Motor Fuels Act.

Recommendations

Based on DOE's assessment of progress toward the overall program goals, there are no new recommendations at this time pertaining to additional R&D programs beyond those included in the FY 1991 budget submission.

1 Introduction and Overview

This is the twelfth annual report on the progress in implementing the Automotive Propulsion Research and Development Act of 1978 (title III of Public Law 95-238). The Act provides for an expanded R&D effort with respect to advanced automotive propulsion systems technology which would complement and stimulate corresponding efforts by the private sector. Implementation of the Act is the responsibility of the DOE's Office of Transportation Technologies (OTT). The programmatic goals of OTT are to increase end-use efficiency of highway vehicles and other transportation modes and to substitute domestic fuels such as methanol, ethanol, and natural gas for petroleum-based fuels. The Lewis Research Center (LERC) of the National Aeronautics and Space Administration (NASA) is the Technical Project Manager for advanced engine projects and Oak Ridge National Laboratory (ORNL) is the Technical Project Manager for advanced materials and alternative fuels utilization R&D. These organizations are responsible for accomplishing the objectives of OTT's Automotive Technology Development Program, which are to:

- Develop proof-of-concept advanced automotive heat engines and demonstrate the capability, relative to current spark ignition (SI) engines, for (1) a 30 percent or greater improvement in vehicle fuel economy; (2) meeting emissions, safety, and noise standards; (3) projected competitive initial and life cycle costs; and (4) alternative fuels utilization capabilities.
- Develop advanced heavy-duty diesel engine technology capable of producing a 30 percent improvement in vehicle fuel economy, relative to 1982 technology, while meeting or exceeding the EPA emissions regulations.
- Establish a structural ceramics and advanced materials technology base in support of advanced heat engine development.
- Establish a technology base for the use of alternative fuels in advanced and contemporary heat engines.
- Find a replacement for the CFC-12 chlorofluorocarbon currently used in automotive air conditioner units.

In summary, the R&D projects in progress address the high-risk areas associated with the development of ceramic components for the gas turbine engine, heavy duty adiabatic diesel engine technology, advanced materials technology, and alternative fuels utilization technology, and replacing the automotive CFC-12 air conditioning fluid.

2 Status of Conventional Powertrain Technology

The subject of vehicle performance has gained rising public interest as a result of high gasoline prices and consumer concern about future fuel price fluctuations, along with keen awareness of environmental concerns and pressure from environmental groups to address pollution control. Thus, automotive manufacturers worldwide have responded to this market demand by developing or improving the means to boost passenger car engine performance, e.g., front-wheel drive, multi-valve cylinders, fuel injection, improved combustion processes, sophisticated electronic engine controls, turbocharging, and supercharging. Performance-oriented advancements improve engine efficiency or permit more sensitive control of engine variables, which can also positively affect fuel economy.

The automotive industry has not, however, neglected powertrain and vehicle R&D which are expected to improve fuel consumption. Notable progress continues to be made in the use of lighter weight materials (plastics, aluminum, and ceramics), weight-reducing component design and fabrication processes (reduced thicknesses and reduced reciprocating mass), lower internal friction (roller bearings and improved lubrication systems), higher compression ratios, and in other areas.

The automotive industry continues to focus on the area of materials. Properties such as higher strength, lighter weight, improved thermal characteristics, improved chemical resistance, and improved friction behavior are being sought for new materials for structural and coating applications. For example, plastic blocks and heads were introduced into marine and industrial engines, with the possibility of similar development for future passenger cars. New ceramic materials have become particularly attractive because of their lightweight, high-strength, and high-temperature properties. Ceramic turbo-chargers are already available in production cars in Japan and are likely to find acceptance in the U.S. Valvetrain wear points such as tappet rod inserts, rocker arms, and cam followers are a very promising application for ceramic materials, and ceramic valves are already being offered by U.S. valve manufacturers. Ceramic thermal barrier materials are being developed worldwide as the foundation for low-heat-rejection ("adiabatic") diesel engine design programs. Cummins Engine Company is producing ceramic links in its fuel injectors, requiring 20,000 links per month. Detroit Diesel Corporation (DDC) is nearing production of a ceramic roller in the valvetrain of its Series 60 engine. Advanced ceramics may potentially be used for piston crowns, connecting rod pins, and exhaust port liners. Mazda Motor Corporation has designed a new twin-rotor rotary engine for a concept car that incorporates ceramic apex seals.

Drivetrain technology has also benefited from some of the same general strategies applied to engine systems, i.e., electronic controls, friction reduction, and lighter-weight materials and designs. Vehicle R&D has focused on reducing aerodynamic drag, rolling resistance, and weight. Various accessories and auxiliaries have also received attention as automotive manufacturers and component suppliers have cooperated to optimize systems performance, meet fuel economy goals, and enhance reliability and safety.

Often led by Japanese and European competition, the automotive industry has pioneered such high-technology items as full-time four-wheel-drive, antilock braking systems, traction aids, automatically adjustable suspension systems, multiplex wiring, and superchargers. Limited introduction of four-wheel-steering and the expected availability in the near future of steer-by-wire technology (the use of electronics to control auto functions) add to the impressive list of advanced technologies being initially offered on higher-priced, and some more widely affordable, vehicles. Although these types of automotive developments are not necessarily intended as fuel conserving techniques, they can present such opportunities (such as weight-saving steer-by-wire technology). They also reflect the intense competition within the industry and the general benefits of computer modeling and manufacturing advances to improve fuel consumption and reduce emissions. Innovations in computer technology and integrated circuit (IC) technology have led to the extensive incorporation of electronic controls in automobiles, thus allowing more precise controls at faster response times. Even evolving technology such as vehicle location systems combined with on-board navigation systems (currently experimental) may help vehicle fuel economy by selecting fuel-efficient routes for travel.

Alternative fuel activities concentrate on developing engines, fuel systems, and vehicles capable of using methanol. Ford Motor Company and General Motors are independently developing vehicles which can run on any mixture of gasoline and neat (pure) methanol; several manufacturers have already demonstrated such a prototype flexible-fuel vehicle.

Reciprocating Spark-Ignition Engine

Most of the automotive industry's R&D resources have gone into the reciprocating spark-ignition (SI) engine. Major advances which appear more widely on today's automobiles include multi-valve cylinders, overhead cams, and increasingly diverse and carefully designed valvetrains for efficient high-speed operation; use of fuel injection (with the option for multi-point versus single-point injection); lightweight materials, especially aluminum and aluminum alloys for pistons, heads, and blocks, plastics for hoses, fuel tanks, and other components, and even composites; increasingly sophisticated micro-processor-based engine controls; turbocharging and the trend towards associated intercooling (cooling of compressed air for the turbocharger); more precise ignition timing; antiknock sensing and control; and reduced internal friction at sliding and rolling surfaces.

Continued research to understand and control the combustion process has led to fast-burn head designs, all-ceramic precombustion chambers, lean-burn operation, and intake swirl capabilities. Such designs help to increase power output, promote more efficient fuel burning, and reduce undesirable thermal and mechanical phenomena in the combustion chamber. In addition, enhanced combustion holds the promise of reduced emissions, to the point where certifiable operation without a catalytic converter has been achieved in special circumstances.

Stratifying the normally uniform intake charge is another option for obtaining better combustion. For example, Honda Motor Corporation's Compound Vortex Controlled Combustion (CVCC) engine, for a time, met U.S. emissions and fuel economy requirements without a catalytic converter. However, a recent study initiated by the West German government and conducted by Volkswagen has shown that, for operation outside the prescribed test cycle, a system which uses a 3-way catalytic converter performs much better for reducing nitrogen oxide (NO_X) emissions than previous systems using a lean burn stratified charge. General Motors Research Laboratories developed an axially-stratified charge, fuel-injected gasoline engine based on a 4-cylinder production unit that improved fuel economy by 6 percent and did not require a 3-way catalytic converter. The development of a stratified charge engine continues to be pursued by industry as an important approach for meeting engine performance and efficiency objectives.

Three of the large domestic automobile manufacturers have shown interest in two-stroke engine technology for automotive applications. This interest results from the prospects for two-stroke engines being substantially lighter than comparable four-stroke engines and for being able to operate on lower-octane gasoline. The timing of the availability of production two-stroke automotive engines in the U.S. is uncertain, but various recent announcements have included the very near term. Much of the activity in this area has been sparked by work in Australia, but at least one smaller U.S. company is promoting two-stroke technology.

Another area of development receiving vigorous attention is Variable Valve Timing (VVT). A VVT mechanism allows better optimization of valve workings to match engine speed and load over the operating regions. Systems that bridge the gap between conventional methods and full-fledged VVT have been seen in the 1990 models of the Chevrolet Corvette 301, Mercedes Benz 3L and 5L, and Honda's Acura Integra. A 3-stage throttle control system employs primary and secondary valves. The stages become operational at different power thresholds.

Two-stroke Reciprocating Engine

The distinguishing feature of two-stroke engines is that every outward stroke of the piston is a power or expansion stroke. This is possible because the pumping function is carried out in a separate mechanism called the scavenging pump, rather than in the working cylinders. Theoretically, this gives a much higher power output compared to that of a corresponding four-stroke engine. The two-stroke engine also offers a reduction in weight, size, and cost, as well as allowing increased fuel economy. Historically, however, such engines have been limited in performance because of poor fuel combustion efficiency. A mixing of the input charge and the exhaust gases leads to partial combustion which in turn leads to higher hydrocarbon (HC) emissions. This fraction becomes significant for higher output engines with correspondingly higher displacements.

A viable two-stroke engine design for automotive and industrial applications has been developed by Orbital Engine Company of Australia. Interest in this emerging technology has generated extensive research in the U.S., Japan, and Europe. Ford Motor Company and General Motors have licensing agreements with Orbital for the manufacture and testing of Orbital's two-stroke engine. Orbital has announced that their design allows production of the engines for automotive/industrial/marine applications on the same production line. American Suzuki Motor Corporation, Yamaha Motor Corporation U.S.A, and the Marine and Industrial Products Division of Acustar Inc. have several two-stroke direct injection (DI) engines in various stages of development and/or distribution. Ford Motor Company has retained Yamaha to develop a two-stroke for automobiles. Japan's Mazda Motor Corporation and Toyota Motor Corporation have each filed for patents for new two-stroke engine designs. An unnamed Japanese automaker is reportedly working on a supercharged two-stroke diesel engine.

The Orbital Company claims that its new two-stroke engine meets all EPA emissions requirements. Significantly, this design uses only an oxidation catalyst which can withstand higher operating temperatures than a reducing catalyst. NO_x emissions are limited by use of a stratified charge and lean burn operation. Ongoing research activity by industry includes fluid flow patterns especially in the context of scavenging. Various hybrid systems, which include ports and valves, are being explored to achieve complete scavenging.

Rotary Spark-Ignition Engine

To date, the rotary engine conceived and designed by Felix Wankel in 1954 is the only version accepted by the auto industry. Wankel's rotary engine offers competitive performance, efficiency, and reliability compared to conventional reciprocating engines, with the added benefits of mechanical and manufacturing simplicity, multi-fuel capabilities, low noise and vibration, low NO_x emissions, and potential modularity.

Mazda Motor Corporation remains the major manufacturer of automotive rotary engines, selling about 1.5 million such engines in Mazda cars, most notably the RX-7 sports car. The rotary engine designers have effected increased engine output, enhanced engine response, improved fuel economy, reduced noise levels, and improved reliability. A twin-scroll turbocharger with intercooler is available on the latest twin-rotor, fuel-injected RX-7 model. Higher fuel efficiency has been achieved by modified gas seals, better-controlled rotor cooling, lighter rotors for reduced bearing friction, better fuel atomization with two injectors per rotor, and electronic control for fuel flows and ignition timing. Mazda is expected to offer a production three-rotor engine first in Japan and then in the U.S. based on racing-car technology; a new computerized engine management system will permit fuel efficiency comparable to the existing smaller two-rotor engine. Mazda has developed a new four-rotor engine for racing purposes. Modified versions of Mazda's turbo-charged four-port RX-7 engine are soon to be used also in marine applications.

Deere and Company has emerged as a second major manufacturer of rotary engines. Deere has focused on designing high-power, compact, multi-fuel, modular rotary engines for military vehicular, manned and unmanned flight, and power generation applications. These engines use stratified charges and offer turbocharging; they are seen as competitors for regenerated turbine and adiabatic diesel engines.

Teledyne Continental has developed a range of air- and charge-cooled rotary engines for small applications and also for remotely-piloted vehicles (RPVs).

Research and development currently sponsored by NASA is aimed at producing a stratified-charge, 400-horsepower rotary engine design appropriate for small aircraft propulsion.

Diesel Engine

The diesel, or compression-ignition (CI), engine is the most fuel efficient and durable heat engine yet devised for surface transportation applications. This preeminence has been achieved by a mechanical design using relatively unsophisticated iron, steel, and aluminum alloy materials. As engine performance is generally related to materials, the potential for further diesel engine performance improvements is quite substantial.

From 1975 to 1979, the use of diesel engines in automobiles and light duty trucks increased rapidly in the United States. At that time, diesel engines in these applications provided a 25 to 50 percent fuel economy advantage relative to SI engines. However, in the mid 1980's, the sale of diesel-powered automobiles dropped abruptly because of the following factors:

- Diesel fuel became more expensive than gasoline
- Significant fuel economy improvements were achieved with SI engines
- Widespread engine durability problems were encountered when some SI engine blocks were converted to CI operation
- CI engines initially cost considerably more than SI engines
- The refining industry had major investments in equipment optimized for gasoline production
- Relatively high particulate emission levels were found.

From a fuel conservation perspective, however, diesel-powered automobiles and trucks would be preferable because the refiner can obtain a greater yield of diesel fuel per barrel of crude oil with a lower expenditure of energy than is the case for gasoline. Diesel engine propulsion is used for virtually all large trucks, buses, off-highway vehicles, railroad locomotives, and inland marine and commercial deep-water ships.

Virtually all of the diesel engine manufacturers' R&D is geared to meeting the EPA 1991 and 1994 Heavy Duty Vehicle Emission Standards. Many of the means to achieve low emissions generally result in a fuel consumption penalty of up to 10 percent. Production engine compliance with the EPA 1994 NO_x and particulate emission standards poses a serious challenge to industry. One of the difficulties is that the engine parameters optimized to reduce NO_x typically increase particulate emissions and vice versa. Particulate control may well necessitate a change from current mineral lubricating oils to a synthetic liquid, probably with an ester base, in addition to engine and fuel modifications and exhaust treatments such as trap-oxidizers. A reduction in emissions is achievable through computerized engine diagnostics and electronic control of fuel introduction using very high pressure fuel injectors, coupled with nozzle designs that accomplish effective fuel/air mixing in a small number of crank angle degrees. A reduction of the sulfur level in diesel fuel to under 0.05 parts per million (ppm) is being planned for October 1993. This will probably increase fuel costs by three to five cents per gallon. This low sulfur fuel is predicted to reduce particulate emissions by 0.1 g/bhp-hr.

Bus manufacturers have been given a 1991 date to meet the 0.10 g/bhp-hr particulate standard, thus creating immediate needs in that sector. Methanol-burning engines are being given serious consideration, partly because they effectively short-circuit sulfur-related direct and secondary particulate emissions.

Compliance with the 1991 and 1994 heavy duty vehicle emissions standards is a top priority, though diesel engine users will not readily accept a compromise in fuel economy, reliability, and durability. Improved fuel economy is being sought in several areas. For example, there is considerable work underway involving the LHR or adiabatic diesel engine concept. This concept involves thermal insulation of the combustion chamber components and exhaust gas passage and entails much higher operating temperatures and pressures than conventional engines. This requires higher temperature liquid lubrication than is currently available or a very large oil cooler with current lube oils. The higher available energy in the exhaust gas of a LHR (low heat rejection) engine suggests that serious consideration be given to waste heat utilization. The biggest gains could be achieved by the addition of bottoming cycles. Unfortunately, these schemes are complex and are not cost-effective with current fuel prices.

Major fuel consumption improvements are obtainable by improving turbomachinery aerodynamic efficiencies and better matching of the turbomachinery to the engine operating power level. The reciprocator requires air as a linear function of power demand while the turbocharger output is exponential. Thus, improved turbomachinery requires variable geometry (the motion of inlet vanes to modify the gas flow) in the gas passage to optimize inlet gas flow to the turbocharger or the use of two or more turbochargers cut in sequentially with increasing power demand. The variable geometry turbocharger (VGT) technology is expected to be applied in trucks by the model year (MY) 1994. Though VGT technology is relatively new, it promises lower emissions in addition to improve fuel economy.

Class 8 truck manufacturers offer aerodynamically shaped cabs, low-rolling-resistance tires, and shielded wheel wells, which combined can provide up to a 20 percent fuel consumption improvement. In Canada, a heavy duty truck economy competition is held annually which attracts international participation. Cummins Engine Company has won this competition for five years; in 1987 they won with a special production L-10 engine-powered truck which achieved 12.4 miles per gallon (mpg), compared to a typical 6.5 mpg for commercial trucks.

Since 1983, major diesel engine development programs have been initiated by foreign firms with support from their respective governments. These programs include the following:

- Ceramics Applied to Reciprocating Engine (CARE) project in Great Britain
- The Eureka programs involving France and West Germany working on the adiabatic diesel concept
- The KEBOD program in West Germany
- The aggressive Japanese "Moonlight" program.

Because of this aggressive international competition, the U.S. diesel engine manufacturers will encounter increasing challenges in domestic and international marketplaces. It is being reported that the diesel two-stroke, which produces less HC and smoke than the four-stroke, will be introduced in transit buses by the MY (model year) 1991.

Transmissions

From a fuel economy standpoint, the most significant recent advances in conventional automotive transmission technology are the application of electronic controls and the availability of four-speed automatic transmissions. Nissan and Mercedes Benz are announcing the introduction of five-speeds in MYs 1991 and 1992, respectively. All of the major automobile manufacturers have been incorporating increasingly sophisticated electronic sensing and control systems for drivetrains. Although improved vehicle fuel economy has not been the sole impetus for these developments, the continued refinement of electronically controlled transmissions (ECTs) is expected to achieve better fuel consumption (as much as 8 percent), especially for large V-8 engines.

Sensors monitor a variety of powertrain and vehicle parameters and a microprocessor controls transmission variables according to a predetermined program. Such electronic controls are combined with an electro-hydraulic power system for the clutches. Many of these ECTs permit the driver to select variable fuel-efficient transmission settings. Four-speed automatic transmissions have been gaining wider acceptance and General Motors has been planning for a line of five- and six-speed ECTs. Porsche A.G. has developed a four-speed automatic transmission called the "Tiptronic," which is installed in the MY 1990 Carrera model. This electronically controlled transmission allows the driver to choose from three programmed driving modes: the program selection, the selective active, and the manual modes. The system is based on the electronically controlled Zahnradfabrik Friedrichshafen (ZF) AG four-speed automatic gearbox, and uses a microprocessor and an assortment of electronic sensors to improve efficiency, fuel economy, and control. The cars are being sold in Europe and are expected in the U.S. by this summer. Electronic controls are being introduced also for transmissions in heavy duty on- and off-highway applications.

In 1958, the concept of a continuously-variable transmission (CVT) which would maintain near-optimal engine speed for minimum fuel consumption was first applied, but various technical and financial problems beset commercial development efforts. After many years of R&D, CVTs were again offered during the first half of 1987 in Europe by Ford of Europe, Inc. and Fiat SpA, and in Japan by Fuji Heavy Industries Ltd. (Subaru). Subaru markets a small CVT-equipped car in the U.S., the Subaru Justy, and plans to introduce CVTs on a 1.6 liter (1.6L) car by 1992. In addition to providing its own CVT-equipped cars, Fuji supplies CVTs to Fiat and the Nissan Motor Company Ltd. Suzuki Motor Company Ltd. recently announced the joint development with U.S.-based Borg-Warner Automotive, Inc. of a more sophisticated electronically-controlled CVT that should be appropriate for larger engines. All of these CVTs are based on the latest Van Doorne technology, which uses a steel belt with variable-radius pulleys.

CVTs are currently offered only on minicars, but Ford's system is said to be suitable for engines up to 1.6L and the new Suzuki/Borg-Warner system may be appropriate for up to 2.5L engines. These CVTs match the fuel economy of a five-speed manual transmission, which is about 10 percent more efficient than a conventional automatic. General Motors' CVT interests are awaiting market demand indicators. Leyland has tested prototype fuel-saving CVTs in a number of experimental British trucks and buses for several years. Volvo Car BV has announced that it will build a $125 million plant in Belgium to build CVTs in 1991. The plant will initially produce 25,000 CVTs annually for use in the Volvo 400 series as well as other automakers' products. The ultimate capacity will be 80-120,000 CVTs per year. The Volvo CVTs will use belts from Van Doorne's model. An electronically controlled version is also being developed.

Several other transmission-related developments on specific models contribute to improved fuel economy. These include the increased use of front-wheel drive on both small and large cars; the increased use of torque converter clutches and split torque features on automatics; lighter weight materials and designs (for example, the tubular aluminum driveshaft on the Ford Aerostar van); reduced friction/drag (the reduced transmission fluid quantity and the use of roller bearings in the new General Motors five-speed, two-shaft transaxle); and upshift indicator lights for drivers on many manual transmission vehicles.

Accessories and Auxiliaries

The continued development and introduction of lighter and more efficient accessories and auxiliaries reflect advances in materials, electronics, and component design and manufacturing. Alternative materials (such as aluminum, ceramics, and super-magnets, which will be used to downsize component motors) are being used to help reduce fuel consumption and engine emissions through weight reduction. Electronics are used to more efficiently operate systems (that is, electronic power brakes and steering; suspension systems; air-bag systems; transmissions; smart diagnostic systems; head-up display (HUD); and more informative electronic instruments such as driver fuel economy readouts). Component design and manufacturing innovations enhance vehicle performance and reliability (multiplex wiring and lighter, more aerodynamic muffler/exhaust systems).

Trends in Fuel Consumption Related Vehicle Characteristics

In 1976, new automobile fuel economy was 17.5 mpg; in 1990, it is an estimated 28.2 mpg. But the rate of growth has not been so dramatic since 1982, especially in light trucks, as can be seen in Table 1. It is very difficult to attribute the changing new automobile fuel economy to particular vehicle characteristics. It is known, however, that reduced weight, increased aerodynamics, and other changes have had an impact on the improved new automobile fuel economy.

It is estimated that only 5 percent of the mpg gain between 1976 and 1990 was achieved by the switch to smaller automobiles (when size is measured by interior space of the passenger and luggage compartments). Thus, the common perception that much of the fuel economy gain has come as a result of buyers choosing smaller automobiles is shown to be overstated.

Table 1, "Fuel Consumption Related Characteristics," presents the new automobile fuel economy by year (from 1976 to 1990) along with several other characteristics. The sales weighted interior volume of all new automobiles dropped from 107.9 cubic feet in 1977 to a low of 104.9 cubic feet, then bounced back to 107.9 cubic feet in 1985 and declined to 107.4 in 1990. In total, new automobile buyers have sacrificed only 0.5 cubic feet of space since 1977.

Another measure of automobile size is the external dimensions (i.e., wheel base), and these have declined much more than has the internal volume. The distance between the front and rear wheels, a proxy for overall exterior dimensions, has dropped from 110.8 inches in 1976 to 103.1 inches in 1990. So it is clear that while internal volume declined only 0.5 percent over the period, the wheelbase measure dropped 7 percent.

Weight is another physical measure of new automobiles. As shown in Table 1, new automobile curb weight declined sharply from 1976 to 1980 but

AUTOMOBILES

MODEL YEAR	MPG (NHTSA)	INT VOL *CU. FT.* (ORNL)	WHEEL BASE *CU. FT.* (ORNL)	CURB WT *POUNDS* (ORNL)	0-60 ACCEL-ERATION *SECONDS* (EPA)	ENGINE SIZE *CU. IN.* (ORNL)
76	17.5	NA	110.8	3608	NA	299
77	18.3	107.9	109.8	3424	14.0	278
78	19.9	107.9	107.7	3197	13.7	264
79	20.3	106.9	105.8	2790	13.8	231
80	24.3	104.9	103.6	3001	14.3	197
81	24.6	105.5	103.0	2744	14.4	182
82	26.6	106.0	103.0	2730	14.4	176
83	26.4	107.3	103.8	2788	14.0	182
84	26.9	108.0	103.5	2788	13.8	181
85	27.6	107.9	103.0	2748	13.3	178
86	28.1	107.0	102.3	2680	13.2	168
87	28.4	106.9	102.2	2694	13.0	164
88	28.7	107.0	102.3	2724	12.6	163
89	28.3	107.5	102.7	2760	12.5	164
90	28.2	107.4	103.1	2810	12.1	165

LIGHT TRUCKS

MODEL YEAR	MPG (NHTSA)	INT VOL *CU. FT.* (NA)	WHEEL BASE *CU. FT.* (NA)	INERTIA WT *POUNDS* (EPA)	0-60 ACCEL. *SECONDS* (NA)	ENGINE SIZE *CU. IN.* (ORNL)
76	14.4			NA		319
77	15.6			4135		307
78	15.2			4151		307
79	18.2			4252		282
80	18.5			3869		264
81	20.1			3806		253
82	20.5			3806		259
83	20.7			3763		244
84	20.6			3782		236
85	20.7			3795		230
86	21.5			3738		223
87	21.7			3713		223
88	21.2			3841		233
89	20.9			3936		240
90	20.9			3952		238

NA = Not Available

Table 1. Fuel Consumption Related Characteristics.

has remained consistent in recent years. The drop in new automobile weight from 3608 pounds in 1976 to 2810 pounds in 1990 was a decline of 22 percent, significantly more than the drop in exterior dimensions. The weight declined most from 1976 to 1980 when fuel economy grew most. But fuel economy continued to improve after 1980, whereas weight reduction did not continue. Some of the weight reduction was associated with the shift to smaller automobiles.

Engine size has, over time, been used as a measure of vehicle power or performance, but this is no longer appropriate since manufacturers have reduced engine size while at the same time increasing horsepower. Table 1 shows that the acceleration performance (as measured by the seconds required to accelerate from 0 to 60 mph) of new automobiles improved by 2.3 seconds from 1982 to 1990 even though the average engine size was reduced by 11 cubic inches. Over the entire period, engine size dropped 45 percent (134 cubic inches) while 0 to 60 acceleration times improved 14 percent. Thus, performance was improved in spite of a very large decline in engine size.

New light truck fuel economy rose from 14.4 mpg in 1976 to 20.9 mpg in 1990. As in the case for automobiles, the light truck fuel economy gains have been very small since 1982.

Comparable data are not available for light trucks for interior volume and 0 to 60 acceleration times. It is known, however, that light truck inertia weight dropped only 4.4 percent over the period, compared with a decline of 22 percent for automobiles. The engine size of the average light truck declined 25 percent over the period, which was less than the percentage drop experienced by automobiles.

The size class changes for both automobiles and light trucks are shown in Figure 1, "Change in Market Share, 1976-1990." There has been a movement toward the midsize classes for automobiles, as about 13 percent of sales have shifted away from the smallest and largest classes to the compact and midsize classes. The shift for light trucks has been from large to small. Over the 1976-1990 period, 50 percent of the sales shifted from large pickups and vans to the other classes. Surprisingly enough, these significant changes in market shares for light trucks accounted for only 39 percent of the mpg gain over the period. For both automobiles and light trucks, manufacturers have been successful in achieving fuel economy gains independent of size class changes, but the fuel economy gains since 1982 have been modest and mpg actually declined in 1990 compared with 1989. Furthermore, the shift to light trucks by many new vehicle buyers has lowered the combined fuel economy for cars and light trucks compared to what it would have been without this shift. For example, new light duty vehicle fuel economy was 25.1 mpg in 1989. If the light truck share had remained at its 1976 value of 20 percent instead of growing to 32 percent as it did in 1989, the light duty fuel economy in 1989 would have been 1.0 mpg higher.

Automotive Mobile Air Conditioners (MACs)

A vapor compression refrigeration cycle, using CFC-12 as the working fluid, is the standard air conditioning system for automotive mobile air conditioners (MACs). Because chlorofluorocarbon-12 (CFC-12) production and use is likely to be phased out by the year 2000, it is imperative to find an alternative to CFC-12 in the immediate future. In 1986, 127 million pounds of CFC-12 was used in automobile, truck, and bus air conditioning systems. This represents 37 percent of the domestic CFC-12 production. CFC-12 has not only been conclusively proven to deplete the Earth's protective ozone layer, but also is a significant contributor to the greenhouse effect.

Industry's approach to this issue has been to find an alternative refrigerant with transport and thermodynamic properties similar to those of CFC-12. The leading candidate at this time is HFC-134a, a hydrogenated fluorocarbon that is non-flammable, has reduced ozone depletion potential, and exhibits modest greenhouse contribution. Compared to CFC-12, HFC-134a has inferior thermodynamic properties which will necessitate larger heat exchangers, higher working pressures, and increased system costs. The resulting loss in overall vehicle efficiency indicates that HFC-134a may not be a suitable long term solution. Nonetheless, it is undergoing long term toxicity testing; preliminary results are encouraging. The remaining unresolved problem with this refrigerant is in finding a compatible compressor lubricant, as HFC-134a is not soluble in conventional napthenic mineral oils. It may be soluble in alkylene glycol oils, but, unfortunately, these oils are somewhat hygroscopic (that is, water absorbing).

Industry is placing all its hopes on the use of HFC-134a. Plans exist to build production facilities,

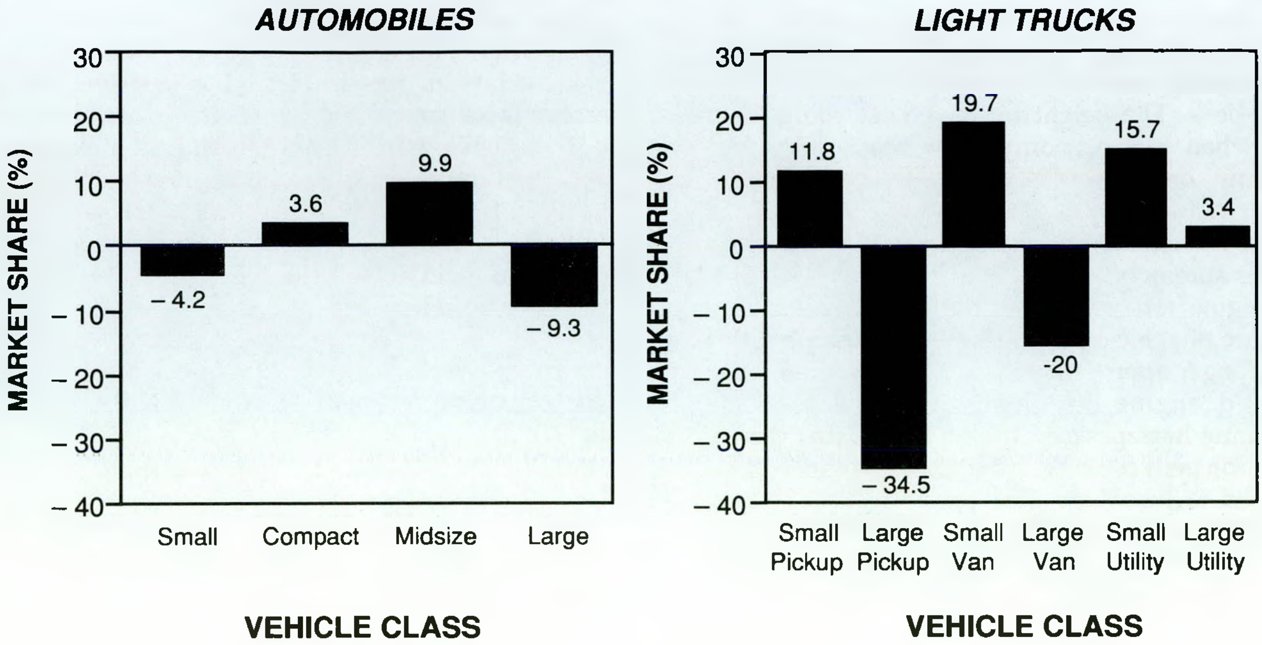


Figure 1. Change in Market Share, 1976-1990.

and auto manufacturers are studying the needed modifications to existing hardware. A large and lucrative market is at stake for the large CFC manufacturers such as E.I. du Pont de Nemours & Company, Allied-Signal, Inc., and Pennwalt Corporation. However, should toxicity testing prove HFC-134a unsuitable or if a compatible compressor lubricant is not found, no alternatives are presently known and no fallback options are being seriously investigated. The transportation CFC Reduction Project addresses these issues. See Section 3.5.

3 Automotive Technology Development Program

On 25 February 1978, Public Law 95-238 was passed by the Congress of the United States. Title III of this Law, entitled "Automotive Propulsion Research and Development Act of 1978," directs the Department of Energy to undertake expanded R&D of new, more fuel-efficient automotive heat engines with multi-fuel capability. In this context, a research program initiated by the Federal government in 1971 identified the gas turbine engine and the Stirling engine as promising candidates for achieving long-term national energy conservation and environmental protection goals. Research and development on the Stirling engine was completed in FY 1989. In 1981, a low-heat-rejection (or adiabatic) diesel engine program was added to extend fuel-saving objectives to the heavy duty truck sector, with expected application of this technology to marine and railroad diesel engine propulsion. An advanced materials development program was initiated in 1982 to address specific and common high-temperature materials requirements in the gas turbine and diesel engine programs. The importance of investigating alternative (non-petroleum) fuels for conventional and advanced engine designs was recognized by incorporating fuel utilization considerations into the overall R&D program. These engine R&D and support efforts have been integrated into the Automotive Technology Development Program (ATDP), which is now the responsibility of the Advanced Propulsion Division within DOE's Office of Transportation Technologies. The ATDP presently consists of four major elements:

- Advanced Turbine Technology Applications Project
- Heavy Duty Transport Technology Project
- Advanced Materials Development Project
- Alternative Fuels Utilization Project.

Each of these elements will be discussed below in terms of the technical plan, technology status, environmental considerations, and recent major accomplishments.

3.1 Advanced Turbine Technology Applications Project

Over the past 30 years, the gas turbine has attained a high state of development in aircraft, marine, and stationary applications. In light duty highway vehicle applications, however, its low efficiency at part load, unsatisfactory acceleration response, and high production cost have overshadowed its potential advantages of low exhaust emissions, multi-fuel capability, high reliability, low maintenance requirements, compactness, and low weight. Technology improvements in the areas noted above are required before the full potential of an automotive gas turbine can be realized.

In the United States, R&D on automotive gas turbines began in the early 1950's at Chrysler, Ford, and General Motors. In the mid 1960's, Chrysler conducted a consumer evaluation of 50 experimental gas turbine powered automobiles. Generally, the users were impressed by the smoothness and reliability of these vehicles, but objected to their poor fuel economy and acceleration. Research on automotive gas turbine engines was largely abandoned by the private sector in the face of the technical and economic obstacles and the long time horizon associated with such a development program. The Federal government has been sponsoring a continuing long term effort in this area as a cornerstone of its advanced heat engine propulsion goals.

Technical Plan

The key to acceptable fuel economy for an automotive gas turbine is operation at much higher temperatures (in excess of 2200°F) than conventional engine materials can withstand. Progress under DOE's Automotive Gas Turbine Engine Development Project demonstrated during 1987 the feasibility of an automotive gas turbine whose hot section consists of parts fabricated from advanced ceramic materials. This was accomplished through the design and testing of experimental engine components in special rigs and prototype engine installations. This proof-of-concept phase was cost shared with DOE by two separate industry teams: the Allison Gas Turbine team, which produced a two-shaft engine design designated the AGT 100, and the Garrett Turbine Engine Company team (now known as Garrett Auxiliary Power Division), which produced a single-shaft design known as the AGT 101. Both of these engines use regenerators (a honeycomb of rotating ceramic material that transfers heat from the hot gas stream to incoming fresh air going into the combustor) and hot-section ceramic components. Supporting research has been directed towards development of non-destructive material evaluation techniques, definition of advanced small turbomachinery concepts, system analyses, and characterization of existing and emerging ceramic materials.

The Automotive Gas Turbine Engine Development Project showed that considerable improvements are needed in areas related to ceramic materials processing, component fabrication, brittle materials design, data base generation, and nondestructive evaluation of ceramic parts. Such improvements are considered achievable, with the expectation that performance objectives for the automotive gas turbine can be met. At the completion of the AGT 100 and AGT 101 programs in FY 1987, a new program was initiated to address these technology areas. This new Advanced Turbine Technology Applications Project (ATTAP) was started by DOE in mid-1987 to continue essential R&D in ceramic materials and components and their application to the gas turbine engine. The goal of ATTAP is to develop and demonstrate structural ceramic technology capable of competitive automotive engine performance and life-cycle cost. ATTAP objectives are to: (1) enhance the development of analytical tools for ceramic component design utilizing the evolving ceramic properties data base; (2) establish improved processes for fabricating advanced ceramic components; (3) develop improved procedures for testing ceramic components; and (4) evaluate component reliability and durability in a gas turbine engine environment.

Ceramic technology applicable to the gas turbine engine will be developed and demonstrated through an iterative process involving design, fabrication, and testing of ceramic components in rigs and engines. ATTAP is being coordinated on an on-going basis with the Advanced Materials Development Project, which is pursuing basic ceramic materials research (see Section 3.3). ATTAP will reach a major milestone in December 1992 with a 300-hour AGT durability demonstration at temperatures approaching 2500°F.

Technology Status

The Federal combined urban/highway cycle fuel economy of a 3000 lb automobile powered by a 100 horsepower gas turbine incorporating structural ceramic components is projected to be 36 mpg of gasoline fuel, based on the efficiency goals established for the compressor, turbine, regenerator, and combustor. This is about 44 percent higher than the 25 mpg of an equivalent weight 1986 model year SI engine automobile operating on gasoline fuel (Oldsmobile Cutlass Ciera) and 10 percent higher than the 30 percent improvement goal of 32.5 mpg. Based on test data from the experimental turbine engines with the current generation of ceramic components, which limits the maximum temperature to 2200°F, vehicle mileage is predicted to be in the area of 32 mpg. Mileage will be improved to the 42 mpg goal using diesel fuel (or to 36 mpg using gasoline fuel) with the development of improved ceramic materials and fabrication processes under ATTAP. These fuel economies appear to be possible on a production scale by the late 1990's. Improved materials will allow operation at higher temperatures for improved efficiency, while improved component quality resulting from further fabrication process development will reduce leakage and clearance losses.

The focus of the FY 1990 effort continues to be on extending ceramic component technology to the 2500°F regime. The Advanced Turbine Technology Applications Project (ATTAP), which involves the engine manufacturers and the U.S. ceramics industry, was initiated to advance ceramic component technology from the current 2200°F level to the 2500°F regime. To establish the baseline state-of-the-art, about forty ceramic companies worldwide were surveyed. More than ten U.S. companies with the potential to provide components within the ATTAP schedule were identified.

Both Allison and Garrett have established development activities with the most promising domestic ceramic companies to develop 2500°F turbine engine components. While foreign ceramic technology was important in establishing baseline engine data at 2200°F, it is intended in ATTAP to focus on development of U.S. ceramic technology. The ceramic companies have identified laboratory materials with properties required for 2500°F operation. Material systems and fabrication processes must now be developed to provide reliable engine components.

In FY 1990, turbine design improvements were made to improve rotor survivability. The turbine motor remains the critical component because of its high temperature, high stress, geometric complexity, and susceptibility to impact damage. Engine test experience has shown the turbine rotor to be the component most susceptible to failure. A combined approach of design and materials properties improvements is being used to increase reliability. Allison is developing axial-flow type components including the turbine rotor, turbine vanes, and scroll structure. Garrett is developing radial-flow type turbine technology. In 1990, Garrett modified its turbine design to be more impact resistant. The Garrett modified radial rotor and the Allison axial rotor are shown in Figure 2 for comparison. Both Allison and Garrett have continued to evaluate and develop the test bed engines and rigs to increase high temperature reliability for the evaluation of the advanced structural ceramic components.

Structural ceramic component development activities are underway at Carborundum, the Corning Glass Works, the Garrett Ceramics Component Division, GTE Laboratories, and the Norton/TRW Company. Through their combined subcontracts, these five companies are working to develop all the critical ceramic components. Also, several emerging companies (including Ceramic Process Systems and Sullivan Mining Company), offering the potential for simplified materials processing for reduced cost, are participating on a limited basis.

During FY 1990, the ceramic companies have demonstrated improvements in their fabrication processes. They have shown significant strength increases in their as-fabricated (unmachined) components. The current generation of U.S. silicon nitride materials has demonstrated test bar properties that meet the design requirements of the

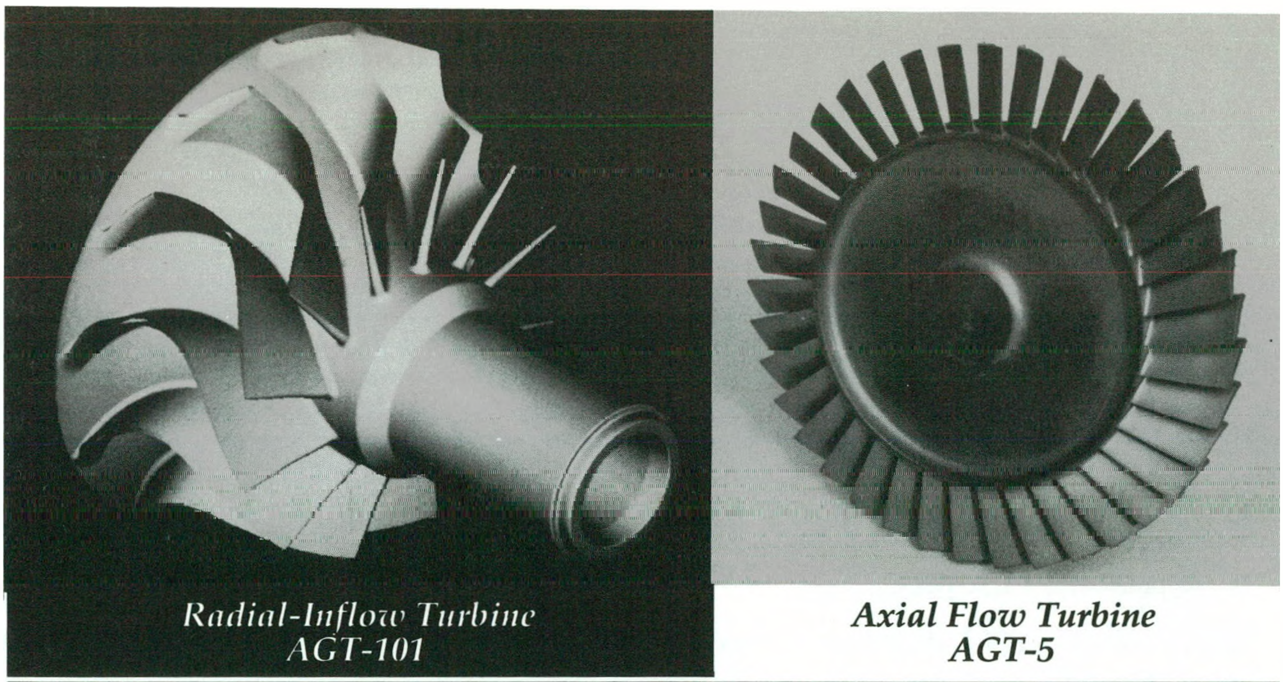


Figure 2. Radial and Axial Ceramic Turbine Rotors Designed for 2500°F Operation.

2500°F turbine engine components. U.S. ceramic companies continue to work toward fabricating engine quality components that have these test bar properties and also meet engine dimensional specification. In the fourth quarter of FY 1990, the first components to meet engine dimensional requirements — and with sufficient strength properties for rig testing — were fabricated by U.S. ceramic companies.

With the availability of these improved quality components, rig testing near 2500°F was initiated in late FY 1990. Initial testing has focused on the critical component, the turbine rotor, in a number of single component tests. The Allison team has successfully tested a ceramic axial tur–bine rotor above 2500°F in a hot turbine test rig which simulates engine operating conditions.

During the next year, as additional engine quality components are fabricated, planned testing will progress to include both rig and test-bed engine evaluation of the entire ceramic turbine section at 2500°F.

Environmental Considerations

Gas turbine engines using the technology developed in this project are expected to meet or surpass current and future Federal or State exhaust emission and noise standards.

Major Accomplishments

Major project accomplishments in FY 1990 are:

- Initiated hot rig testing above 2500°F in support of one of the project goals.
- Completed the design of Garrett's modified radial type turbine stage components based on improved 2500°F ceramic materials.
- Established ceramic component fabrication process parameters for the 2500°F materials systems.
- Fabricated initial ceramic components to be used for rig and test-bed engine evaluation.

3.3 Heavy Duty Transport Technology Project

Diesel engine propulsion dominates the heavy duty transport sector because of its low fuel consumption, high reliability, long service life, and commercial viability. While the diesel engine holds a considerable fuel economy advantage over other competitive engines, it also incorporates a very considerable potential for extending this advantage even further. The current diesel engine operates with relatively low temperatures and pressures and is fabricated for the most part with iron, steel, and aluminum alloys. Further fuel economy improvements are obtainable through the application of emerging technology such as the low-heat-rejection (LHR) diesel engine concept (which has evolved from the earlier "adiabatic" diesel engine), better exhaust gas utilization, advanced synthetic liquid lubrication, low friction and low wear materials, precision cooling of thermal critical areas allowing elimination of the engine block water cooling system, and computer control of the fuel introduction and air management, as well as optimizing the transmission gearing. All potential fuel reduction technologies must take into account compliance with EPA emissions regulations. The major challenge in managing emissions is the simultaneous reduction of particulates and NO_x since favorable adjustment of one type of emission tends to unfavorably affect the other.

The LHR diesel engine concept involves thermal insulation of the combustion chamber components, exhaust passages, and possibly the inlet air passage, as well as operation with higher lubricating oil sump temperatures. In principle, the LHR diesel engine is based on reducing the heat loss to the engine block water cooling system, thereby increasing the more readily used energy available in the exhaust gas and cooling only those areas of the engine that must be cooled. The in-cylinder efficiency with higher surface temperatures involves inadequately understood interactions of the fuel delivery system, combustion parameters, heat transfer, heat release rate, and cylinder pressure. The tribological performance, i.e., the combined effects of lubrication, friction, and wear of the moving parts, must be improved to cope with the higher operating temperature regime. LHR engine concepts require the use of advanced materials and lubrication to provide reliability and durability at temperatures considerably higher than those found in conventional engines. Material peak surface temperatures in excess of 2000°F (1093°C) are projected in some areas of the combustion chamber, while high-temperature liquid lubrication would be necessary to accommodate top ring reversal (TRR) temperatures as high as 932°F (500°C).

The key to success in this project is to integrate a series of small improvements into the developmental engine in an evolutionary manner. The development of materials and a high-temperature synthetic liquid lubricant that can provide adequate service life under the thermal and mechanical stresses encountered in high-temperature engine operation is considered fundamental to this objective. Ceramics (including ceramic coatings) for either insulation, improved thermal mechanical fatigue resistance or reduced friction and improved wear resistance, ceramic fiber or whisker reinforced metals or ceramics, and monolithic ceramics hold great potential for diesel engine applications. Cost, reliability, and availability are currently inhibiting factors in such material applications. In addition to these materials needs, high temperature combustion, including hot wall effects of LHR engine concepts, should be optimized for performance within emissions constraints. After-treatment schemes to reduce particulate and/or NO_x emissions may be necessary. The LHR engine concept also requires effective exhaust gas utilization.

Compliance with the simultaneous reduction of NO_x and particulates requirement of the 1994 EPA emission regulations for heavy duty vehicles is considerably more difficult and complex than previously anticipated. Operation of diesel engines on natural gas or methanol involves modifications for combustion effectiveness as well as materials changes to provide durability comparable to that obtained with conventional diesel fuel. Consequently, the Heavy Duty Transport Technology Program Plan is being modified to include work directed specifically at emission reduction and engine development to provide effective combustion and durability operating on natural gas and methanol fuels.

Technical Plan

The overall goal of the Heavy Duty Transport Technology Project is to assist U.S. diesel engine manufacturers in the development of engines which provide 30 percent better fuel consumption compared to 1982 production engines. The Department of Energy through contracts with industry has as a goal accelerating the development of engines with a specific fuel consumption of 0.25 lb/bhp-hr. The Project supports the technology development process through the proof-of-principle stage. The initial schedule for the sponsored R&D indicated a mid 1990's time frame for success. The introduction of very challenging Federal emissions constraints will delay accomplishment of Project goals by a few years. The Project consists of multi-faceted tasks in seven areas:

- Engine Component Development
- Combustion, Heat Transfer, and Emissions
- Lubrication, Friction, and Wear
- Exhaust Heat Utilization
- Integrated Propulsion Systems
- Emission Reduction
- Enhanced Alternative Fuel Operation.

The purpose of the Engine Component Development task is to develop the critical engine components for the LHR diesel engines. This effort will involve iterative single cylinder development testing and will culminate in multi-cylinder engine performance testing. The intent is to develop and validate the technology necessary for the critical hot-section engine components, including pistons, cylinders, heads, piston rings, seals, bearings, valves, cylinder liners, and insulation for LHR engine operating conditions.

The Combustion, Heat Transfer, and Emissions task objective is to determine the interrelationships of combustion, engine design, and emissions as a function of temperature and operating conditions representing LHR engine analytical predictions. This task also includes after-treatment methods of compliance with the 1991 and 1994 EPA emissions standards.

The Lubrication, Friction, and Wear task includes development of a liquid lubricant capable of sustained operation with TRR temperatures of up to 932°F (500°C). Synthetic liquid lubricants will probably be necessary for diesel engines to meet particulate emissions standards. Fuel hydrocarbons are absorbed by petroleum-base lubricants to a much greater extent than they are by most synthetic oils. It has been recently established that particulates emitted from diesel engines consist of carbon (in the form of soot) which has absorbed a range of hydrocarbons. Approximately five times as many of the absorbed hydrocarbons are derived from unburned lubricating oil as are traceable to unburned fuel. A synthetic liquid lubricant is being developed with an additive pack that will provide all the functions necessary for an upper cylinder lubricant without decomposing to the detrimental ashes typical of conventional liquid lubricants. This latter feature should improve engine life and extend oil drain intervals. Another benefit of some synthetic lubricating oils is a much lower oil consumption rate than current lube oils under similar conditions. Switching to synthetic liquid lubricants by the heavy duty truck community could reduce petroleum use by 1 percent in the heavy duty sector.

The Exhaust Heat Utilization task involves the evaluation and development of cost-effective means of LHR engine exhaust gas energy utilization.

The largest improvement in diesel engine fuel economy by the mid 1990's will be obtainable through advanced turbomachinery. The aerodynamic efficiency of turbocharger turbines and compressors could be improved such that at least a 5 percent improvement in fuel usage could be achieved. Further advances could be obtained by using ceramic fiber reinforced metal or ceramic rotors, advanced bearings, and new technology for the duct work and enclosure. Since the reciprocator requires air as a linear function of power output, and the turbocharger output is exponential, there are matching problems. Variable geometry turbocharging can provide a better turbocharger match to the reciprocator for operating profiles over the full range of power levels. Variable geometry turbocharging has demonstrated significant emissions reductions during transient operation.

The addition of a power turbine in the exhaust path which is mechanically coupled to the engine output shaft through a viscous coupling is referred to as "turbocompounding." Most of the major diesel engine manufacturers have already completed preliminary designs for integration of turbocompounding into their production engines. Integrating turbocompounding with advanced turbochargers would result in further fuel savings. Thermoelectric devices convert exhaust gas energy directly to electricity. Major reduction in thermoelectric device costs through advanced mass production techniques might produce a cost-effective replacement for the alternator which could provide up to a 4 percent fuel savings. Current thermoelectric devices are made in batch lots by "cottage industry" methods.

The Integrated Propulsion Systems task involves using computer control to optimize engine parameters and transmission shifting. The engine design could be optimized for this operational system, thereby eliminating some propulsion system inefficiencies. This approach has been projected to double tank mileage in medium-size heavy duty trucks.

Technology Status

During FY 1990, the Project through contracts with industry continued to support research accelerating development of the technology necessary for more fuel-efficient and emission standard compliant diesel engines for transportation applications. The initial emphasis is focused on low-heat-rejection (LHR) diesel engine concepts for heavy duty truck applications. Planning has begun to extend this technology to railroad and inland marine diesel engines as well as to smaller diesels for lighter weight trucks.

The primary areas of development include: the piston-ring pack/cylinder-liner interface, including lubrication development; engineering thick thermal barrier coatings to diesel components; insulated engine combustion, heat transfer, and emissions investigations; reduced friction and extended wear at ceramic valve train wear points; and cost-effective waste heat utilization. A major challenge to the development of the LHR diesel engine is accommodation of the higher thermal excursions and related stresses encountered in the combustion chamber. These elevated temperatures present particularly difficult tribological problems at the piston-ring/cylinder-liner interface, where the operating limits of current materials and lubricants are exceeded.

The Project relies on the development of materials and tribology for advanced diesel engines conducted by the Oak Ridge National Laboratory and the Argonne National Laboratory for the Office of Transportation Technologies (see Section 3.3). Materials development supported by other agencies and the private sector is also reviewed for potential relevance to diesel engines. The Project screens promising candidate materials for engine applications and for designing components using these materials. Ceramic thermal barrier coatings are already being used in limited production.

The major redirection of the LHR engine concept is the move to high temperature liquid lubrication that has been stimulated by major strides made recently in the field of synthetic liquid lubrication. Interest in synthetic liquid lubricants has also arisen because a major fraction of diesel particulate emissions emanate from petroleum-base lubricating oils and testing indicates dramatically lower oil consumption rates with some synthetic oils. The viability of high temperature liquid lubrication has been supported by two single-cylinder engine tests which were conducted for a total of 450 hours with top ring reversal temperatures of up to 850°F. Virtually no ash deposits were formed during these tests. Successful development of a high temperature liquid lubricant will permit engine designs with dramatic reduction, or even elimination, of the engine-block water cooling system and the associated parasitic losses of the water pump, fan, and piping (see Figure 3).

The development of ceramic thermal insulation coating systems for minimal heat rejection and metal protection of in-cylinder components is continuing, with emphasis on plasma sprayed zirconia thermal barrier coatings. Two parallel contracts have been competitively awarded to the Cummins Engine Company and the Caterpillar Tractor Company with the objective of engineering low thermal conductivity, relatively thick zirconia coatings to combustion chamber components. Both companies are adapting plasma spray coating technology developed for aircraft gas turbine applications. United Technologies, who pioneered this technology, is under subcontract to Cummins to engineer the thick thermal barrier coatings to the diesel engine piston crown, exhaust valves, and cylinder head or fire deck. Caterpillar is using similar technology from its Solar Turbines Division. These contracts have been amended to include coating surface sealing for emissions considerations, emissions measurements, and extension of the engine testing by 200 hours to 300 hours.

Fuel injectors and fuel nozzles for the LHR diesel engine are required to finely atomize the fuel and inject it into the cylinder at higher pressures than current injectors, such that the fuel is introduced precisely to meet engine temperature, power demand, and emission needs.

The Detroit Diesel Corporation has developed a single cylinder test engine for the LHR concept which features advanced electrohydraulic fuel injection and electrohydraulic valve actuation (cam-free valve actuation based on electronic control of solenoids). This engine features ceramic valves, valve guides, and fire deck, as well as a ceramic air gap exhaust port. Advanced wear coatings are used on rings and valve stems. This advanced concept

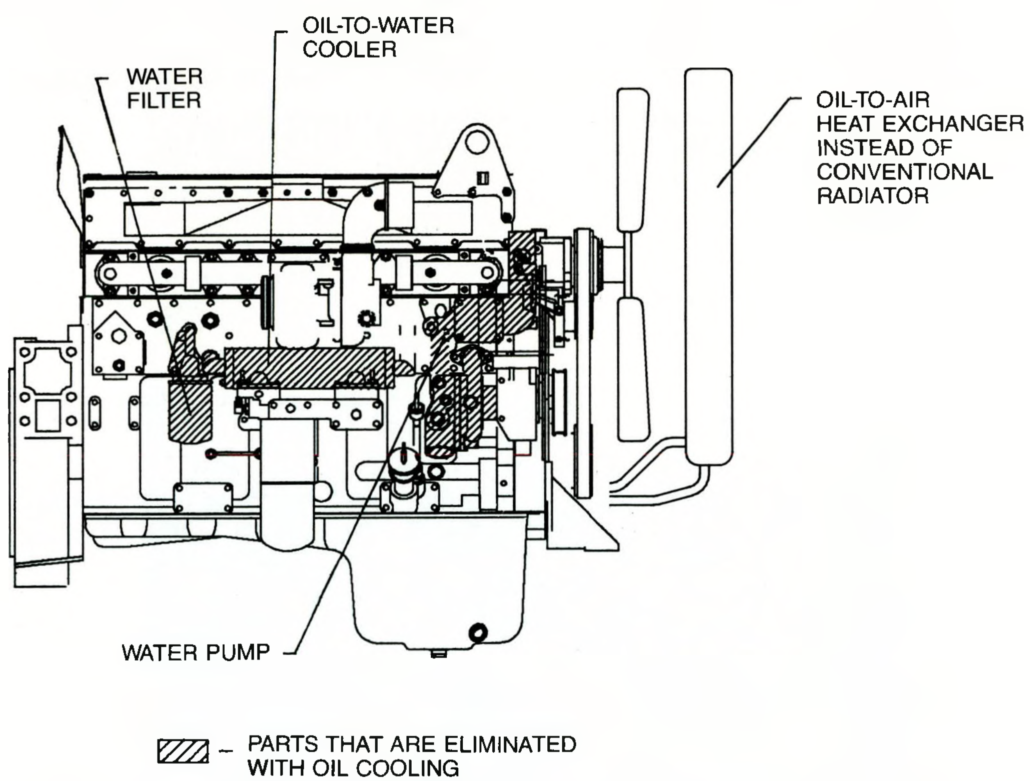


Figure 3. Engine Concept Using One Fluid for Lubrication and Cooling as Adopted by Caterpillar and Cummins.

uses a hybrid lubrication scheme, which includes a conventional liquid-lubricated piston with an extended cap and a headland ring which is lubricated with a vapor-phase lubricant, tricresol phosphate. Test results with this advanced concept are being evaluated.

The major work in the program is the in-cylinder components development at Caterpillar and Cummins. Phase I of these contracts involved engine designs with cycle analysis which achieve the program fuel consumption goal for production engines in the year 2000. Both designs involve elimination of the engine block water cooling system. One liquid will be used for both lubrication and cooling, and this will be a synthetic liquid lubricant. Turbocompounding, which consists of a power turbine added in the exhaust gas path after the turbocharger and connected through a viscous coupling to the engine output shaft, will be used. A cutaway of a turbo-compound system added after the turbocharger on a Caterpillar engine is shown in Figure 4. Advanced fuel injection systems with electronic control and peak cylinder pressures about 50 percent higher than those in current engines will be used.

Although both companies chose the same external configuration for truck installation, Caterpillar chose a 7 liter (7L) displacement design; Cummins chose a 10L configuration. Caterpillar is developing an articulated piston with an aluminum skirt and a steel crown connected with a wrist pin. Cummins is developing a spherical joint piston which has a much larger bearing area and is symmetrically loaded. The spherical seat piston has a uniform temperature distribution and will have a symmetrical thermal growth. Both pistons are expected to extend operating capabilities beyond current piston limitations in heavy duty engine designs. A cross-section of the new spherical seat piston is shown along with a conventional piston for comparison in Figure 5. Both companies are looking at ring pack designs which will operate at higher temperatures with minimal oil consumption and wear. The new synthetic liquid lubricants will allow the top ring location near the piston headland which reduces emissions. The In-Cylinder Components Development Program is now in the Phase II engine rig test work. Traditional iterative fabrication, test, analyses, and redesign is anticipated to effectively integrate components into the desired fuel-efficient and emission-compliant engine. Validation of emissions and performance data will require multi-cylinder engine testing.

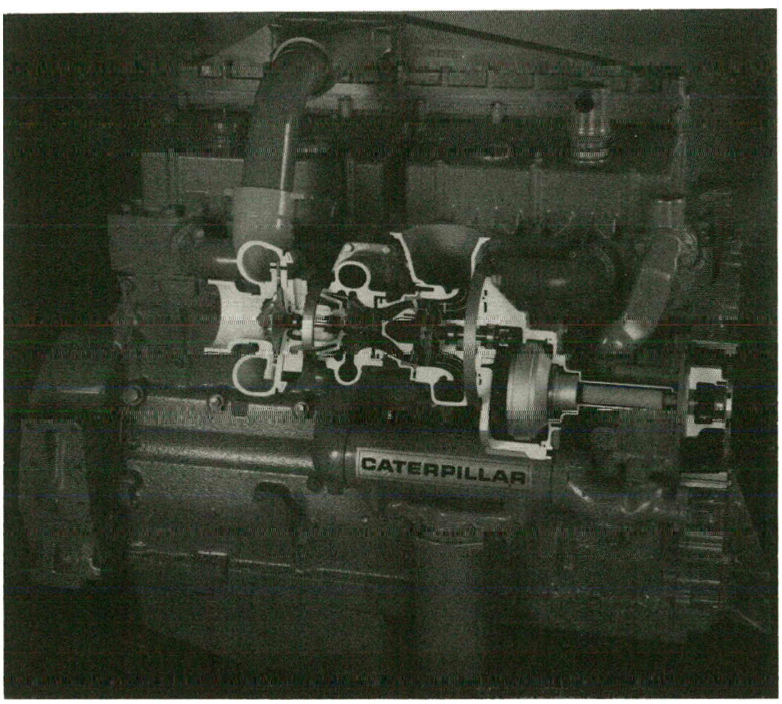


Figure 4. Cutaway of Turbocharger and Turbocompound System on Caterpillar Diesel Engine.

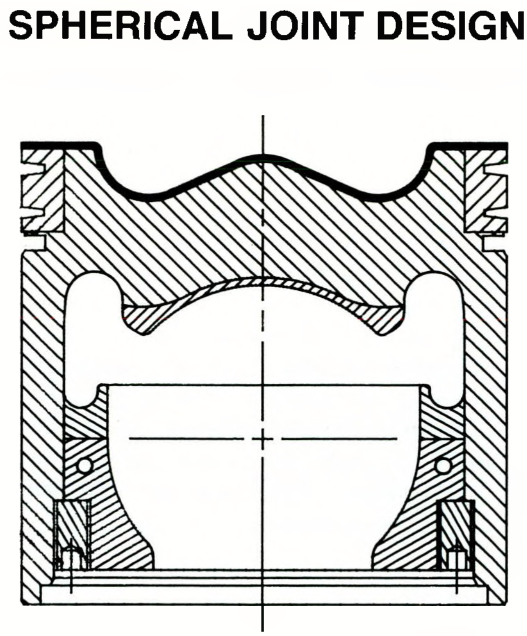
Environmental Considerations

Increasingly stringent EPA emissions regulations have been imposed on heavy duty transport diesel engines since the program's inception. The simultaneous attainment of 1994 NO_x and particulate emissions levels with production engine variances is a very difficult challenge. Project contracts with the engine manufacturers are being modified to include particulate-trap oxidizers, advanced fuel injection systems with rate shaping of injection and electronic control, and variable geometry turbocharging .

Recent work has indicated that 25 percent of particulate emissions is attributable to unburned oil and a significant fraction of the carbon measured as particulates comes from burned oil. Considerable work is underway to reduce oil consumption and particulate emissions. Development of an advanced ring pack computer model is being supported as well as contracted work in ring pack design to obtain adequate in-cylinder lubrication with minimal oil consumption. The High Temperature Liquid Lubricant Program is being modified to include emissions reductions achievable with synthetic liquid lubricants which can reduce oil consumption by 50 percent.

Global warming is caused by the build-up of many atmospheric gases which absorb and reflect infrared radiation from the earth's surface that would otherwise be radiated to deep space. This is referred to as the "greenhouse effect." The major contributor appears to be CO_2. Fossil fuel consumption worldwide generates roughly 10^9 metric tons of CO_2 per year. Roughly 10 percent of this worldwide CO_2 generation is attributable to highway vehicles and 20 percent of the highway vehicle generated CO_2 comes from the U.S. The heavy duty truck sector in the U.S. is responsible for roughly 1/4 of the highway vehicle emitted CO_2, or 0.5 percent of worldwide fossil fuel generated CO_2. The CO_2 output of diesel engines operating on fossil fuels is strongly related to the engine's fuel efficiency. Since the diesel engine is the most fuel-efficient engine by a significant margin, the amount of CO_2 generated for commercial transportation is relatively low. The program to further improve fuel economy will proportionately reduce CO_2 emissions.

An after-treatment scheme invented by Dr. Robert Perry at the Sandia National Laboratory is showing excellent NO_x reduction. This system, called RAPRENOX, involves metering HCNO gas, which is formed by heating cyanuric acid pellets, into the engine exhaust. A 96 percent reduction of NO_x in the exhaust from a 4-cylinder diesel engine has been demonstrated under steady state



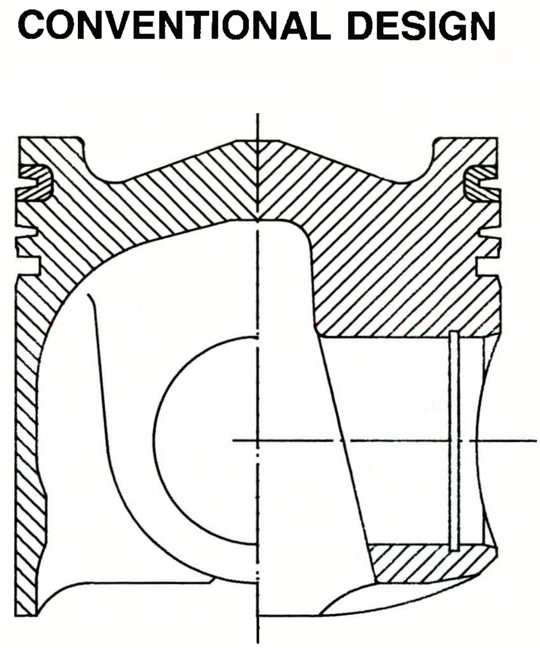


Figure 5. Comparison of Spherical Joint and Conventional Piston Design.

conditions. The project involves development and test of an under-the-hood delivery system that can accommodate engine transients and work effectively for 270,000 miles. Development of a liquid to replace the pellets is being done in parallel. If RAPRENOX is adopted, engine optimization to reduce particulate formation could be done effectively while improving fuel economy.

Major Project Accomplishments

Major project accomplishments in FY 1990 are:

- Continued engine testing of the Detroit Diesel Corporation (DDC) concept reference LHR single cylinder test engine with a hybrid liquid and gas phase lubrication scheme. This DDC reference engine includes an electrohydraulic fuel injector, ceramic valves and exhaust port liners, and an electrohydraulic valve actuation system enabling variable valve events.

- Completed the evaluation of a low ash, high temperature liquid lubricant in both single cylinder and multi-cylinder engine tests.

- Completed the design phase and began the hardware test phase with Caterpillar and Cummins in the development of in-cylinder components and applied tribology for their respective LHR engine concept.

- Continued thick thermal barrier coating development for diesel hot section components, modified the work to encompass coating surface sealing, extended the test period by 200 hours, and included emissions measurements.

- Continued a joint effort with the Advanced Materials Tribology program at the University of Michigan to analyze friction and wear in the valve train of a Cummins L-10 diesel engine using candidate ceramic wear points and using both conventional and synthetic lubricating oils. In-situ measuring equipment has been designed, installed, and calibrated. Testing began in October.

- Completed an evaluation of chemical filter materials to control engine lubricant acidity when using ashless lubricants.

- Completed a computational fluid mechanics (CFD) computer study on the effects combustion flames have on boundary layer heat transfer in a diesel engine combustion chamber.

3.3 Advanced Materials Development Project

The timely availability of advanced structural ceramics is required to attain the OTT advanced gas turbine and low-heat-rejection diesel engine development goals. In part, this requirement stems from the inability of available metal alloys to maintain their structural integrity at the high component operating temperatures needed to achieve high thermodynamic efficiencies in turbine engines. In addition, the high cost and limited availability of metal alloys commonly used in high-temperature environments preclude their widespread use in automotive applications.

The promising candidate materials for use in the high temperature regions of advanced automotive heat engines are silicon carbide, silicon nitride, and oxide ceramics. Although specific monolithic and composite formulations of these ceramics meet many of the critical property requirements needed for application in heat engines, other properties and characteristics require improvement. Decreased material brittleness, increased fracture toughness, and increased oxidation resistance, all of which have a major impact on component reliability are especially important. These and other properties influencing reliability are determined by a large number of processing, fabrication, and environmental variables affecting the material microstructure. Furthermore, understanding of the interrelationships among these variables is meager in terms of their impact on material properties. Thus, a critical need exists for well-organized, extensive, generic R&D in the areas of ceramic starting powders, fabrication and densification processes, mechanical characterization, life prediction, and nondestructive evaluation of materials. The Advanced Materials Development Project addresses these needs.

Technical Plan

The overall goal of the Advanced Materials Development Project is to provide the technology base required for the manufacture of reliable and cost-effective ceramic components for advanced automotive heat engines. Project focus is on the development of structural ceramic technology for the key hot section components of advanced engines, ceramic bearings, attachment methods, and ceramic coatings for thermal barrier and wear applications.

Efforts are closely coordinated with complementary ceramic efforts funded by other DOE offices, NASA, the Department of Defense, and industry. The Project consists of the following major technical elements:

- Materials and Processing
- Material Design Methodology
- Data Base/Life Prediction
- Technology Transfer.

The Materials and Processing element is concerned with the development of processes for the synthesis of improved, high purity, uniformly sinterable silicon carbide and silicon nitride powders, and for the fabrication of these into near net shape monolithic components with improved high temperature mechanical properties and corrosion resistance. In addition, this element focuses on improving the fracture toughness of silicon carbide and silicon nitride by developing dispersion toughened and short fiber reinforced composites. Other areas addressed are the development of oxide matrix composites, thermal and wear coatings, and material joining technology.

The Material Design Methodology element is concerned with the development of technology important to modeling of the quantitative characterization of material property changes that occur at ceramic to ceramic and ceramic to metal alloy interfaces at elevated temperatures. Property changes at both static and dynamic interfaces are examined. Specific areas of study address interfacial reactions and the effects of friction, environment, time, and stress on material properties under simulated conditions of a low-heat-rejection diesel and contact stress conditions expected in a ceramic gas turbine. Also, improved models of strength in structural ceramics are being developed to allow accurate prediction of component survival probability based on the measured strength of material samples.

The Data Base/Life Prediction element is aimed at characterizing the time-dependent, high temperature strength and toughness of state-of-the-art ceramics, and at developing cost-effective, quantitative nondestructive evaluation (NDE) technology. In the characterization work, emphasis is placed on understanding the effects of time-dependent and environmental parameters and the role of microstructure in material strength and fracture toughness. In the area of NDE, appropriate technology is being developed to support the fabrication of reliable ceramics by inspection of starting powders, green state ceramics, and finished components.

The Technology Transfer element is aimed at transferring the technology developed by the Advanced Materials Development Project to U.S. industry. The primary approach is based on extensive involvement of private industry in the: (1) planning and implementation of Project tasks; (2) assessment and coordination of task activities; and (3) conduct of technical work under government contracts. These primary transfer mechanisms are aided by distribution of technical reports and newsletters to U.S. industry, exchange of industry and government technical personnel, and conduct of technical meetings and workshops addressing specific areas of activity. International cooperation in the development of material standards for structural ceramics is encouraged through U.S. government and industry participation in an agreement to exchange selected technical information with participating laboratories in West Germany and Sweden.

Technology Status

The Advanced Materials Development Project is in the midst of three-year major efforts by the Norton Company and GTE to develop and demonstrate significant improvements in processing methods, process controls, and in-process nondestructive evaluation which can be commercially implemented to produce high reliability Si_3N_4 components for advanced heat engine applications at temperatures to 2500°C. The critical issue in the development of reliable ceramics is processing the materials in a manner that will not introduce strength limiting flaws. Overall reliability will be achieved through process control (NDE and characterization), and development of cause-effect relationships following factorial experimental design and innovative process improvements.

Norton has established tensile strength and Weibull modulus data from testing injection molded and colloidally consolidated tensile bars and will select a preferred forming technique early in 1991 for the remainder of the program. Additionally, various NDE (non-destructive evaluation) techniques were developed for in-process monitoring of suspensions and green and densified samples, and their flaw detection capabilities were established. These improvements are being made to the NT-154 composition (nominally 96 percent Si_3N_4 and 4 percent yttria), being used to make turbine rotors and other components for ATTAP, as well as turbine blades and stator blades for several developmental aircraft engines.

The GTE PY6 silicon nitride composition used for ATTAP is the basis for processing improvements. The adoption of a "wet processing" approach for powders and material compounding along with the use of new molding equipment has significantly minimized contaminant flaws. Furthermore, in work at England's Cranford Research Center, improved mold design and mold fill technology are reducing flaws during complex shape fabrication. The critical binder removal process step is being improved to control the component green microstructure and prevent void formation associated with binder evolution.

Microwave processing of Si_3N_4 at ORNL involves both microstructure development by microwave annealing of commercially produced silicon nitride ceramic, and sintering of Si_3N_4 from ceramic powder. The sintering R&D includes sintered Si_3N_4 powder and sintered reaction-bonded silicon nitride (SRBSN/RBSN). Sintering experiments are done in a 28 Gigahertz (GHz) microwave furnace and several much less costly furnaces, which are based on the 2.45 GHz microwave energy used for home ovens. The SRBSN process retains the traditional RBSN advantages of low cost raw materials and ease of fabrication of complex shapes; the silicon metal powder works well using the 2.45 GHz furnace. SRBSN is achieved using a two-step process: react silicon metal powder and nitrogen to RBSN, and then sinter to SRBSN at higher temperatures (above 1400°C) where silicon nitride reacts well with the microwave field. Initial results are promising. Further efforts are directed at scale-up of the size of the specimens which can be sintered, and at reducing the quantity of sintering aids required to fully densify the ceramic. Development continues on the gelcasting processing at ORNL and, beginning this year, through a collaborative agreement with an industrial ceramic company (see Figure 6). Garrett Ceramic Components Division has provided their GN-10 material for gelcasting into simple, and then complex, net-shape components. Garrett will densify the formed pieces by hot isostatic pressing (HIP), and then both ORNL and Garrett will characterize and evaluate the results. Gelcasting is distinguished from slip casting, used by Garrett and others, by the inclusion of a polymerizable component which gels the slurry in the liquid phase. Under the program, ORNL has developed a mold and casting system and a drying and debinding procedure for green bodies, which are then sintered. The initial development was done on alumina ceramics but, with the acquisition of higher temperature processing equipment, work has also proceeded on aqueous gelcasting systems for silicon nitride.

Ceramic powder synthesis research in the program by Ford Motor Company for silicon nitride, by Carborundum for silicon carbide, and by Norton Company for oxide ceramics have all been completed. Two companies have made proposals to Ford to license its patent and technology for eventual commercial production of silicon-nitride powder in the U.S. The Carborundum effort to produce SiC powder by plasma synthesis was generally successful, but was deemed not commercially feasible. The National Institute for Standards and Technology (NIST) is conducting attrition powder milling experiments with commercially available equipment and is characterizing silicon nitride powders.

The Norton Company improved powders were developed as part of a successful larger effort to produce transformation-toughened zirconia (ZrO_2) and zirconia-toughened alumina (Al_2O_3) ceramics. Norton has commercialized these ceramics for wear, die-forming, and cutting applications. Its zirconia is one of the strongest ceramics available. In early 1990, the mechanical properties of the two materials developed — Y-TZP (yttria stabilized tetragonal zirconia polycrystals) and Ceria (cerium oxide) — were characterized and the processing of the materials was optimized with respect to mechanical properties. These include room temperature and high temperature strength and toughness, and low temperature (200 to 300°C) stability. The result of this effort was to optimize transformation-toughened ceramics for use in advanced diesel engines (see Figure 7).

Another successful development of transformation-toughened oxide ceramics was made by Ceramatec, Inc. Ceramatec produces layered oxide ceramic composites which incorporate zirconia or hafnia as a second phase to

Figure 6. Development of Gelcasting Technology for Forming Complex Shapes of Silicon Nitride and Other Structural Ceramics.

achieve improved strength and toughness at temperatures up to 1000°C. Slip casting methods were developed to produce three-layered composites with strengths in excess of 1200 megapascals (1200 MPa) at room temperature, and 800 MPa at 1000°C. Strengthening is a result of incorporating transformation-toughened residual stresses in sintered surface layers. It has fabricated automotive cam-roller prototypes with this method for evaluation.

Whisker-toughened composite development over the last year by industrial contractors, universities, and the ORNL has generally all been successfully completed. Past emphasis has been on silicon nitride matrix composites for advanced turbine engines. The result gained was a 30 percent improvement in strength and a 50 percent increase in toughness over a comparable monolithic silicon nitride. This result was far from the earlier success with alumina matrix whisker-toughened composites where the strength and toughness were essentially twice that of monolithic alumina. During the year, efforts to produce this microstructure were increased at ORNL and the University of Michigan. Garrett Ceramic Components Division has produced Si_3N_4 with substantially higher fracture toughness. The lessons learned from optimizing the whisker-toughened ceramics are now being used to improve and scale up the in situ toughened silicon nitride.

There are three coating development contracts in progress. A planned fourth coating project is in the RFP preparation stage for a competitive procurement. GTE Laboratories is using graded chemical vapor deposition (CVD) methods to develop adherent ceramic coatings to reduce contact stress damage of ceramic components. The coatings for silicon based ceramics are required to be oxidation-resistant and have high strength and toughness for use in an AGT engine. The project has succeeded in developing a very adherent coating of graded aluminum nitride (AlN) and dispersion-toughened alumina (DTA) on silicon nitride and silicon carbide. Oxidation resistance at 1200°C is the only contract goal that remains to be met. Work is continuing on the evaluation of the deposition parameters to increase the oxidation resistance of the coating. A new CVD reactor was built to allow coatings to be deposited at higher temperatures. Testing is underway to determine the effectiveness of the contract stress coating in protecting the substrate from salt corrosion. A companion project at ORNL — which is testing beta alumina as a protective coating for salt corrosion — provides an alternative approach.

Both Caterpillar, Inc. and Cummins Engine Company are developing wear-resistant coatings for application to in-cylinder metallic components for LHR diesel engines. These wear-resistant coatings will be applied and then characterized in terms of physical and mechanical properties. The coatings will be evaluated in screening tests by the contractors prior to their submitting samples to Battelle Columbus for evaluation. The wear-resistant coatings technology will be transferred to the Heavy Duty Transport Technology (HDTT) Program. Caterpillar is fabricating coatings by plasma spraying and CVD. Three plasma spray and two CVD coatings have shown promise in screening tests. Work continues to improve the coating techniques. Robotic techniques coupled with the plasma spraying are being developed to generate reproducible coatings under computer control. Cummins is investigating coatings prepared by plasma spraying, slurry spraying, and ion-nitriding processes. APS Materials, United Technology Research Center (UTRC), and Boyd Machine are working with Cummins on the plasma spraying process. Three families of materials have shown promise in screening tests: chromium-based, tungsten carbide based, and cobalt materials. Slurry spraying is being used to prepare silica-chromia-alumina (SCA) coatings using room temperature slurry spraying followed by low temperature heat treatment.

Thermal barrier coatings (TBCs) are of interest for use on the LHR diesel engine to reduce thermal losses and to protect metallic components from high temperatures. TBCs are required to withstand high temperatures and corrosive environments under cyclic conditions where thermal and mechanical stresses through the coatings can lead to premature failure. In recognition of the demands placed on TBCs, industry input was formally solicited in FY 1990 to determine the need for TBC technology development for LHR diesel engine applications and to formulate an RFP as a step toward a competitive procurement for the development needed.

Three industry contracts for the joining of ceramics are in progress. The contracts, which emphasize generic shapes and analytical modeling, are for different attachment classifications: Norton Company for non-oxide to non-oxide ceramics, GTE

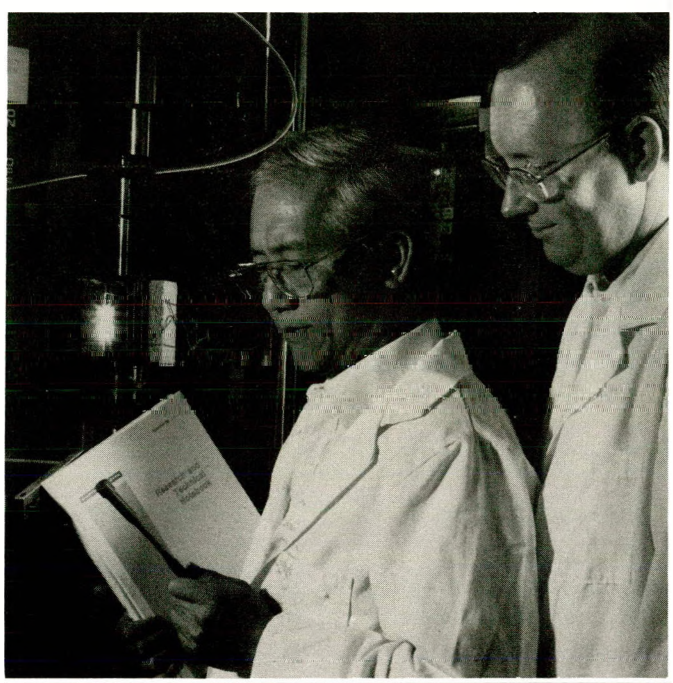


Figure 7. Determining High Temperature Mechanical Properties of Silicon Nitride Using Button-Head Specimens.

Laboratories for non-oxide ceramics to metal, and Battelle Columbus Laboratories for oxide to oxide ceramics and metal. Norton is developing techniques for producing reliable SiC-SiC and Si_3N_4-Si_3N_4 ceramic joints and analytical modeling to predict the performance of the joints under a range of loading conditions, environments, and temperatures. The Si_3N_4 joints are based on the ASEA hot isostatic press process and the SiC joints on co-sintering of green parts. Successful joints have been prepared and characterized for both types. Analytical modeling is in progress and on schedule.

GTE Laboratories is developing technology to join structural ceramics — such as Si_3N_4 and SiC rotors — to metal shafts, with emphasis on the development of understanding and techniques needed for design of joints. A method was previously established to relate finite element analysis prediction of joint geometry to test results. A need was demonstrated for new braze alloys and interlayer materials to meet high temperature strength requirements. Work is concentrating on stress analysis of a braze joint with two intermediate layers and on modifying its analytical expressions to account for the interlayer and other geometrical variations.

Battelle is developing the technology for more efficient, cost-effective, and more general joint design procedure. Analytical models based on stress analysis and fracture mechanics are being formulated. Joints between PZT and PZT (partially stabilized zirconia) and between PZT and nodular iron were successfully demonstrated. The Battelle models are undergoing continual refinement as more data becomes available.

An ORNL in-house companion project for developing technology for strong reliable joints is focused on joining PZT to nodular cast iron, and on joining ceramics such as silicon nitride and silicon carbide.

Technology from the industrial contracts and the ORNL effort continues to be transferred to the ATTAP and the HDTT programs as progress is made to increase the reliability of joined subassemblies in the engine test beds.

There are three active contracts in materials design methodology covering: (1) three-dimensional modeling by the University of Tennessee, (2) contact interfaces by Battelle Columbus, and (3) new concepts by the General Electric R&D Center. Overall concentration is on determining analytical techniques for predicting structural ceramic mechanical behavior from mechanical properties and microstructure, tribological behavior at high temperatures, and improved methods for describing the fracture statistics of structural ceramics. The subsequent results will assist U.S. companies to optimize mechanical properties through microstructural control, to predict and minimize interfacial friction and bonding, and to develop a properly descriptive statistical database for structural ceramics. The University of Tennessee is developing three-dimensional mathematical modeling for crack fracture with realistic geometry. Experiments for verification of the model are continuing. Battelle Columbus is using a unique test rig to study friction and wear behavior of selected materials in low heat rejection diesel environment. The performance of advanced wear-resistant coatings, ceramic composites, and newly developed lubricants is being determined, which will ultimately improve wear coatings and lubricants for long-term operation at 1112°C. The statistical tools developed by General Electric are being incorporated into the NASA CARES finite element brittle design code and are freely available.

The database and life prediction task focuses on the understanding and the predictive models for structural ceramic mechanical reliability, measurement techniques for determining long-term mechanical property behavior in structural ceramics, and physical understanding of the time-dependent mechanical failure. Five tasks are being investigated: (1) structural qualification, (2) time- dependent behavior, (3) environmental effects, (4) fracture mechanics, and (5) nondestructive evaluation.

This is a coordinated effort among many researchers and is coordinated with activities in the ATTAP and the HDTT programs.

The ORNL continues to build and maintain a comprehensive computer database containing the experimental structural and other data properties of ceramic materials generated in the program. This is a personal computer-oriented system intended to provide a convenient and efficient mechanism for the compilation and dissemination of the large amount of unique data involved.

Two major three-year life prediction contracts with Allison Gas Turbine Division and Garrett Auxiliary Power Division are underway. The efforts include tasks in materials selection, database and design methodology development and application of nondestructive examination, and confirmatory testing. The first generation life prediction models and data requirements were completed in FY 1990. A variety of test items (for example, flexural and tensile specimens, spin discs) are being prepared by GTE (PY6 silicon nitride) for evaluation by Allison, and by Norton (NT-154 silicon nitride) for evaluation by Garrett.

A significant effort in uniaxial tensile testing of ceramics was started in FY 1984. It encompasses work at ORNL on cyclic fatigue, at North Carolina A&T University on high temperature fast fracture, and at NIST on fracture creep. A tensile testing effort in the International Energy Agency (IEA) cooperative study was initiated in FY 1990. At ORNL, the effects of surface finish and grinding damage on tensile strength are being investigated because the introduction or removal of surface flaws on the test specimen can affect the tensile strength greatly.

A companion effort at ORNL to generate high temperature mechanical properties data on candidate gas turbine ceramic rotor materials continues to be coordinated with the NASA gas turbine project managers, the ATTAP contractors, and leading ceramic suppliers. Results of creep rupture and tensile testing of silicon nitride were reported. The present multilaboratory experiments (GTE Labs, NIST, NC State, and ORNL) to characterize the creep behavior of whisker-toughened silicon nitride were initiated in FY 1989 and are still in progress.

An effort initiated at the NASA Lewis Research Center on toughened ceramics life prediction was continued with stress rupture and creep testing. The research is aimed at determining the room temperature and high temperature behavior of toughened ceramics, especially SIC whisker-toughened silicon nitride, as a basis for developing a life prediction methodology.

The fracture behavior of toughened ceramics is being investigated at ORNL. This work has provided fundamental insight into the processes responsible for toughness and time-dependent strength degradation of zirconia (PZT) and dispersion-toughened and whisker-reinforced oxides and nitrides. Particular attention focuses on the effects of environment, temperature, and compositional and microstructural characteristics upon these mechanisms.

The environmental degradation processes operative in toughened ceramics were determined by the University of Dayton. A large body of data, useful for engine design, was produced during the contract. A follow-on contract for investigating environmental effects on candidate silicon nitride and silicon carbide ceramics is on-going.

A test facility has been established at ORNL to allow samples of ceramic materials and metal-ceramic joints to be exposed to the diesel combustion environment in a single cylinder engine. Exposure studies and analysis of candidate materials and joints were conducted in FY 1990.

The detection and measurement of microscopic flaws and the nondestructive determination of selected physical and mechanical properties in structural ceramics (e.g., density, elastic properties, fracture toughness) are critical to improving and controlling material reliability for highly stressed applications — such as those found in advanced heat engines. A FY 1986 industry assessment of nondestructive evaluation and material characterization needs and priorities established guidelines for a majority of this present work.

ORNL supports an on-going effort in materials characterization and flaw detection through ultrasonic inspection. A state-of-the-art microfocus x-ray tomography system (developed by the firm of Scientific Measurements) is used to examine components from ATTAP and the HDTT program.

An investigation on nuclear magnetic resonance (NMR) inspection of green ceramics was begun by Argonne National Laboratory in FY 1987 continued in FY 1990. This work will determine the feasibility of using proton NMR imagining systems to measure the distribution of organic binder/ plasticizer systems in various stages of the injection molding processes used to form silicon nitride components. The NMR characterization of injection molded green ceramics, provided by Garrett Ceramic Components, was undertaken.

Research in special topics on ceramic powder characterization was initiated in FY 1989; work continues at Pennsylvania State University, the University of Wisconsin, and Rutgers University. ORNL is coordinating the contracts, which involve spectroscopic characterization, surface adsorption, and thermodynamics of surfaces.

Support for the IEA agreement with West Germany and Sweden on Ceramics for Advanced Engines and other Conservation Applications was continued in FY 1990. Japan formally entered the agreement.

High Temperature Materials Laboratory

The High Temperature Materials Laboratory (HTML) at Oak Ridge, Tennessee, supports Government and industry efforts as both a research and a user facility. As a DOE user facility, the HTML provides a unique capability for high temperature materials research which (1) makes available a broad, multidisciplinary professional staff, (2) provides a common focal point for industry, university, and government participation, (3) provides access to high-cost research equipment which would otherwise be denied many researchers. Direct cost sharing is not required by industry and university users unless the work is proprietary. Results of nonproprietary research are made available to the scientific and industrial communities.

The HTML user facility is comprised of four original and two new user centers. The four original centers are used for materials analysis, mechanical properties, x-ray diffraction, and physical properties. The two new designated user centers being installed are for ceramic specimen preparation and residual stress research. They are expected to become fully functional at a later date when the required state-of-the-art research instruments are acquired. The centers are used by industry, university, and government researchers to help solve high temperature structural ceramics and other materials problems. The HTML is also used to support the Advanced Materials Development Program and, indirectly, the ATTAP and HDTT programs. Since the user program began in 1987, 100 user agreements have been executed (18 proprietary, 46 industry nonproprietary, and 36 university nonproprietary). See Figure 8.

Major Accomplishments

Major project accomplishments in FY 1990 are:

- Initiated a collaborative research agreement between ORNL and Allied-Signal to transfer gelcasting technology to Allied-Signal for forming complex shapes of silicon nitride ceramics.

- Developed ceramic joint design methodology and joining technology for ceramic to metal and ceramic to ceramic joints (Battelle, GTE, and Norton).

- Developed environmentally sound aqueous powder milling and powder treatment technology as the first stage in a program to develop highly reliable silicon nitride ceramics for applications in advanced engine components (Norton Company).

- Completed one stage of an international cooperative research program with West Germany and Sweden to characterize the properties of ceramic powders and dense ceramic shapes in order to develop international testing standards.

- Successfully completed a program with industry to develop ceramic matrix composites with enhanced strength and toughness (GTE and Norton).

- Developed high performance, low-cost toughened ceramics by a unique "3-layer composite" process and fabricated automotive cam roller followers for engine rig testing (Ceramatec, Inc.).

- Completed initial tensile strength, fatigue, and creep characterization of candidate ATTAP rotor materials and incorporated data into the program data base (ORNL, U. Dayton).

- Established in-process NDE inspection procedures and detection limits in programs at Norton and GTE to develop highly reliable ceramics for ATTAP rotors and stators.

- Developed first generation life prediction models and determined ceramic test specimen requirements in programs at Allison Gas Turbine Division of General Motors and Garrett Auxiliary Power Division of Allied-Signal for development and demonstration of ceramic life prediction methodology.

- Evaluated friction and wear in numerous prototype piston-ring cylinder-liner couples made by applying ceramic coatings to metal substrates (Cummins and Caterpillar).

- The High Temperature Materials Laboratory user program passed the 100 user mark in providing university, industry, and government researchers access to state-of-the-art research instruments.

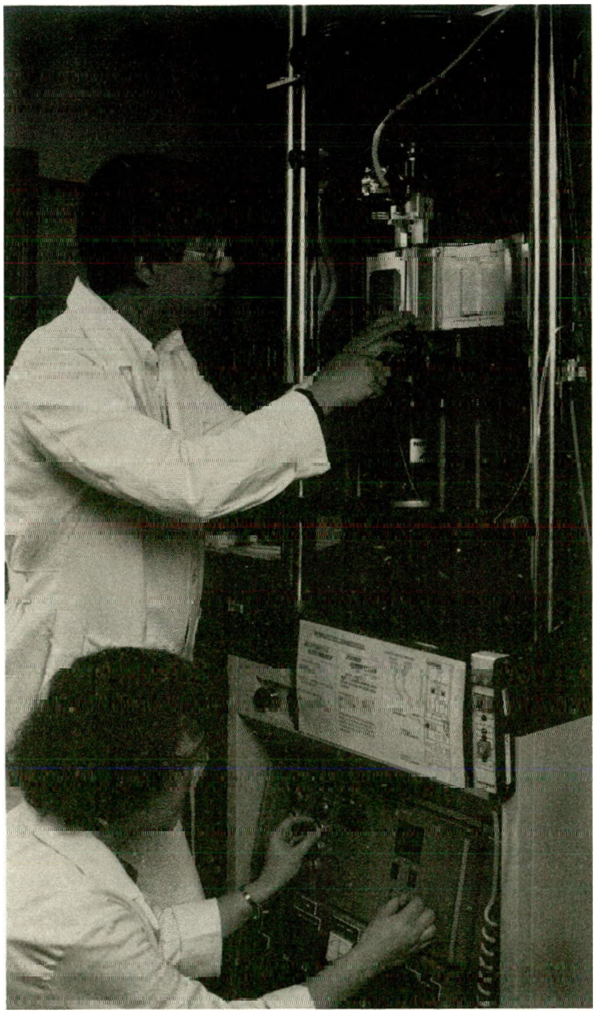


Figure 8. HTML Users from Institute for Defense Analyses, Alexandria, Virginia, Preparing to Perform Measurements on a Tensile Test Instrument in the Mechanical Properties User Center.

3.4 Alternative Fuels Utilization Program

The use of alternative fuels in place of conventional gasolines and diesel fuels remains a viable means of significantly reducing the nation's dependence on petroleum. Current interest in alternative fuels centers, however, on their potential to reduce emissions from transportation engines. Legislation requiring the use of "clean fuels" to improve air quality is being considered at the local, state, and Federal levels, resulting in careful scrutiny of the true low emission potential of alternative fuels, such as alcohols, in comparison to reformulated conventional fuels. Diverse opinions exist in government and industry as to the most effective clean fuel, but it is widely accepted that fuel selection to control emissions is a necessary companion to engine technology improvements for emission reduction.

The barriers to widespread implementation of alternative fuels are somewhat fuel specific, but include the high cost of production, inadequate supply/distribution infrastructure, and inadequate utilization technology. The Alternative Fuels Utilization Program (AFUP) addresses remaining deficiencies in data or technology of fuel utilization. Research to establish mature, if not optimal, utilization technology will allow decisions regarding alternative fuel implementation to be based on energy security needs, environment, or economics. In assessing emissions in particular, research and development in fuel utilization must ensure that a valid and equitable base of information exists for comparing alternative fuels, and that the true potential of each fuel candidate is clearly understood. In this regard, the AFUP projects seek not only to characterize existing technology but also to advance the state of the art to fully realize the potential of viable fuel candidates. The broad range of research spans rather fundamental bench-top experiments to emissions and fuel economy characteristics of alternative fuel vehicles in daily service.

Technical Plan

The primary focus of the AFUP has been to foster the use of non-petroleum-based transportation fuels by establishing a technology base for the use of such fuels in both contemporary and advanced engines. In recent years, growing emphasis has been placed on developing a more thorough database on the combustion and emission characteristics of alternative fuels in concert with projects aimed at identifying or developing technologies to positively enhance their combustion performance. In FY 1989 and early FY 1990, representatives of the Office of Transportation Technologies (OTT) and the Oak Ridge National Laboratory (ORNL) Project Office made visits to industry, universities, and laboratories to review the issues in alternative fuels utilization. The industry comments were factored into the FY 1990 plan for the AFUP.

The DOE alternative fuels activities consist now of two major thrusts: 1) the research and technology development activities which have continued at a modest level since the 1970's, and 2) the Alternative Motor Fuels Act of 1988, involving demonstrations, tests, and special studies.

The research and technology work breakdown structure in AFUP is organized by classes of fuels. The fuel types currently being addressed include:

1) Alternative hydrocarbon fuels (synthetic fuels)

2) Alcohol fuels (includes Federal Methanol Fleet originated in FY 1985)

3) Methane and related gaseous fuels.

In addition, there is a work element on combustion enhancing technologies that cuts across all fuel types.

Alternative hydrocarbon fuels (synfuels) utilization projects have historically fallen in one of two categories: 1) investigation of fuels produced from coal or shale derived crude that meet practically all modern fuel specifications, but may be unconventional in chemical composition, or 2) research on using fuels that meet critical specifications (such as related to storage stability) but may otherwise differ substantially from conventional hydrocarbon fuels. In the current energy and economic climate, industry interest and activity in producing fuels from coal and oil shale is very limited and it is deemed that sufficient engine screening tests of these fuels have been performed and documented. However, a considerable amount of work in AFUP, although conducted under a synfuels label, has been targeted toward the more generic problem of isolating the key chemical and physical properties of fuels which dominate their combustion and emission characteristics. This continues as a challenging research subject since the very fundamental combustion information is not complete and since many engine specific parameters tend to mask fuel related effects. A new initiative under the AFUP program will commence in FY 1991 to determine the exhaust emissions species atmospheric reactivity of the various alternative fuels.

Indeed, relating fuel composition to engine emissions is paramount in identifying a so called "clean fuel." Projects are to continue with the purpose of further defining the dominant properties of hydrocarbon fuels and examining how those properties can be adjusted to improve emissions. The DOE owned test fuel preparation equipment housed at Southwest Research Institute is used to formulate fuels for investigation of the influences of fuel chemistry. Fuel compositions are studied as they relate to low emission hydrocarbon fuels for future comparison with alternative fuels in demonstration programs.

A modest level of research conducted to date has led to an understanding of most aspects of using methanol or ethanol in conventional engines. However, the recently accelerated interest in methanol utilization (mostly for its air quality benefits) gave reason to reassess the unresolved technical issues through industry visits and literature reviews. Among the remaining concerns in methanol vehicle technology are lubrication and wear control, engineering development of durable emission control systems, and identification of a widely acceptable fuel specification, including content of other hydrocarbons. If M100 (neat methanol) use were to be adopted as a long range goal, then these above mentioned problems would be exacerbated and other problems, such as cold-start, must be included. The potential efficiency and emissions of dedicated, optimized methanol/ethanol vehicles also remains in question since the majority of data is from minimally modified vehicles originally developed for gasoline.

The vehicles in the Federal Methanol Fleet have been in operation from two to four years at three respective sites. It is likely that the oldest fleet at the Lawrence Berkeley Laboratory will be phased out at the end of FY 1990. Other sites will continue for at least one more year and, as appropriate, the vehicles are to be used in detailed evaluations of specific issues.

For the past several years, AFUP has had no funding for natural gas and other gaseous fuels, but new emissions regulations for truck and bus diesel engines have renewed interest in natural gas. Although there are disadvantages and inconveniences in the storage and refueling of natural gas, its potential for low emissions makes it worthy of re-evaluation. The technical status of natural gas utilization has been reviewed and, with input from interested trade and industry groups, new DOE projects are being considered.

Projects in combustion enhancement (a work element formed in FY 1987) aim to evaluate and develop technologies that will clearly improve combustion and emissions characteristics with alternative fuels. Activities are designed to expand on work in companion programs on combustion fundamentals, and investigations are considered to tailor fuels to control combustion and evaluate new developments in materials, ignition fundamentals, and fuel-air management, while emphasizing alternative fuels. Investigations of advanced technologies, at least in a preliminary sense, are carried out.

The Alternative Motor Fuels Act (AMFA) was signed into law in October 1988; it provides for demonstrations, tests, and studies pertaining to alternative fuel (alcohol and natural gas) vehicles. A substantial amount of planning was carried out in FY 1989 in anticipation of an appropriation in FY 1990. A draft implementation plan was completed in mid FY 1989. AMFA includes the following major project elements:

1) Federal Light Duty Vehicle Project
2) Truck Commercial Applications Projects
3) Alternative Fuels Bus Project
4) Special Studies and Reports

An interagency agreement between DOE and the General Services Administration (GSA) provides that GSA is responsible for vehicle procurement and disposal as well as certain aspects of data collection and testing in the Federal Light Duty Vehicle Project. The Truck Commercial Application Project is to be carried out by DOE laboratories and subcontractors in collaboration with those states which have compatible programs. A high level of participation from truck engine manufacturers will be sought.

The Alternative Fuels Bus Project section of AMFA requires coordination with the DOT/ Urban Mass Transit Authority (UMTA) alternative fuels transit bus program. AMFA funds are to be used to test buses (i.e., generate and collect data) in the UMTA program with state and local agencies. An interagency agreement between DOE and the Department of Transportation (DOT) provides the means for the joint effort. Overall data collection and analysis for AMFA will be conducted by the Solar Energy Research Institute (SERI).

AMFA requires several special studies and reports including an electric vehicle assessment (to be led by DOE), a residential energy pricing study, and an environmental assessment (to be led by EPA). The approach and schedule to completing these studies have been addressed in the overall AMFA plan.

Technology Status

During FY 1990, research continued to identify fuel composition effects on emissions; subsequently a comparison of alternative fuel engine emissions was published. Technologies for improving methanol engine combustion were evaluated and emissions tests were conducted on some high mileage vehicles in the Federal Methanol Fleet.

Screening tests of oil shale and coal derived fuels have been performed to the extent warranted at this time, but the more generic issues of how fuel properties affect engine performance and emissions remain valid research topics. The fuel/engine interface, once a concern with synfuels, is now receiving considerable attention since clean fuels are being publicized as an alternative solution to emissions problems (i.e., alternative to engine development). In a project to study clean diesel fuel formulations, diesel fuel blend stocks have been fractionated and blended to allow assessment of the emissions contributed by each fraction. The results are to be reported in early FY 1991. A project on the interactions of gasoline composition, engine deposits, and pre-ignition was completed wherein lubricant additives were ranked for their tendency to form deposits and promote surface ignition. The project focused on simulated synthetic gasolines.

Emissions tests were conducted on some high-mileage vehicles from the methanol fleet at Argonne National Laboratory. The results were very vehicle-specific but in general the methanol vehicles show elevated levels of carbon monoxide (CO) and formaldehyde compared to their gasoline counterparts, as was observed in tests conducted during 1988. A second round of emissions tests on the ORNL fleet vehicles was also completed and the results will be published in early FY 1991.

Two of the ORNL methanol Buicks were engaged in a special evaluation of methanol effects on lubrication and wear. During an accelerated test procedure involving short trips, lubricant and coolant temperatures were monitored in methanol and gasoline vehicles running in parallel, with oil samples collected and analyzed at various times. This project was conducted with guidance from General Motors Research Laboratories and from a Coordinating Research Council committee formed to address methanol engine lubrication.

A project was initiated to examine how engines might be configured for optimal application of methanol and natural gas. The first phase of the effort is analytical. A workshop to obtain industry guidance has been scheduled.

Results of comparative emissions tests of natural gas, methanol, and diesel heavy duty engines were published. The engines were all variations of a Caterpillar 3406 and the transient emissions tests were performed by Caterpillar. The most significant challenges appeared to be control of particulates attributable to the lubricating oil (in all engines) and high hydrocarbon (HC) and formaldehyde emissions from the methanol and gas engines.

Improvement of ignition and reduction of emissions have been the subject of an AFUP project at Detroit Diesel Corporation (DDC). DDC found that a combination of two-stage fuel injection and decreased swirl in the combustion chamber reduced HC emissions without increasing NO_x. In a parallel project, Caterpillar, Inc. is examining several combustion system improvements and advanced concepts. The use of catalysts to assist ignition and combustion is being evaluated by Pennsylvania State University, and ORNL continues research on thermal barriers and related surface treatments for HC emission control. A KIVA II simulation of a research engine at ORNL has been completed to guide experimental evaluations.

Diesel fuels formulated to maintain a high ignition quality — even with a high alcohol content — have undergone screening tests in engines and combustion bombs. These fuels are expected to exhibit, relative to standard diesel fuel, reduced emissions and could be used in near-conventional diesel engines. Fuels containing up to 60% alcohols have been found to have ignition quality similar to standard diesel fuel.

Under interagency agreements with DOE, the GSA and DOT have initiated their respective parts of the AMFA. GSA requested bids for alternative fuel cars in mid-FY 1990 with the intent that the cars be sited principally in areas which are in non-attainment of air quality standards. Funds were transferred from DOE to GSA for the initial purchase of the vehicles. Funds were also transferred to the UMTA to allow it to begin data collection on alternative fuel buses to assess their durability, safety, fuel economy, and emissions.

For the Truck Commercial Applications Project, work statements were drafted for solicitations to enlist engine manufacturer participation as well as operational and logistical assistance. Meetings with state agencies in California and New York (which are engaged in similar projects) explored avenues of collaboration. Agreements between DOE and the West Virginia University (WVU) were completed whereby WVU will assist in some of the emissions characterizations of AMFA trucks and buses. The establishment of a data center for all parts of AMFA was initiated at the Solar Energy Research Institute.

Several of the studies and reports specifically required under AMFA were completed:

- A report entitled Impacts on Home Heating Costs of Incentives for Alternative Fuels Vehicles was completed in November, 1989. This was required under Section 9 of AMFA.

- A report entitled Federal Regulations Needing Amendment to Stimulate the Production of Electric/Solar Vehicles was completed in January, 1990. This was required under Section 9 of AMFA.

- On April 26, 1990, the National Highway Traffic Safety Administration (NHTSA) issued a final rule on the Minimum Driving Range for Dual Energy and Natural Gas Dual Energy Passenger Automobiles. This was required under Section 6 of AMFA.

Major Project Accomplishments

Major project accomplishments for FY 1990 were:

- Published results of a comparison of methanol, natural gas, and diesel fuels in similar heavy duty engines. Transient emissions data showed high levels of hydrocarbon and formaldehyde from both methanol and natural gas.

- Continued technology transfer through the organization of sessions at the SAE Fuels and Lubricants Meeting, as well as the Windsor Workshop on Alternative Fuels.

- Identified, at Detroit Diesel Corporation, advantages of two-stage fuel injection and decreased swirl for hydrocarbon emission control in a methanol engine.

- Conducted evaluation of lubricant performance in methanol engines subjected to short-trip service, using methanol vehicles at ORNL.

- Completed emissions tests of several high mileage vehicles in the Federal Methanol Fleet.

- Completed interagency agreements with GSA and DOT, thus initiating the major activities in the Alternative Motor Fuels Act.

- Completed three studies and reports required by the Alternative Motor Fuels Act.

- Initiated an alternative fuels data center at the Solar Energy Research Institute.

3.5 CFC Reduction Project

About 37 percent of domestically produced CFCs are used in automotive air conditioners. Eventually, all of this CFC is released to the atmosphere as a result of system leaks; release during initial charging, servicing, and accidents; and vehicle disposal. When the CFCs rise to the stratosphere, they participate in a complex photochemical reaction wherein ozone molecules are destroyed by atoms of chlorine. The ozone layer which blankets the Earth filters out much of the sun's harmful ultraviolet radiation. Ozone depletion will increase health risks to animal and plant life through increased incidence of skin cancer, melanoma, cataracts, suppression of the immune system, genetic damage to crops and aquatic organisms, and increased ground level ozone. Also, CFCs are considered a significant contributor to the greenhouse effect.

The Montreal Protocol on Ozone Depleting Substances was adopted in 1987 and has since been signed by 38 nations, including the U.S. The Protocol calls for an immediate freeze on production and consumption of CFCs at 1986 levels and sets a schedule for a gradual reduction to 50 percent of 1986 production levels by 1998. President Bush has since called for a total ban on CFC production by the year 2000, assuming suitable substitutes are found.

The CFC Reduction Project is aimed at helping industry to make an energy-efficient and environmentally sound transition away from the use of CFCs in the transportation sector and particularly in mobile air conditioning. This transition can be accomplished by providing innovative and economically viable options to the current technology. The project has three main thrusts: (1) development of solar control coatings for automobile glass, (2) identification of alternative refrigerants, and (3) identification of alternative refrigeration cycles. By reducing solar heat gain into an automobile's passenger compartment, it will be possible to downsize the air conditioning plant. Downsizing permits evaluation of air conditioning options that are not currently feasible. The load reduction effort has the additional potential benefit of increasing overall vehicle efficiency and passenger safety. The two efforts aimed at the air conditioner itself address how to effectively provide passenger comfort within the constraints of system cost, safety, and overall vehicle efficiency. The following summarizes the tasks which will accomplish these ends:

- Lawrence Berkeley Laboratory (LBL) is conducting a study on thin film coatings for automobile glass. Because large areas of sloped glass are appearing in more vehicles — for aesthetic and aerodynamic reasons — there is a need to control the solar heat gain into the passenger compartment. LBL is developing prototype laminated electrochromic switching devices which can selectively limit the transmission of solar radiation. These devices can, at the flip of a switch, completely opacify the windows on a parked car, thereby reducing the peak load on the air conditioning system. Work is also being done to develop more durable solar control/low emissivity coatings for side and rear windows. Exploratory work is being conducted on angle selective coatings which will allow the transmission of light at angles within the driver's field of view while limiting most of the radiation from the higher sun angles. An auto heat transfer model is being used to estimate the reduction in loads associated with the above glazing technology.

- Arthur D. Little, Inc. is conducting a feasibility study on the use of non-inert refrigerants (common hydrocarbons such as propane) as air conditioner working fluids. These substances have higher heat transfer coefficients than current CFC alternatives, are reasonably compatible with common construction materials and lubricants, are chemically stable, are low in cost, and have low toxicity. Flammability is the major drawback of these hydrocarbons. A major study is underway to analyze the potential performance, safety, and overall efficiency of a hydrocarbon based air conditioning system. This is the first phase of Arthur D. Little's three-phase effort which will be followed by preliminary design of a system and laboratory testing.

- The Oak Ridge National Laboratory (ORNL) is performing a technology assessment of alternative non-CFC mobile air conditioning systems. Options will be investigated including mechanically driven systems and waste heat powered devices. The evaluation will be done using the reduced cooling loads predicted by LBL's modeling and glazing work. The assessment will be accomplished through cycle model analysis to estimate the performance potential of non-CFC air conditioning options under baseline automobile operating conditions. Recommendations will be made regarding further R&D needs for those options which appear feasible.

- The viability of a CFC/non-CFC mixture for use as a substitute refrigerant in existing automotive air conditioning systems will be investigated. Such a substance is needed to prevent the premature obsolescence of the millions of CFC-based systems after production of CFCs is curtailed. Potential substances will be evaluated for their cost, safety, material compatibility, and physical and thermodynamic properties. Laboratory testing will be conducted to evaluate performance and durability effects.

Major Accomplishments

- Thin Film Coatings for Automobile Glass
  - Completed development of prototype electrochromic window materials. Samples have been produced as part of a formal collaboration with Dow Chemical Company incorporating its proprietary polymer electrolyte.
  - Modified thin metal coatings by ion-beam bombardment to increase durability for use on exposed surfaces.
  - Accomplished encouraging preliminary investigations into the microstructures of potential angle selective materials.

- Non-Inert Refrigerant Study
  - Developed a detailed screening procedure for evaluating alternative refrigerants.
  - Compiled a preliminary list of candidate non-inert refrigerants and thermal performance data.
  - Collected and analyzed collision data. Examined crash-tested vehicles to assess the potential for system rupture and intrusion of refrigerant into the passenger compartment.

- Technology Assessment, CFC/Non-CFC Refrigerant Mixture
  - Completed the examination of non-CFC cycle options and conducted modeling analyses to determine their performance potential.
  - Initiated the study of CFC/non-CFC mixtures. Identified candidate mixtures with requisite thermodynamic properties.

4 Recommendations

Based on DOE's assessment of progress toward the overall program goals, there are no new recommendations at this time pertaining to additional R&D programs beyond those included in the FY 1991 budget submission

5 Appendices

Procurement information for ongoing contracts and grants of the Advanced Turbine Technology Applications Project, the Heavy Duty Transport Technology Project, the Advanced Materials Development Project, the Alternative Fuels Utilization Program, and the CFC Reduction Project is summarized in Appendices A, B, C, D, and E, respectively. Each Appendix lists major contracted efforts, including cost-sharing contracts, contract start dates, and actual or projected completion dates. Appendix F presents information regarding certification of new R&D contracts. These Appendices are provided to satisfy Sections 310(a)(3) and 304(f)(4) of Public Law 95-238.

5.1 Appendix A – Procurement Summary — Advanced Turbine Technology Applications Project

Organization	Description	Period of Performance	Dollar Value $(000)
Garrett Auxiliary Power Division	3500-Hour Durability Testing of Ceramic Materials	02/78-04/90	1,552
Garrett Auxiliary Power Division	ATTAP	08/87-12/92	32,105 25,684 *
Allison Gas Turbine Division	ATTAP	10/87-12/92	35,024 28,019 *

* Federal Government share

5.2 Appendix B – Procurement Summary — Heavy Duty Transport Technology Project

Organization	Description	Period of Performance	Dollar Value $(000)
University of Wisconsin	Combustion Modeling	10/89–10/90	260
Northwestern University	Lubricant Decomposition	2/90–2/91	54
Detroit Diesel Corporation (DDC)	1) Extended Life Glowplug for Methanol Engines	9/90–9/91	90
	2) Adiabatic Diesel Engine Component	05/85–11/90	5,075
	3) Fuel Injector Plugging - Methanol	07/90–07/91	109 *
Case Western Reserve University	High Temperature Solid Lubricant Coatings	01/89–01/90	50
Cummins Engine Company	1) Thick Thermal Barrier Coatings	04/86–06/90	758 *
	2) Advanced In-Cylinder & Applied Tribology	06/88–03/91	5,000 *
	3) RAPRENOX	10/89–09/90	125 *
Caterpillar Tractor Company	Thick Thermal Barrier Coatings	03/86–06/90	762 *
Cummins/Akzo	High Temperature Liquid Lubricant	01/88–06/91	1,014 *
Caterpillar Tractor Company	Advanced In-Cylinder & Applied Tribology	04/88–03/91	4,295 *
Hi-Z	Thermoelectric Waste Heat	10/89–10/90	90
Teledyne	Thermoelectric Waste Heat	07/90–12/90	78
MIT	1) Lubrication Consortium	01/89–07/90	35
	2) Ceramics in Adiabatic Engines	04/86–05/89	250
University of Michigan	Ceramic Wear Points in Valve-train Friction & Wear	09/89–09/91	50

* The contractor has cost-shared an additional 15 percent.

5.3 Appendix C – Procurement Summary — Advanced Materials Development Project

Organization	Description	Period of Performance	Dollar Value $(000)
Allison Gas Turbine Division, General Motors	Ceramic Life Prediction	11/88–12/92	3284 2627 *
Garrett Auxiliary Power Division	Ceramic Life Prediction	04/89–03/93	4844 3536 *
Battelle Columbus Laboratories	1) Dynamic Interfaces I & II 2) Oxide-Metal Joining	09/84–07/90 09/87–06/92	901 1211
North Carolina A&T University	High Temperature Tensile Tests	10/84–09/90	1090 1000 *
University of Dayton	Environmental Effects in Toughened Ceramics	09/87–08/90	2345 2095 *
GE Research Laboratories	Advanced Statistical Concepts I & II	12/84–02/91	836
Ford Motor Company	Silicon Nitride Powder I & II	02/85–12/89	1874 1462 *
GTE Laboratories	1) Injection Molded, Whisker-Toughened Si_3N_4 Composites I & II	06/85–03/90	1748 1398 *
	2) Contact Stress Coating Development	01/87–09/91	1741 1392 *
	3) Joining Nitride/Carbide to Metal Alloys	08/87–09/89	1514 1211 *
	4) Advanced Processing for Reliability	10/89–03/93	6129 4290 *
Ceramatec	1) Layered Zirconia Composites II	05/88–08/90	305
Argonne National Laboratory	1) X-Ray Computed Tomography 2) NMR of Green Ceramics	01/87–09/91 06/87–12/91	430 860

* Federal Government share

5.3 Appendix C – Procurement Summary — Advanced Materials Development Project (continued)

Organization	Description	Period of Performance	Dollar Value $(000)
Carborundum	1) SiC Powder Synthesis II	07/86–01/89	424 352 *
	2) Component Testing	07/90–06/91	25
	3) Toughened SiC	07/90–06/92	700
University of California	Processing Science for Si_3N_4 Ceramics	10/89–09/92	499
Sullivan Mining Corporation	Synthesis/Fabrication of Si_3N_4 Ceramics	06/90–05/92	1000
Norton Company	1) Synthesis/Processing of Transformation Toughened Ceramics II A & B	12/87–09/90	557 446 *
	2) Glass Encapsulated HIP Si_3N_4 Composites II	02/88–06/90	1237 990 *
	3) Si_3N_4 and SiC Joining	11/87–10/90	1205 964 *
	4) Advanced Processing for Reliability	06/89–11/92	7063 5085 *
Army Materials Technology Laboratory	Characterization Development	09/86–06/91	2485
Virginia Polytechnic Institute	Ultra Low-Expansion Ceramics II	11/89–10/92	953 798 *
Caterpillar Corporation	Wear Coatings for Diesels	10/87–06/90	681 497 *
Cummins Engine Company	Coating Development for Diesels	07/87–09/90	617 488 *
Garrett Ceramic Components Division	1) Si_3N_4 Matrix Composites II	06/88–04/91	1629 1303 *
	2) Component Testing	10/89–10/90	35
Keramont Research Corporation	Titanium Diboride Whiskers	06/88–02/90	177 131 *
Southern Illinois University	Turbomilling of SiC Whiskers II	03/88–09/90	467 261 *

* Federal Government share

5.3 Appendix C - Procurement Summary — Advanced Materials Development Project (continued)

Organization	Description	Period of Performance	Dollar Value $(000)
Carborundum	1) SiC Powder Synthesis II	07/86–01/89	424
University of Michigan	1) Liquid Phase Sintering of Ceramics I	01/87–07/90	565 485 *
	2) Liquid Phase Sintering of Ceramics II	06/90–05/93	830
National Institute of Science & Technology	Ceramic Technology	07/85–10/90	2120
NASA-Lewis Research Center	Toughened Ceramics Life Prediction	12/87–09/90	913
Pennsylvania State University	Surface Absorption	02/89–01/92	210
Rutgers University	Controlled Doping	02/89–01/92	210
University of Wisconsin-Madison	Spectroscopic Characterization	02/89–01/92	210
University of Tennessee	1) Coating Adherence	07/85–09/90	99
	2) Brittle Fracture in Ceramics	06/87–02/92	233
Vanderbilt University	Fracture Toughness of Ceramics	02/88–12/89	83
Rice University	Development of Fracture Toughness Microprobe	04/90–03/91	66
Detroit Diesel Allison	Component Testing	08/90–07/91	40

* Federal Government share

5.4 Appendix D - Procurement Summary — Alternative Fuels Utilization Program

Organization	Description	Period of Performance	Dollar Value $(000)
Southwest Research Institute	Synthetic Fuel Center Operation	11/85–12/90	1334
Belvoir Fuels and Lubricants Research Laboratory (SWRI)	Ignition Quality Techniques and Analyzer	02/85–09/90	507
Caterpillar, Inc.	Alternative Fuel Heavy Duty Engine Data	04/88–03/90	155
Caterpillar, Inc.	Methanol Combustion System Improvement Phase II	TBD	427
Detroit Diesel Corporation	Ignition Enhancement for Methanol in Heavy Duty Engine	06/89–05/91	278
Michigan Technological University	Photographic Visualization of Methanol Ignition	03/89–02/91	117
Pennsylvania State University	Enhancement of Methanol Combustion with In-cylinder Catalysts	07/89–10/90	132
E.A. Mueller, Inc.	Natural Gas Infrastructure Analysis	02/88–06/90	140
SWRI	Emissions Characteristics of Diesel Fuel Fractions	TBD	130

5.5 Appendix E - Procurement Summary — CFC Reduction Project

Organization	Description	Period of Performance	Dollar Value $(000)
Lawrence Berkeley Laboratory	Develop Thin Film Coatings	05/89–12/89	85
Lawrence Berkeley Laboratory	Develop Thin Film Coatings	02/90–01/91	215
Oak Ridge National Laboratory	Technology Assessment	03/90–02/91	120
TECOGEN	CFC/Non-CFC Mixtures	06/90–05/91	130
Arthur D. Little, Inc.	Non-Inert Refrigerant Study	03/90-09/90	115

5.6 Appendix F - Certification of New R&D Contracts, Grants and Cooperative Agreements

Section 304(f)(1) of Title III of Public Law 95-238 requires that all new research and development for advanced automotive propulsion system alternatives to existing internal combustion engines funded under the authority of the Act supplement, but neither supplant nor duplicate, the automotive R&D efforts of private industry. To assure compliance with this requirement, Section 304(f)(2) requires the Secretary to issue regulations specifying the procedures, standards, and criteria to be used in the administration of the Automotive Technology Development Program to ensure that each new R&D contract, grant, or cooperative agreement for a DOE project or for a project of another Federal agency (such as NASA-LERC) funded under the Act meets the statutory requirement. These regulations are set forth at 10 CFR Part 473. Section 304(f)(4) requires that the Annual Report include a detailed discussion of how the research and development contracts, grants, and cooperative agreements funded pursuant to the Act satisfy the requirement expressed in Section 304(f). A discussion of DOE's efforts in compliance with Section 304 follows.

To be considered for a contract or to receive financial assistance under the Act, the regulations require the applicant to submit, in addition to the routine information required in a procurement or financial assistance initiative, specific information justifying certification by the manager of the proposed project under 10 CFR paragraph 473.24. Form NASA C-356 is used for this purpose.

Upon receipt of an application, whether unsolicited or in response to a solicitation, the manager causes a notice to be published in the Commerce Business Daily describing the nature of the proposal and inviting any interested person who believes that the proposal does not meet the criteria of 10 CFR paragraph 473.30, implementing section 304(f)(1), to submit a written objection. Following the close of the objection period, the manager makes an initial determination of compliance with the Act and submits appropriate proposals to the interagency review panel. The panel consists of representatives from DOE, NASA-LERC, the Environmental Protection Agency, and the National Highway Traffic Safety Administration who are knowledgeable in the areas of industry and government research and development on automotive propulsion. Following the appropriate review and consideration of each proposal, the panel makes a recommendation to the manager, who then makes the final determination of compliance and, if the determination is affirmative, certifies the proposal pursuant to 10 CFR paragraph 473.24.

These procedures were followed for all advanced automotive propulsion system R&D contracts, grants, and cooperative agreements listed in Appendices A through E which were entered into, made, or formally approved and initiated after February 25, 1978, the date of the Act's enactment. No written objections to any of the proposals summarized in the Commerce Business Daily were received and certification was recommended in each case by the interagency review panel.

As a result of adherence to the procedures described above, the requirements of Section 304(f)(1) of the Act have been satisfied.

UNITED STATES
DEPARTMENT OF ENERGY
WASHINGTON, D.C. 20585

CE-322