DOE Research and Development Portfolio

Energy Resources

Volume 2 of 5

April 1999

U.S. Department of Energy

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Energy is the vital force powering business, manufacturing and movement of goods and services throughout the country. The energy-related challenges facing our Nation in the next century are significant. Our economic well-being depends on reliable, affordable supplies of clean energy. Our environment requires a mix of energy sources that minimizes pollution and other undesired effects, even as our demands for energy services expand. Our national security requires secure supplies of oil and safe and affordable alternatives. Restructuring of the electricity sector may demand new end-use and grid technologies. For these reasons, as well as our country's stature in the global community of nations, we must maintain a strong leadership position in energy supply and end-use technology and in the related and supporting sciences.

Over the past year, the Department of Energy (DOE) has undertaken a major effort to ensure that our research and development programs are balanced and that our Federal investments are appropriately coordinated with the needs of the public and the marketplace. To do this, we have begun instituting a new portfolio approach to managing our R&D activities. This entails building a comprehensive document that, for the first time, provides in one place, a clear description of our entire $7 billion research portfolio. Following is DOE's *Energy Resources R&D Portfolio*. It is Volume II of the DOE's five volume R&D Portfolio.

This document is intended to help (1) describe our current R&D activities and showcase recent accomplishments, (2) evaluate whether our portfolio is appropriately balanced to meet our long term strategic mission goals, (3) align our technology investments with broader national policy goals; and (4) plan for future investments through technology roadmapping.

The investments presented in the *Energy R&D Portfolio* are important and creative steps toward bringing forth the knowledge, innovation, technologies, and partnerships required to meet the challenges of the next century successfully. It is our hope that this document will provide the means for illuminating our proposed investments for Fiscal Year 2000 and beyond, as a unified portfolio and serve as a useful framework and resource for further analysis and dialogue among all interested parties.

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Foreword

The United States spends over one-half trillion dollars annually for energy, which is also the largest contributor to environmental impacts and waste production. While more efficient use of energy has occurred over the last few decades, total domestic energy produced and consumed continues to grow due to population and economic growth. Our nation's ability to continue to achieve its energy goals will depend on a balanced research portfolio, complemented by an appropriate public policy and regulatory regime.

The Department of Energy (DOE) is the lead Federal agency working to assure clean, affordable, and dependable supplies of energy for our nation. In carrying out this mission, DOE has developed an *Energy Resources R&D Portfolio* that has made significant contributions to the United States in helping to achieve the nation's energy goals. This portfolio was developed as a first step to help ensure that the Department maintains a balanced portfolio of R&D investments to meet our nation's challenges in environmental quality, economic prosperity, and energy security.

Chapter 1 of the *Energy Resources R&D Portfolio* provides introductory remarks, including background for the goals of the *Energy Resources R&D Portfolio*. **Chapter 2** summarizes and attempts to describe the portfolio's characteristics from a number of viewpoints. Chapters 3 through 9 delve into the details of the Energy Portfolio's major technology areas and address various aspects of the research including: national drivers, uncertainties and technology challenges motivating the DOE-supported R&D, specific R&D activities, and past accomplishments. These seven chapters are organized into three broad energy areas:

- **Chapters 3 and 4** focus on activities supporting a ***Reliable and Diverse Energy Supply*** to address the Nation's need for stable, secure and clean sources of domestic energy. R&D is directed toward: domestic gas and oil supply; energy from geothermal sources; clean, alternative liquid fuels from coal, natural gas and biomass; and hydrogen fuels.

- **Chapters 5 and 6** deal with ***Clean and Affordable Power*** activities, the largest portfolio area. These chapters describe the broad range of generation technology needed to deliver affordable, reliable, and clean electric power. Technology options include the use of fossil fuels, renewable energy resources, and nuclear power, in both large, high efficiency energy systems and in distributed and hybrid energy systems. Also included are details on R&D for advanced delivery and control systems that will help ensure the availability of a robust, reliable electricity infrastructure required to serve emerging, competitive regional and interregional markets.

- **Chapters 7, 8, and 9** describe ***Efficient and Productive Energy Use*** R&D, which seeks to reduce the growth of energy use in buildings and the industrial sector, and to

dramatically improve the efficiency of passenger vehicles and light and heavy trucks, while increasing long-term economic benefits.

The applied research and development activities in the *Energy Resources R&D Portfolio* are supported by a strong portfolio of basic research activities which is summarized in **Chapter 10**.

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Executive Summary

Introduction

Energy needs of the United States are diverse and extensive. Energy is the vital force powering business, manufacturing and movement of goods and services throughout the country. The processes that link U.S. energy supply, conversion, and transmission systems to end uses comprise a complex system of technologies and scientific disciplines. Energy research and development (R&D) provides a systematic path to attaining the advanced technologies that enable achievement of our energy, environmental, and economic goals. Our energy needs can be satisfied and the nation's continued leadership in science and technology assured when R&D and appropriate policies and market forces are used together.

The United States consumes over 94 quads[1] of energy annually, representing an annual expenditure of over one-half trillion dollars. Energy use is also the largest contributor to environmental impacts and waste production. While more effective use of energy has occurred over the last few decades, total domestic energy produced and consumed continues to grow due to population and economic growth.

Energy Supply

Current U.S. energy consumption is sustained by oil (40 percent), gas (24 percent), coal (24 percent), nuclear (8 percent), and renewable sources (4 percent). The Energy Information Administration's 1999 Annual Energy Outlook (AEO99) projects energy supply and demand through 2020. These are "business-as-usual" projections that do not assume new policies (e.g., incentives to encourage greater energy efficiency) or regulations (e.g., greenhouse gas constraints).

AEO99 projects that by 2015, U.S. consumption of oil will increase more then 20 percent to over 23 million barrels per day, of which 60 percent will be imported; a higher ratio than at the time of the oil shocks of the 1970s. Demand for petroleum in non-industrialized countries is projected to nearly double by 2015, with the Middle East controlling nearly 70 percent of the world petroleum export market. Increasing U.S. import dependence is related not only to increasing demand, but also decreasing domestic production. Advanced technology can contribute to U.S. production by making it economical to recover some of the two-thirds of original oil-in-place that is typically not recovered.

Domestic natural gas consumption is projected by AEO99 to increase over 33 percent by 2015 to nearly 31 trillion cubic feet (Tcf) per year, with a significant share of this increase for electricity production. While the domestic natural gas resource is large, sustained consumption at these

[1] One quad equals a quadrillion Btus, and is approximately equal to a trillion cubic feet of natural gas, 0.5 million barrels of oil per day, or 48 million tons of coal.

levels will require significant production from more geologically complex, harder-to-produce formations, and better technology to ensure reasonable gas prices.

U.S. recoverable reserves of coal are greater than in any other nation, and more than twice those of China, the world's leading coal producer. Every year the United States produces more than one billion tons of coal and exports roughly one-tenth of this production to a variety of markets. It uses almost 90 percent of the remainder to generate electricity. While coal is abundant and relatively inexpensive to produce, large-scale use presents a number of environmental control technology challenges due to emissions of carbon dioxide (the most pervasive greenhouse gas), very small particulates, and potentially hazardous air pollutants.

Nuclear energy is the second largest source of U.S. electricity, after coal, producing more than 20 percent of our electricity. There are sufficient known domestic inventories of uranium to support the existing fleet of nuclear power plants throughout expected operating lifetimes. While there are advanced nuclear fuel cycles capable of generating their own fuel from non-fissile isotopes that are the subject of academic interest around the world, today's economics favor the simple uranium fuel cycle. Continued operation of existing nuclear plants is a growing concern as licenses, which must be renewed, expire in large numbers beginning around 2010.

Renewable energy includes hydropower, biomass (primarily wood and waste), geothermal, wind and solar resources. Although more than half of U.S. renewable energy produced is used to generate electricity, it is also used for transportation fuels (e.g., ethanol), and for heating industrial processes, buildings, and water. While renewable sources are currently dominated by hydropower, which provides about 10 percent of total U.S. electricity generation, other renewables are beginning to enter the market in specialized situations.

Energy Demand

Energy demand in the United States is dominated by four key areas: electric power generation; transportation; industry; and heating, cooling, and lighting of residential and commercial buildings. The U.S. consumes some $200 billion of electricity, more electricity than Europe and Japan combined. AEO99 projects that approximately 250,000 megawatts of new power generation additions will by required by 2015 (current capability is about 750,000 megawatts). Electricity generation accounts for 36 percent of U.S. primary energy consumption and a similar share of U.S. greenhouse gas emissions, and in some areas adversely impacts local and regional air quality.

The electric power industry is in the midst of restructuring. Many in Congress and State legislatures and many Federal and State regulators have acknowledged that competition in electric supply is both possible and desirable. However, a new competitive electric marketplace will require the Nation's utility infrastructure to operate in ways for which it was not originally designed, and may not include sufficient incentives for developing and deploying more advanced technology. New technologies will be required to ensure that adequate, reliable, reasonably-priced, and environmentally sensitive electricity supplies are available during and after the restructuring process.

Transportation is 97 percent dependent on petroleum-derived fuels and uses 73 percent more petroleum than the United States produces. While there have been many improvements in vehicle/engine fuel efficiency, transportation fuel consumption continues to increase due to the growing economy and numbers of drivers and miles traveled, as well as in the demand for larger vehicles and lower fuel-economy vans, pickup trucks, and sport utility vehicles. Unless new technologies significantly increase vehicle efficiency, these trends are likely to continue and exacerbate our petroleum import concerns, including the impact on the U.S. balance of trade.

Homes and commercial buildings consume 34 quads annually, which is 36 percent of the Nation's energy, as well as two-thirds of all electricity generated. Again, the growth in the economy and of the Nation's population is leading to more, larger, and better equipped homes, resulting in increasing energy consumption in this sector. Introduction of new technology to increase energy efficiency can have significant economic and environmental benefits. The production of energy, primarily electricity, that is consumed in buildings represents a major source of acid rain, smog, and greenhouse gas emissions, and includes 47 percent of U.S. sulfur dioxide emissions, 22 percent of nitrogen oxide emissions, and 35 percent of carbon dioxide emissions.

The U.S. industrial sector accounts for well over one-third of the Nation's energy consumption and relies on a mix of fuels. In particular, industry is the major consumer of natural gas. This energy use is concentrated in a relatively small number of industries, in particular the major materials processing and extraction industries. Nine of these industries alone account for about two-thirds of industrial energy consumption, and for them, energy use and waste disposal represent important fractions of operating costs and the cost of the end product. The industrial sector spent about $110 billion for energy in 1997. Industry also generated 14 billion tons of waste, including 200 million tons of hazardous and toxic waste (in 1994) to manufacture the goods we all consume. These wastes often impose expensive clean up and disposal costs. However, advanced technologies offer the potential to recover the "embedded" energy and materials value from this waste.

Manufacturing employs about 19 million people and these industries face increasing global competition. A thriving and growing economy will require more energy and energy efficiency to remain competitive. There is also a rapidly growing world market for energy efficient technologies and more advanced energy supply products, particularly in developing countries.

Future environmental concerns and regulations could affect the development and adoption of advanced technologies by changing relative compliance costs. Future air emissions standards, concern over climate change, and electric utility restructuring, for example, could have a significant affect on the attractiveness of different fuels and technologies.

Energy prices, particularly for oil, are now relatively low, and electric utility restructuring is expected to support this general trend by subjecting the pricing of electricity to the discipline of market forces. If energy prices remain low for the near future as many project, private sector investments in energy R&D could be reduced and introduction of new, commercial-scale technologies into the market delayed or deferred. But R&D and adoption of new technologies is

a long-term process. The size and complexity of the U.S. energy system, and the large capital requirement of many energy investments are such that the transition to new energy sources and fuels has historically taken from several decades to half a century. A substantial period of R&D, in some cases decades, may be needed to ensure that robust technological and energy options are available when the need inevitably arrives.

Federal Role and Linkage to Comprehensive National Energy Strategy

The Department's energy R&D portfolio is keyed to national needs regarding energy security, environment, and economic prosperity. DOE is the lead Federal agency working to assure clean, affordable, and dependable supplies of energy for our Nation. The Federal government's energy role is articulated through the goals, objectives, and strategies in the April 1998 Comprehensive National Energy Strategy (CNES)[2], that was developed by the Department and other Federal agencies with input from many stakeholders. The CNES includes actions that help increase energy supply diversity and fuel choices, bring renewable energy sources into the market, strengthen domestic production of oil and gas, support commercial nuclear energy research, and increase the efficiency of both power and end use technologies. The Department is also the lead agency for the Administration's strategy to bring competition to the electricity industry.

The Department's energy R&D portfolio supporting the CNES is managed by three principal organizations: the Office of Energy Efficiency and Renewable Energy, the Office of Fossil Energy, and the Office of Nuclear Energy, Science and Technology. Their combined R&D portfolio is centered on developing the technologies in support of the 3 energy R&D goals and 7 objectives shown in Figure 1. R&D associated with the 7 objectives is shown in Figure 2 (color-keyed to the managing DOE organizations), and discussed in Chapters 3 through 9 of this report. While the blocks under the objectives show applicable R&D areas, there is a large variation in the scope/funding and potential impact of activities in the different blocks.

The reasons why industry does not adequately invest in R&D important to meeting U.S. environmental, energy security, and economic goals vary by market. Figure 3 provides examples of why and where the private sector has underinvested in strategically important energy R&D.

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[2] The five CNES goals are:

1. Improving the efficiency of our energy systems.
2. Ensuring against energy disruptions by reducing the threat of supply interruptions and increasing the security and reliability of our energy infrastructure.
3. Promoting energy production and use in ways that protect our health and environment.
4. Expanding future energy choices.
5. Cooperating internationally on energy issues.

R&D Goals	R&D Objectives
Reliable and Diverse Energy Supply	● Enhancing Domestic Supplies ● Producing Clean Fuels
Clean and Affordable Power	● Advanced Power Systems ● Enhancing Utility Infrastructure
Efficient and Productive Energy Use	● Clean and Efficient Vehicles ● Efficient and Affordable Buildings ● Clean and Productive Industries

Figure 1

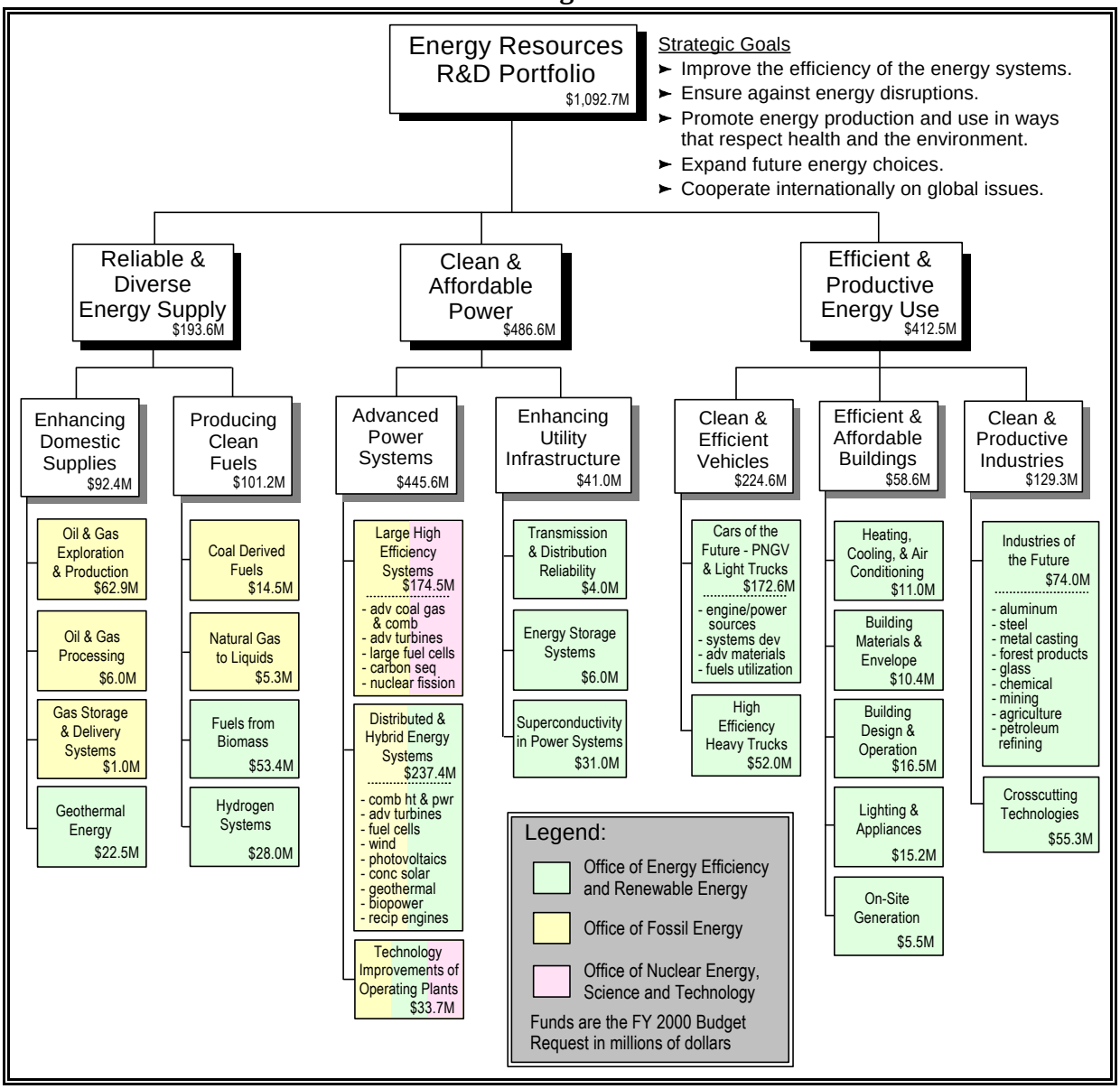


Figure 2

Reasons for Industry Underinvestment in Energy R&D	Examples of Areas Affected by Underinvestment in Energy R&D
Industry too fragmented and/or members too small to fund significant R&D	Buildings and some industrial technologies; marginal oil/gas properties operated by small independent producers
Deployment time frame so long that increased uncertainty makes business risk unacceptable	Advanced coal, nuclear and renewable power technologies; hydrogen and biomass fuels
Investment so large that risk is unacceptable	Higher efficiency vehicles; central power systems
Low consumer demand for better technology due to high initial price and/or long payback	Higher efficiency vehicles; buildings-related technologies
Electric utility restructuring focuses utility discretionary funding away from mid- and longer-term R&D to near-term, competitiveness issues	New power and utility infrastructure technology
Expertise not readily available in private sector	Fundamental research in areas such as materials

Figure 3

Portfolio Summary, Trends, and Accomplishments

Funding and Characteristics

Funding shares for DOE's FY 2000 Energy Resources R&D portfolio of applied research and development activities are shown in Figure 4 for 2 levels of detail. Shares of the overall FY 2000 budget request of $1.07 billion are 17 percent for energy supply, 44 percent for power, and 39 percent for energy use.

Energy R&D is conducted by leading private sector companies and organizations, DOE laboratories, that are world-class research facilities, and preeminent universities. Within the DOE program, industry R&D consistently accounts for 40-50 percent of the work in each area, and R&D with Federal Funded Research Centers (primarily National Laboratories) typically ranges from 30-40 percent. Work with universities and non-profits is more variable, ranging from 5-20 percent, and R&D supported in other Federal agencies is typically only a few percent.

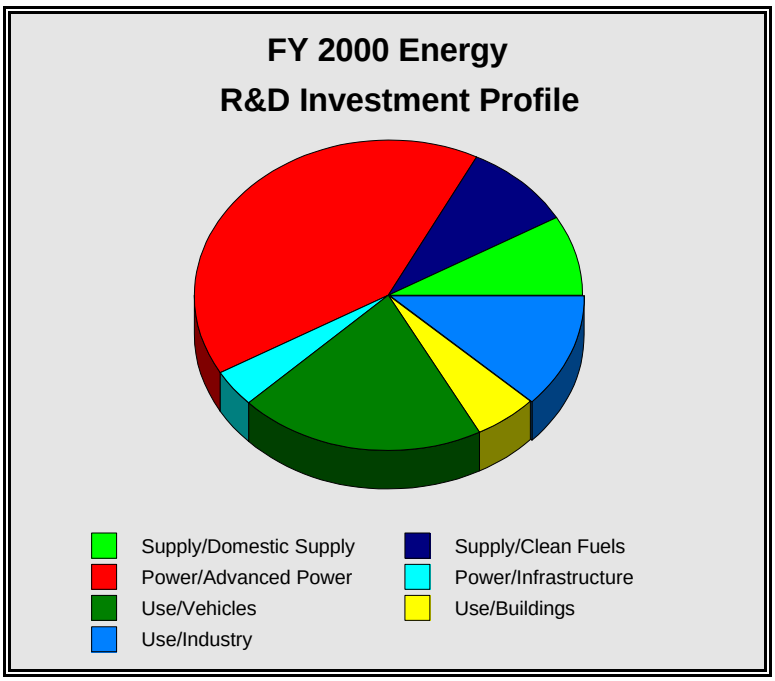


Figure 4

The mix of R&D performers is closely related to the mix of projects in different parts of the R&D cycle. Because industry must ultimately commercialize new technology, it is important to have industry's perspective in planning R&D and their direct involvement in the latter part of the R&D cycle, the "development" phase. This is also the phase where significant DOE-industry cost-sharing occurs. Most work performed by National Laboratories and universities is in the earlier R&D phases, that include basic and applied research. The vast majority of basic research related to energy is carried out by DOE's Office of Science. The Office of Science energy portfolio is discussed in Chapter 10, and treated in more detail in a separate Science Portfolio volume.

Federally-sponsored energy R&D should also be considered in the context of R&D support by the private sector. Private sector energy R&D investment, which is down about 30 percent from 1980s levels, is estimated to be about twice Federal R&D funding. Such estimates are subject to considerable uncertainty, however, due to industry activities that are proprietary and not reported. The major energy producers (i.e., integrated oil and gas producers, refiners, and transporters) account for the majority of industry expenditures, although much of this is for near-term operational issues, which is not the primary focus of DOE activities. Funding for the electricity industry has also declined in recent years, due in part to uncertainties associated with restructuring. Therefore, DOE energy R&D funding is a substantial part of the Nation's overall energy R&D expenditures, and is far more heavily focused on earlier R&D stages than that carried out by the private sector.

Portfolio Trends and Accomplishments

The major components of the energy R&D portfolio shown in Figure 2 are discussed below, along with selected accomplishments that reflect progress toward goals.

Reliable and Diverse Energy Supply. These activities address the Nation's need for stable, secure, and clean sources of domestic energy, and include R&D related to: domestic gas and oil supply; energy from geothermal sources; clean, alternative liquid fuels from coal, natural gas and biomass; and hydrogen fuels.

The R&D emphasis for oil and gas is on exploration and production, and work in areas such as diagnostics, imaging and reservoir life extension. Much of the U.S. resource is in mature producing areas, and remaining new sources are frequently difficult to find and produce. An increasingly important thrust of activities for clean, alternative fuels is fuel additives to solve environmental problems. R&D for liquids from coal and natural gas includes diesel additives to reduce emissions in high efficiency engines. Biofuels R&D is stressing ethanol production as a gasoline additive and replacement fuel. Hydrogen fuels R&D, in addition to finding ways to economically produce hydrogen, is addressing the lack of a utilization infrastructure through development of gaseous hydrogen storage and distribution technologies.

Considerable progress has been made through DOE support toward achieving energy supply goals:

- A successful demonstration of a unique oil field waterflooding approach could, when replicated by the private sector in other parts of the region, double or triple reserves and increase Federal tax and royalty revenues by $500 million.

- Two technologies, 3-D seismic and vertical seismic profiling, were first used in the Texas Gulf Coast and Fort Worth Basins, and resulted in a substantial increase in reserve growth (estimated at 60 Tcf) from established gas fields which were thought to be depleted.

- Geothermal drilling-related advances led to a 30 to 50 percent reduction of geothermal exploration drilling costs.

- Coal liquids R&D reduced the crude oil equivalent cost to approximately $30 per barrel, versus $60 per barrel in the late 1970s.

- Recent breakthroughs in air separation via ceramic membranes created the potential for reducing the cost of liquids from natural gas at least 25 percent below conventional technology and significantly reducing costs from coal-based synthesis gas.

- Over the last 2 decades, the predicted cost of biomass-derived ethanol was reduced by at least 50 percent, and commercial production of biomass ethanol from low-cost cellulosic feedstocks, particularly agricultural and forest wastes, is expected by 2002.

- Experimental results achieved on a Sorbent Enhanced Reformer validate expectations for a system that will reduce the cost for the production of hydrogen by 25 percent from conventional steam reforming methods.

Clean and Affordable Power. The Department's power R&D portfolio includes a broad range of generation technology options that utilize fossil fuels, renewable energy resources, and nuclear power in both large, high efficiency energy systems and in distributed and hybrid energy systems to deliver affordable, reliable, and clean electric power. Also included is R&D on advanced delivery and control systems to ensure the availability of the robust, reliable electricity infrastructure required to serve emerging, competitive regional and interregional markets.

Advanced coal and natural gas-fueled power technologies are emphasizing high efficiency and low emissions, with eventual integration into "Vision 21" plants to achieve even higher efficiency, product flexibility, reduced emissions, and lower cost. Carbon sequestration is seen as an increasingly important option for coping with greenhouse gas emissions. The Nuclear Energy Plant Optimization program, proposed for FY 2000, will help ensure that nuclear plants can deliver affordable supplies beyond their initial 40 year license period. Effort on distributed and hybrid systems, that includes renewable technologies, the industrial cogeneration turbine and fuel cell technology, continues to expand in recognition of potential environmental benefits and advantages of increasing distributed generating capacity. R&D for enhancing utility infrastructure is phasing out electric and magnetic fields activities and increasing emphasis on power system and energy storage technologies.

Considerable progress has been made through DOE support toward achieving advanced power systems goals:

- A new generation of coal gasification-based, higher-efficiency, cleaner, coal-fueled technologies is being demonstrated that will also be attractive in hybrid applications with advanced turbines and fuel cells.

- Successful demonstration of a variety of low-NO_x burners has led to installation of these low-polluting burners in about half of U.S. coal-fired capacity.

- Three advanced light water reactor designs, supported by DOE R&D, were certified by the Nuclear Regulatory Commission for construction in the United States. These plants, which are ready for export (with royalties accruing to DOE), are safer, more reliable, and more economic to construct and operate compared to existing technology.

- R&D has continued to reduce the cost of renewable systems suitable for distributed and base-load applications.

  – Biomass power is being demonstrated at scales from 10-75 MWE for dedicated feedstocks and for co-firing with coal.

- Recent advancements in geothermal technology have reduced costs by increasing power plant efficiency 5-10 percent for certain key resources.
- The cost of producing photovoltaic modules has decreased 50 percent since 1991, making it cost-competitive in certain applications.
- The cost of wind power has decreased by 85 percent since 1980, making it competitive in some areas that have good wind resources.

- Advanced fuel cells and turbines are being demonstrated and commercialized and are expected to achieve significant deployment in distributed and hybrid applications in the next decade.
- Fusion research has continued to raise the power achieved in test reactors (the Princeton Tokamak reached 10 MW in 1996) and is increasing the understanding of how to control plasma conditions and improve energy confinement.
- Important advances have been made in superconductivity, including development of breakthrough methods for making superconducting wires with over 10 times the current-carrying capability of wires made with older methods, and development and successful testing of the world's largest superconducting motor (200 horsepower).

Efficient and Productive Energy Use. This part of the R&D portfolio seeks to reduce the growth of energy use by vehicles, in buildings, and in the industrial sector while increasing long-term economic benefits.

Clean and efficient vehicles R&D continues to stress advanced engines, batteries, and fuels cells to dramatically improve the efficiency of passenger vehicles and light and heavy trucks. Increased emphasis has been placed on achieving effective, affordable emissions control technologies for diesel engines. R&D for efficient and affordable buildings most heavily focuses on heating, cooling, air conditioning, building material and envelope, and building design and operations. Technology roadmapping is underway with industry that is likely to impact the thrust of the buildings R&D portfolio for FY 2000. Technology roadmapping carried out by industry continues to drive DOE's R&D agenda for clean and productive industries. Mining and agriculture (particularly the bioproducts area) have been added to the industries R&D portfolio, bringing the industries total to nine. Based on prior research results, two areas where major breakthroughs are possible, have received increased priority: development of carbonless anodes and wettable cathodes that could lead to a totally new electrolytic smelting method for making aluminum, and an advanced black liquor gasification technology which could have significant environmental and economic benefits for pulp and paper manufacture. R&D emphasis has also been increased in areas such as advanced sensors and controls, advanced combustion technologies, and chemical catalysis.

Progress toward goals is illustrated by the following accomplishments from DOE-sponsored activities:

- The auto industry is moving toward adopting many of the technologies developed in the DOE program, as demonstrated by their use in industry concept cars at recent auto shows. DOE-supported technologies shown included advanced compression-ignition, direct-injection (CIDI) engines, parallel-hybrid vehicle configurations, a proton exchange membrane (PEM) fuel cell, a methanol reformer, and a nickel-metal hydride battery. Ford and other major manufacturers have begun mass marketing vehicles that can use ethanol, a biofuel.

- Five Federal investments in building efficiency technology development made in the 1970s-80s have resulted in present value savings in the U.S. economy totaling nearly $33 billion through 1997, while simultaneously eliminating more than 60 million metric tons of cumulative carbon emissions. These 5 investments include building design software, electronic fluorescent lamp ballasts, low emissivity windows, advanced oil burners, and efficient refrigerator compressors.

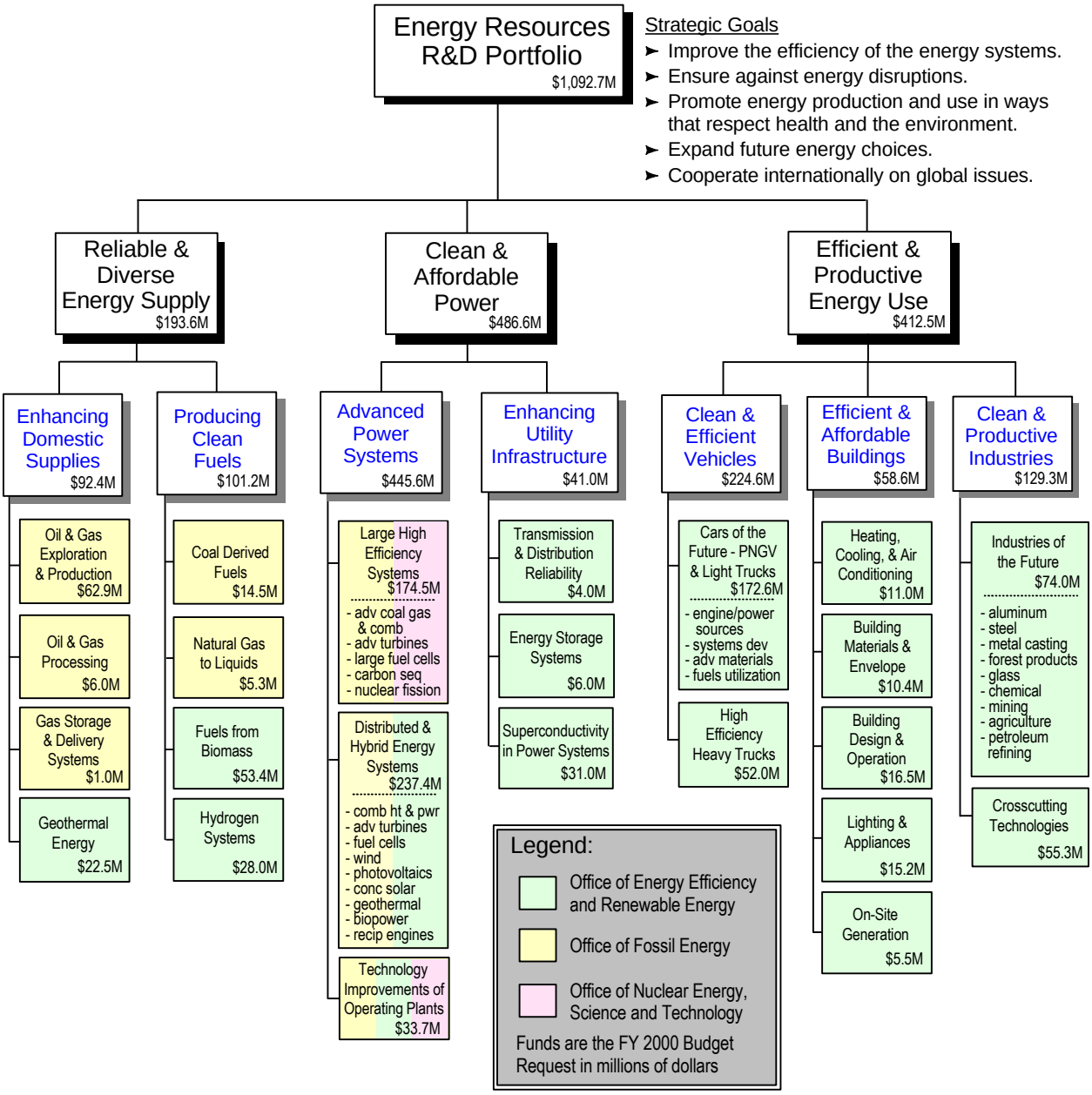
- A series of improvements to the lost foam casting process for steel and aluminum have resulted in reducing defects and producing higher quality, higher precision lost foam castings with less waste. There has been a continuing increase in the use of more advanced lost foam processes and by 2010 it is expected to be used for 29 percent of aluminum and 15 percent of steel castings, saving 4.6 trillion Btus/year of energy and nearly a half-million tons of waste.

- New cleaning technology allowing the use of lower grades of recycled paper by papermakers will permit 50 percent recycling of all paper used, reducing energy used for recycling by 0.l quad/year and lowering CO_2 emissions by 0.6 million tons annually.

- Oxy-fuel firing for glass melting furnaces is in commercial use in 20 percent of glass furnaces, reducing a manufacturer's fuel use by 48 percent, NO_x emissions by 70 percent, and particulates by 60 percent, and increasing productivity by 25 percent.

Development of the Energy Resources R&D portfolio has occurred over a long period of time with the cooperation of many experts and stakeholders, and guidance by Congress. This, however, is the first time that the portfolio has been articulated and presented for evaluation aligned with National and Departmental goals, rather than by organizational or budgetary structures. As a result, the Department, as well as its many stakeholders, will be in a better position to understand the existing and future contributions from the portfolio, its successes, limitations, balance, and potential effectiveness. The Department will continue to analyze its portfolio to improve its effectiveness, reduce possible duplication of effort, and better balance its priorities, if necessary.

Chapter 1
Introduction



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Introduction

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Background

"The United States faces major energy-related challenges as it enters the twenty-first century. Our economic well-being depends on reliable, affordable supplies of energy. Our environmental well-being—from improving urban air quality to abating the risk of global warming—requires a mix of energy sources that emits less carbon dioxide and other pollutants than today's mix does. Our national security requires secure supplies of oil or alternatives to it, as well as prevention of nuclear proliferation. And for reasons of economy, environment, security, and stature as a world power alike, the United States must maintain its leadership in the science and technology of energy supply and use."

Final report of the Energy Research and Development Panel of the President's Committee of Advisors on Science and Technology (PCAST), November 1997

The energy-related challenges expressed in this quote from the PCAST report succinctly identify the major factors that make a reliable and diverse energy supply vital to the future security and prosperity of the United States. Affordable energy supply and efficient energy use are indispensable ingredients of the economic well-being of individuals and nations. In the United States and worldwide, energy accounts for 7 to 8 percent of gross domestic product and a similar share of international trade. Global investments in energy supply technology (energy supply and conversion to power) total hundreds of billions of dollars per year and annual global expenditures on items whose energy-using characteristics are potentially important to their marketability (vehicles, buildings, industrial machinery, etc.) run into the trillions. When and where energy becomes scarce or expensive, recession, inflation, unemployment, and the frustration of aspirations for economic betterment are the usual results.

Energy is no less crucial to the environmental dimensions of human well-being than to the economic ones. Energy supply, electricity production, and energy end-use have greater impacts on the environment than any other peaceful human activity. It accounts for a striking share of the most troublesome environmental problems at every geographic scale—from wood smoke in Third World village huts, to regional smog and acid precipitation, to the risk of widespread radioactive contamination from accidents at nuclear-energy facilities. The public places a high priority on having a clean environment.

If current energy supply and use patterns persist, the expected future growth will lead to increasing environmental emissions of global pollutants such as greenhouse gases, as well as regional and local pollutants. The importance of finding cost-effective means of reducing greenhouse gas emissions cannot be overemphasized. The Framework Convention on Climate Change (FCCC) and the Kyoto and Buenos Aires meetings (in December 1997 and November 1998, respectively) where most of the world's nations agreed to devise feasible, acceptable means for reducing greenhouse gas emissions, demonstrate the importance of climate change issues to the world community. Scientific and technical advances applicable to energy conversion and use, along with regulatory and other public policies compatible with a reduction

in greenhouse gas emissions, will be essential towards meeting internationally agreed upon reduction goals. As the President's Committee of Advisors on Science and Technology stated in its November 1997 report:

> *"…there is a significant possibility that governments will decide, in light of the perceived risks of greenhouse-gas-induced climate change and the perceived benefits of a mixed prevention/adaptation strategy, that emissions of greenhouse gases from energy systems should be reduced substantially and soon…because of the large role of fossil fuel technologies in the current U.S. and world energy systems, the technical difficulty and cost of modifying these technologies to reduce their carbon dioxide emissions, their long turnover times, their economic attractiveness compared to most of the currently available alternatives, and the long times typically required to develop new alternatives to the point of commercialization, the possibility of a mandate to significantly constrain greenhouse-gas emissions is the most demanding of all the looming energy challenges…"* [3]

The importance of energy to national economies and the fact that more than a quarter of the total world energy supply (including more than half of the oil) is traded internationally, make energy a national security issue as well as an economic and environmental one. Gaining or protecting access to foreign energy resources has been a contributing motivation in a number of major conflicts during the twentieth century and could be again in the twenty-first. Another national security dimension of energy is the potential for large-scale failures of energy strategy with economic or environmental consequences serious enough to generate or aggravate social and political instability. This is a concern in both developing and industrialized countries.

It should be clear by now that living in a global economy as we and other nations do, means that one fundamental base of that economy, the energy system, is interconnected and interdependent between nations. All nations share common interests in economic, energy, and environmental security. Consequently, U.S. participation in international cooperative activities is essential to ensure its energy security, economic, and environmental interests are properly addressed as part of the global economic/energy equation.

Comprehensive National Energy Strategy

Improvements in energy technology and the widespread penetration of these improvements in the marketplace in the twenty-first century are necessary to enhance the positive connections between energy and economic well-being and to ameliorate the negative connections between energy and environment and between energy and international security. Thus, technological improvements can lead to lowering the monetary and environmental costs of supplying energy, reducing its effective costs by increasing the efficiency of its end uses, helping to minimize our dependence on oil imports, slowing the buildup of heat-trapping gases in the atmosphere, and enhancing the prospects for environmentally sustainable and politically stabilizing economic

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[3] Federal Energy Research and Development for Challenges of the Twenty-First Century, Report of the Energy Research and Development Panel, The President's Committee of Advisors on Science and Technology; November 1997, pp. ES10 & ES11.

development in many of the world's potential trouble spots.

To address these energy-related challenges, the Department of Energy engaged in an interactive strategic planning process, involving other agencies and energy stakeholders, that produced the Comprehensive National Energy Strategy (CNES) in April 1998. This strategy is based on five common-sense goals:

- Improve the efficiency of the energy system.
- Ensure against energy disruptions.
- Promote energy production and use in ways that respect health and environmental values.
- Expand future energy choices.
- Cooperate internationally on global issues.

A more complete description of the CNES strategic goals and objectives is shown on the following page.

The Comprehensive National Energy Strategy at a Glance

Goal I. Improve the efficiency of the energy system—making more productive use of energy resources to enhance overall economic performance while protecting the environment and advancing national security.

Objective 1. Support competitive and efficient electric systems.
Enact electric utility restructuring legislation, develop advanced coal/gas power plants, improve existing nuclear power plants

Objective 2. Significantly increase energy efficiency in the transportation, industrial, and buildings sectors by 2010.
Develop more efficient transportation, industrial, and building technologies

Objective 3. Increase the efficiency of Federal energy use.
Adopt new/innovative energy-efficient and renewable technologies

Goal II. Ensure against energy disruptions—protecting our economy from external threat of interrupted supplies or infrastructure failure.

Objective 1. Reduce the vulnerability of the U.S. economy to disruptions in oil supply.
Stabilize domestic production, maintain readiness of Strategic Petroleum Reserve, diversify import sources, reduce consumption

Objective 2. Ensure energy system reliability, flexibility, and emergency response capability.
Ensure reliable electricity/gas supply, refining, and emergency response

Goal III. Promote energy production and use in ways that respect health and environmental values—improving our health and local, regional, and global environmental quality.

Objective 1. Increase domestic energy production in an environmentally responsible manner.
Increase domestic gas production, recover oil with less environmental impact, develop renewable technologies, maintain viable nuclear option

Objective 2. Accelerate the development and market adoption of environmentally friendly technologies.
Increase near-term deployment, expand voluntary efforts, design domestic greenhouse gas trading program, work with developing countries, design international trading/credit system

Goal IV. Expand future energy choices—pursuing continued progress in science and technology to provide future generations with a robust portfolio of clean and reasonably priced energy sources.

Objective 1. Maintain a strong national knowledge base as the foundation for informed energy decisions, new energy systems, and enabling technologies of the future.
Pursue basic research, including research on carbon/climate; support energy science infrastructure

Objective 2. Develop technologies that expand long-term energy options.
Develop long-term options, such as fusion, hydrogen-based systems, and methane hydrates, that can have major impacts

Goal V. Cooperate internationally on global issues—developing the means to address global economic, security, and environmental concerns.

Objective 1. Promote development of open, competitive international energy markets, and facilitate the adoption of clean, safe, and efficient energy systems.
Encourage adoption of favorable legal/policy framework in other countries, promote clean/efficient energy systems, and science/technology collaboration

Objective 2. Promote foreign regional stability by reducing energy-related environmental risks in areas of U.S. security interest.
Prioritize concerns and develop cost-effective solutions

From Strategic Planning to R&D for Required Technologies

Research and development is the only systematic means for creating the needed technical improvements and, therefore, is a necessary (although not always sufficient) condition for improving the energy systems that are actually deployed to meet strategic objectives. What is deployable today is the result of the energy R&D that was done in the past; what will be deployable in the future depends on the R&D that is being done now and will be done tomorrow. It is important to understand, moreover, that while some kinds of energy R&D can bring quite rapid returns (such as research on finding oil and gas or improving the efficiency of electric light bulbs or motors), the time scales on which most kinds of energy R&D exert a significant influence on deployed energy systems are longer. This relates not only to the time required to complete the R&D, but also to the long turnover times of most energy supply and energy end use equipment. On the supply side, for example, electric power plants and oil refineries have a useful life of 3 to 5 decades; on the end-use side, residential and commercial buildings last for 5 or more decades. Even the stock of automobiles and major household appliances takes 10 years or so to turnover.

The Energy Resources R&D Portfolio

The Department of Energy, in seeking to characterize and integrate the many programs which make up its energy resources R&D, developed an Energy Resources R&D Portfolio. The PCAST panel succinctly captured DOE's Energy Portfolio challenge when it stated:

> *"Developing the appropriate degree of diversity and balance in the Department's overall energy R&D portfolio is difficult. Technologies have many different attributes—cost… performance, risk, return, potential contributions over time to energy and environmental goals, and others. How can one fairly evaluate the many R&D alternatives and select an R&D portfolio that best meets our Nation's goals and needs? No single quantitative measure can encompass the range of relevant attributes."* [4]

DOE assembled its energy resources R&D portfolio recognizing the nature of this challenge, and the continuity implicit in DOE's current research activities, which in part reflect past Congressional guidance and intent. The Department also acknowledged that the complexity and inter-relatedness of the energy system means research in most any scientific or technological area may have direct as well as indirect effects on achieving the common sense goals of the Comprehensive National Energy Strategy. The R&D goals and R&D objectives of the Energy Resources R&D portfolio are shown below and are followed by a figure that illustrates their relationship to the energy R&D programs.

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[4] Federal Energy Research and Development for Challenges of the Twenty-First Century, Report of the Energy Research and Development Panel, The President's Committee of Advisors on Science and Technology; November 1997, p. ES-25.

R&D Goals	R&D Objectives
Reliable and Diverse Energy Supply	▪ Enhancing Domestic Supplies ▪ Producing Clean Fuels
Clean and Affordable Power	▪ Advanced Power Systems ▪ Enhancing Utility Infrastructure
Efficient and Productive Energy Use	▪ Clean and Efficient Vehicles ▪ Efficient and Affordable Buildings ▪ Clean and Productive Industries

Figure 6

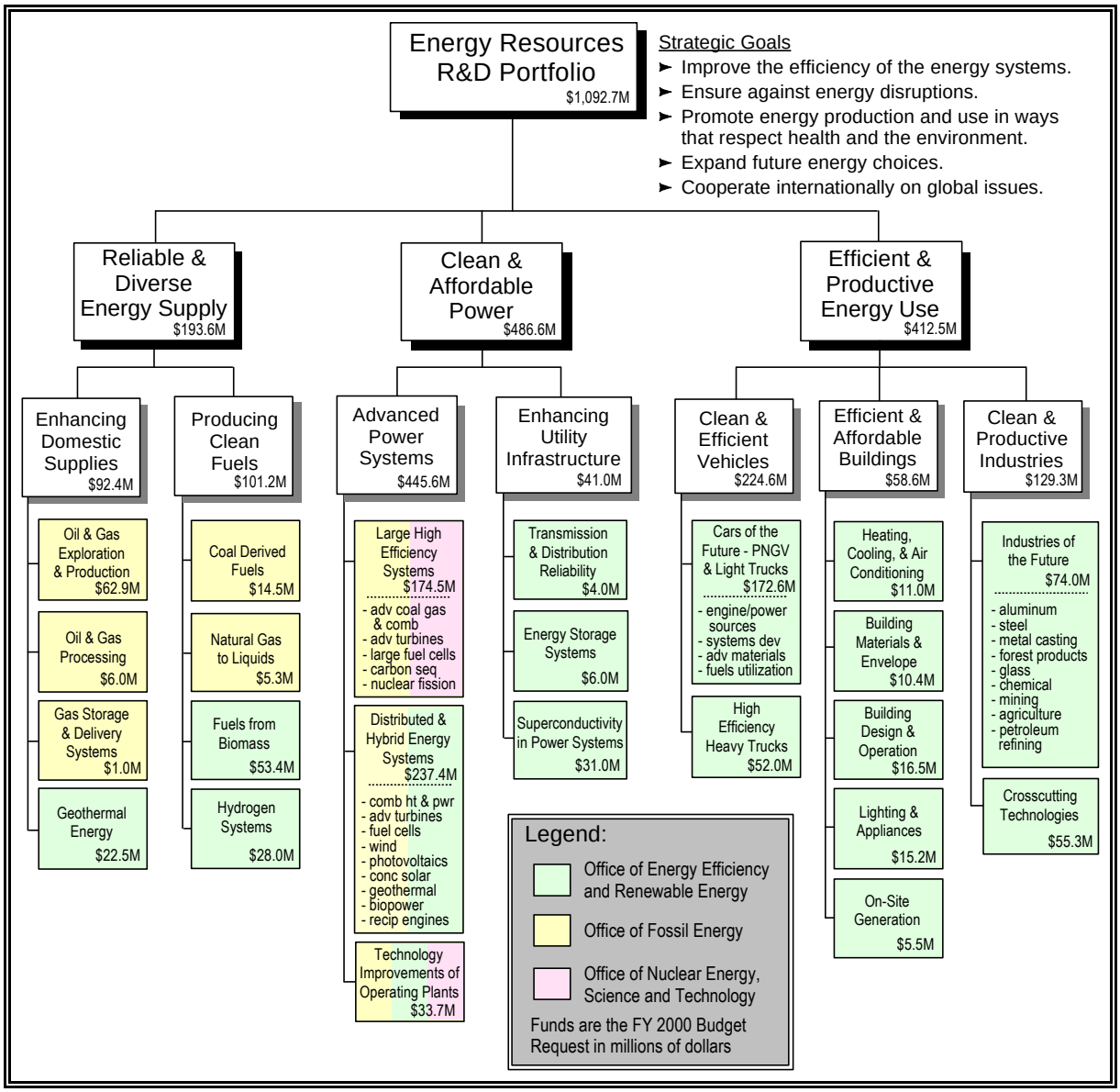


Figure 5

Introduction to the R&D Goals of the Energy Resources R&D Portfolio

To understand the Energy Resources R&D Portfolio, we need to examine each of the energy R&D goals used to best represent how the CNES common sense goals are supported. This sets the stage for the chapters on each of the seven R&D objectives.

Reliable and Diverse Energy Supply

Achieving a reliable and diverse energy supply includes activities involving the exploration, production, refining, storage, and transport of energy resources. These are addressed in the subsequent chapters on **Enhancing Domestic Supplies** and **Producing Clean Fuels**.

Oil and gas account for 63 percent of the total U.S. energy consumption, and 97 percent of transportation fuels. Consumption of oil and gas will continue to increase well into the next century (more than any other source of energy) despite energy efficiency improvements. Therefore, security of supply (primarily oil) remains a prominent issue despite the relative tranquility in the market in recent years. It is projected that by 2015:

- Demand for petroleum in non-industrialized countries will nearly double.
- Domestic consumption of natural gas will increase over 33 percent to 30 trillion cubic feet (tcf) per year, due mainly to its relative cleanliness and cost competitiveness with other fuels.
- U.S. petroleum consumption will increase to more than 23 million barrels of oil per day, of which 60 percent will be imported.
- The Persian Gulf will control over 60 percent of the world petroleum export market compared to 45 percent today.

The effect of supply disruptions is two-fold. First, and most obvious, is the potentially serious impact on our economic well-being. The supply disruptions of the mid and late 1970s amply demonstrated the importance of adequate and reasonably priced energy to the domestic economy. Second, and nearly as significant, is the effect of supply disruptions on other nations and the consequent impact on the global economy, of which the United States is an integral part. Enhancing our domestic energy supplies through technological advances, and cooperating internationally to see such technologies are used elsewhere can protect us from the direct and indirect effects of global supply disruptions, while maintaining U.S. prominence as an innovator and leader in technology development and application.

The Department's approach to address the situation described above and meet U.S. needs to enhance its energy supply is two-pronged. First, it supports research activities designed to reduce the cost of finding new supplies of oil and gas, and to make recovery from existing oil and gas fields larger, more efficient and cost effective. Research in the gas area is particularly attractive because supplies of domestic natural gas appear abundant and gas can

provide a low cost means to slow the rate of carbon dioxide emissions. Appropriate research to foster and nurture the application of new discovery and production technologies is thus an important component of the portfolio supporting the attainment of a reliable and diverse energy supply.

The second prong of the Department's research approach to the reliable and diverse energy supply issue is aimed at developing cost-effective and competitive clean fuels from indigenous sources. Clean fuels include liquid fuels from coal, natural gas, and biomass, as well as hydrogen fuels. These fuels can be used in a manner that significantly reduces environmental impacts compared to conventional fuels. For example, liquid transportation fuels from coal, natural gas, and biomass are well-suited for advanced, clean, high efficiency engines. This is important because of the large contribution that vehicles make to urban and regional pollution. Fuels from biomass, and in the longer term, hydrogen from renewables, can help reduce greenhouse gas emissions. Carbon emissions, which account for over 80 percent of U.S. greenhouse gas emissions, are projected to increase 33 percent by 2020. Clean fuels can potentially be provided in significant quantities. Therefore, not only can they help decrease greenhouse gas emissions and other air pollutants; clean fuels also can offset oil imports, thus contributing to a reliable and diverse energy supply.

Clean and Affordable Power

Achieving clean and affordable power includes research focused on developing a better suite of electro-technologies. This involves electricity generation and energy transmission and distribution. These areas are addressed in the subsequent chapters on **Advanced Power Systems** and **Enhancing Utility Infrastructure**.

Electricity generation represents the conversion of energy from a primary source (fossil fuel, uranium, or renewable forms) into a clean, easily transported, and flexible secondary energy source with innumerable uses. U.S. electricity generation has grown almost every year during the past four decades. The United States is the world's largest producer of electricity, generating more than all of Western Europe and Japan combined. More than half of all domestic electricity is generated by burning coal; about one-fifth is derived from nuclear power plants; renewable resources, primarily hydropower, provide about one-eighth; and the remainder is fueled by natural gas (about 9 percent) and oil (about 2 to 3 percent).

The electric power sector is the largest direct consumer of energy in the United States. It used 36 percent of all primary energy consumed in the country in 1996, while providing power worth approximately $200 billion annually to serve 120 million U.S. residential, commercial, and industrial electricity customers. Most energy projections show the United States requiring an increase of 100,000 to 200,000 megawatts of power generation capacity by 2010. Electricity generation currently contributes 35 percent of the carbon emissions in the United States resulting from human activities. Adding more power without compromising the Nation's environmental standards is therefore essential to sustaining the Nation's economic growth, while at the same time protecting the health of our citizens and the environment.

The U.S. electric power industry is restructuring itself to become more competitive. The reasons why are many and varied, but the Congress, as well as State legislatures and Federal and State regulators have acknowledged that competition in electric supply is both possible and desirable. They have thus taken steps to foster it. In response to increased competitive pressures, utilities and other companies that traditionally have invested significantly in power generation research have reduced or eliminated these investments. At the same time, many power generators, either in response to public pressure or State and Federal regulatory trends, are seeking to diversify their fuel choices and add renewable energy resources to their fuel mix.

To meet the needs and challenges of insuring the country continues to have adequate, reliable, and environmentally sensitive electric power supplies in an evolving competitive market, the Department is pursuing research in advanced power systems; both large-scale high efficiency systems and smaller distributed power systems. Research to help make traditional large-scale power systems more efficient has been ongoing and will continue. This research includes advanced coal gasification and combustion systems, advanced gas turbines, large-scale fuel cell power systems, next-generation nuclear fission systems, and combined heat and power systems. Important research on carbon sequestration is also being supported. Smaller distributed power systems can enhance the efficiency of the transmission system and in some cases provide a lower cost alternative to new large-scale power systems. Expansion or strengthening of the existing transmission and/or distribution network by distributed power systems is a relatively new and very promising concept. Department supported research on distributed power systems includes distributed fuel cells, wind energy, photovoltaic systems, solar concentrators, and smaller, efficient reciprocating engines.

Because it powers other critical infrastructures such as telecommunications, water supply, and transportation, electric infrastructure is basic to the functioning of U.S. society. As the competitive electric marketplace unfolds, the Nation's utility infrastructure will be asked to operate in ways for which it was not designed. A host of new technologies will be required throughout the grid and at customer locations to optimize performance and reliability. These systems will make the benefits of advanced energy conversion technologies and renewable resources available to the Nation. DOE's energy resources R&D portfolio thus contains components addressing the need to upgrade electric infrastructure systems. These include research into electrical storage systems and utility systems and network areas such as real time system control, power electronics, distributed utility applications, and high capacity transmission.

Efficient and Productive Energy Use

Attaining efficient and productive energy use involves research in both end-use and processing. These are addressed in the subsequent chapters on **Clean and Efficient Vehicles**, **Efficient and Affordable Buildings**, and **Clean and Productive Industries**.

Energy is consumed in the three basic demand sectors of our economy—transportation, industry, and residential and commercial buildings. Nearly all (97 percent) of transportation

energy comes from petroleum, and transportation energy use accounts for about two-thirds of the petroleum consumed in the United States. The explosive popularity of low fuel-economy pickup trucks, vans, and sport utility vehicles used for personal transport, coupled with a growing economy, falling fuel prices, increasing numbers of drivers, and increasing miles traveled by each vehicle is pushing transportation fuel consumption higher. This situation will not change without a significant improvement in vehicle fuel efficiency. R&D must be undertaken to significantly reduce transportation's dependence on oil, to reduce vehicle emissions, thereby improving urban air quality, and to maintain the economic competitiveness of a major industrial sector of the economy. Specific DOE R&D activities in the transportation sector include fuel cell development, high power storage, power electronics, work on advanced materials, natural gas storage technologies, and high efficiency engines.

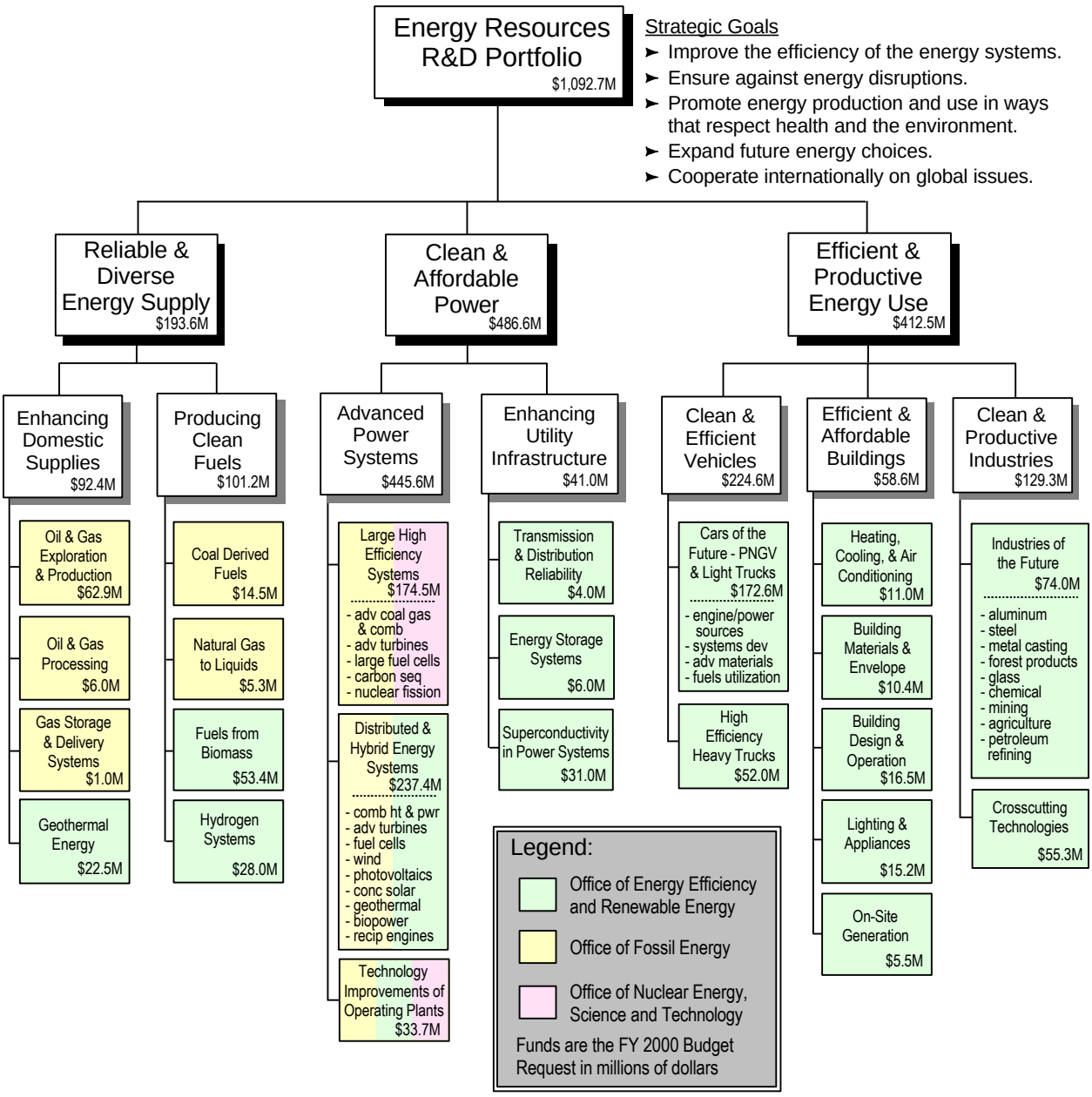
The United States consumes roughly 94 quadrillion Btu's (quads) of primary energy. The Nation's 80 million homes and commercial buildings consumed 36 percent or 34 quads of this total. Buildings also consume two-thirds of all electricity generated nationally. More than $230 billion is spent each year in the United States to provide heating, cooling, lighting, and related energy services for buildings. As more buildings are constructed, even with improvements in energy efficiency, energy consumption and associated economic and environmental costs will likely continue to rise. Energy consumption in buildings is a major cause of acid rain, smog, and greenhouse gas emissions in the United States, representing 35 percent of carbon dioxide emissions, 47 percent of sulfur dioxide emissions, and 22 percent of nitrogen oxide emissions. Given the large opportunity in the buildings sector for resource conservation and minimization of pollutant emissions, the Department has and continues to conduct important R&D related to buildings. This R&D includes high efficiency heating and cooling systems, building materials, building design and operation, advanced lighting systems, and appliances (e.g., refrigeration and water heaters, including solar hot water heaters).

Industry accounts for about 38 percent of U.S. energy consumption and relies on a mix of fuels to produce a myriad of products and services. The industrial sector contains extraction, material processing, and product manufacturing industries. By far, the bulk of energy consumption, emissions, and waste occurs in the processing industries, as well as in a few extraction industries. These process industries, such as steel, chemicals, aluminum, glass, forest products, and metal casting are highly capital intensive, have far larger energy and pollution abatement costs per unit sales, and typically invest far lower percentages of sales into research and development than the U.S. average. Two extraction industries, mining and agriculture, have somewhat similar characteristics. Reducing energy costs, waste, and environmental emissions are key to increased productivity, quality, profitability, and global competitiveness. The Department's R&D activities are grouped by industry, with crosscutting research in enabling technologies (e.g., ceramics, alloy/polymers, sensors and controls) supporting work in the 9 industrial groups.

The Role of the Government in Energy-Related R&D

The long time scale required for energy R&D to exert significant influence on deployed energy systems is one reason that energy R&D is not and should not be left entirely to the private sector; even in a free enterprise based economic system such as that of the United States. It is in society's interest to pursue, as part of its strategy for preparing for an uncertain future, some potentially high payoff energy alternatives. The combination of long time horizons, uncertain economic returns, technological risk, and cost of research, development, and deployment makes investing in R&D unattractive to private firms. Another reason for a government role in R&D is that some of the most desirable improvements in energy technologies relate to "externalities" (such as environmental impacts) and to "the public good" (such as national security) that are not valued in the marketplace and hence do not generate the market signals to which firms respond. Still another reason is that the fruits of some kinds of R&D are difficult for any one firm or small group of firms to capture, even though these innovations may be highly beneficial to society as a whole. Finally, the structure of particular energy industries and markets may mask or dilute incentives for firms to conduct R&D from which they, their customers, and society as a whole would all greatly benefit. All of these reasons support publicly funded R&D as one means of insuring continued economic prosperity, environmental quality, and energy security.

Chapter 2
Portfolio Analysis



Chapter 2
Portfolio Analysis

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The Context for the Energy Resources R&D Portfolio

The availability of low-cost energy supplies and efficient energy services have been critical to the Nation's prosperity. Technological advances resulting from both Federal and private sector R&D investments have reduced the cost of energy production and electricity, enhanced the ease and affordability of transportation, improved the comfort and utility of buildings, and supported a vibrant and competitive industry, while also limiting or reducing environmental damage.

One example of the impact of the technological advances is the fact that in the post-1970s era the rate of economic growth, as measured by the Gross Domestic Product (GDP), has outpaced the rate of primary energy consumption (see Figure 7). While both GDP and primary energy consumption have risen, and are projected to continue to do so, energy intensity—the ratio of energy consumption to GDP—is forecasted to continue to decrease. Technological advances that led to improvements in primary energy production, energy conversion and delivery, and energy end use in our buildings, industrial sector, and transportation systems have been a key driver of the decrease in energy intensity.

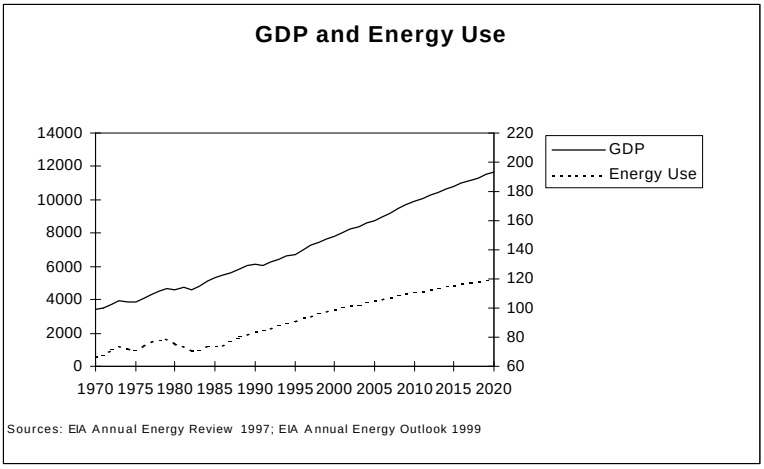
While energy use per GDP has been decreasing, energy use per capita has been increasing in the 1990s due to low energy prices and changing consumer habits and preferences (e.g., suburbanization, larger vehicles and buildings), as well as an increase in the use of electrical appliances in our homes and businesses (e.g., air conditioners, computers, motors, etc.). Assuming energy and electricity prices remain low into the twenty-first century, this trend is projected to continue, although at a modest rate due to technological advances (see Figure 7). When coupled with an increasing population, the net effect is a projected increase in energy consumption. At the same time, the Energy Information Administration (EIA) is projecting a much smaller increase in domestic energy production. Thus we are facing a growing disparity between energy use and energy production in the years ahead (see Figure 7). If this situation occurs, America will be increasingly reliant upon energy imports, particularly oil imports, to meet energy needs in the twenty-first century.

America's expanding energy needs will present a number of challenges for the Nation in the coming years, a few of which are highlighted here. First, the Nation will face increasing energy demands in all three sectors (see Figure 8):

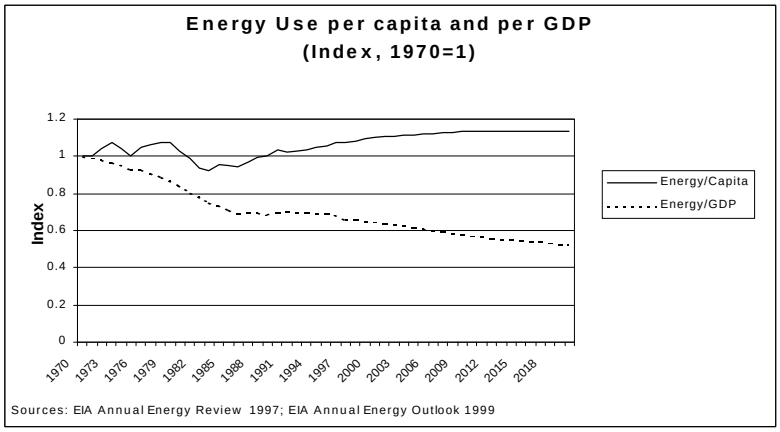
- In buildings, to energize expanding building stocks for the commercial services and in the home, comfort and entertainment of an increasing population.
- In industry, to power the industrial production for expanding GDP.
- In transportation, to meet the Nation’s increasing household and industrial transportation demands.

It is generally accepted that while shifts in the makeup of energy supplies and use patterns will occur, there are no single “silver bullet” technologies to address the energy demands across the three sectors. Instead, the Nation will continue to require a broad portfolio of energy resource,

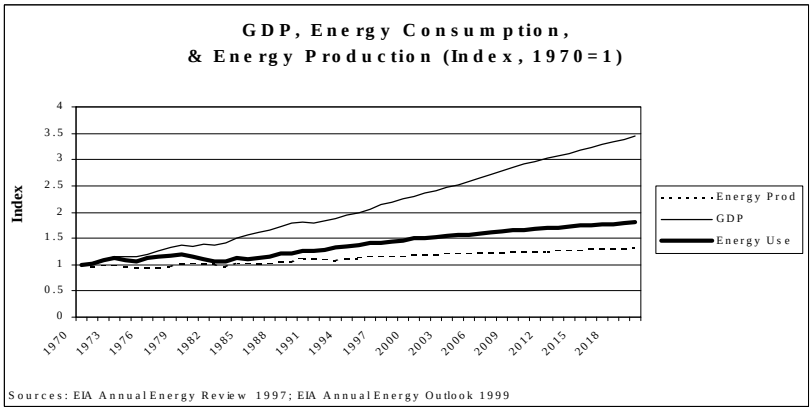
production, conversion, delivery and storage, and end-use technologies to meet the growing energy needs of the buildings, industrial, and transportation sectors.



GDP growth is expected to continue at approximately the level of the past 2 decades. Energy use is also expected to increase, at a somewhat lower rate than GDP.

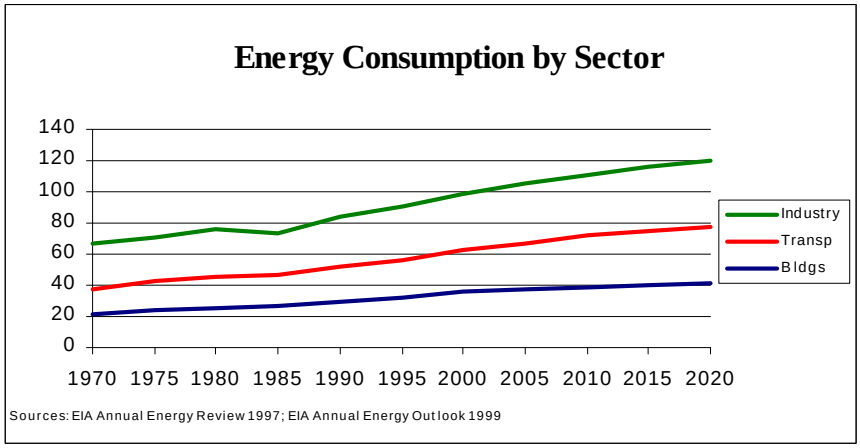


Energy use per unit of GDP is projected to continue to decrease. Advancing technology and shifts to less energy intensive industries are the primary contributors to that decrease. However, energy per capita is expected to continue to grow slowly.

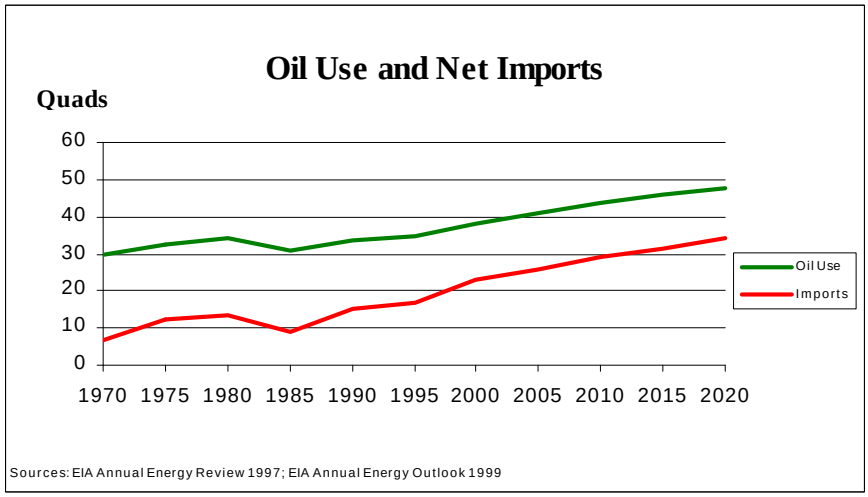


Domestic energy production is projected to continue to lag energy consumption, implying an increasing dependence on imports.

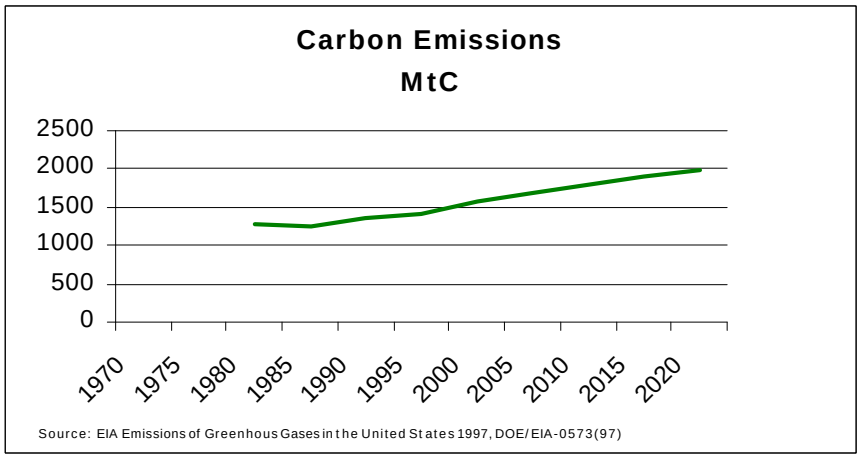
Figure 7



The growth in energy consumption is occurring across all three energy sectors.



Total petroleum consumption and petroleum imports are projected to continue to rise steadily, with imports representing 65% of total use by 2020.



Carbon emissions have risen steadily since 1990 and that trend is projected to continue under current laws and regulations.

Figure 8

A second energy challenge facing the Nation is the forecast growth in oil imports, up from about 50 percent of total use today to 65 percent in 2020 (see Figure 8). This has both economic and national security implications for the country. Economically, it represents a massive export of U.S. dollars and jobs to foreign countries. From a national security standpoint, it means that our country will become increasingly dependent upon foreign oil reserves in the 21st century, should recent trends continue. This challenge makes the Department's R&D activities that are designed to increase the availability of low-cost domestic oil or alternative fuels (e.g., biofuels) a prudent investment for the country's continued economic well-being and national security.

A third energy challenge facing the Nation is reflected in the growing concerns about the emissions associated with the current approaches to fossil energy recovery and use, both locally as smog and regionally through transmission by winds, and even globally in the form of emissions of greenhouse gases. For example, energy production and use are the primary sources of the Nation's carbon emissions, accounting for 98 percent of total U.S. carbon emissions in 1997 (Source: EIA "Emissions of Greenhouse Gases in U.S. 1997). With increasing energy consumption, and absent any change in energy policies or regulations, carbon emissions are projected to increase about 33 percent over 1997 levels by 2020. The Department's Energy Resources R&D Portfolio is addressing the carbon emissions challenge by investing in a variety of clean fuel options, such as natural gas and renewable energy technologies, as well as energy efficiency technologies applicable to the buildings, industry, transportation, and utility sectors.

The composition of the Energy Resources R&D Portfolio has evolved over the past few decades as our understanding of energy system challenges and technological opportunities have developed. For example, 10 years ago the concerns about carbon emissions were not widely shared. Today, however, advances in our scientific understanding of global warming have raised a number of concerns about carbon emissions that have led to an R&D investment in a number of carbon management technology options. As another example, conversion of natural gas to liquid fuels is receiving increased attention because it could enable use of large, remote domestic natural gas supplies to alleviate our need for imported oil. Finally, R&D on technologies such as fuel cells is increasingly emphasized today with our expanding appreciation of the conversion efficiency and low emissions potential of that technology for both stationary and transportation power systems.

In summary, the Nation is facing a range of serious challenges associated with our future energy economy. The Department's Energy Resources R&D Portfolio, which is described in detail in this report, is focused on addressing those challenges. The contents of this portfolio have been defined and are continually re-focused through an ongoing process of portfolio planning and analysis and technology roadmapping activities. The results of those processes are presented annually to the Nation in the Administration's budget request for this Energy Resources R&D Portfolio.

The Energy Resources R&D Portfolio in Brief

This section provides summary information on some of the key characteristics of the Energy Resources R&D Portfolio, including range and types of R&D activities, budgets, and R&D performers. Detailed information on the portfolio is presented in the following seven chapters. In addition, Chapter 10 discusses basic science programs that provide fundamental research support for the entire Energy Resource R&D Portfolio.

DOE and Private Sector R&D Funding

Research and development funded by DOE must be considered in context with that being funded by the private sector and others. While DOE has a large energy R&D program, it represents less than one-half of what is spent by the private sector, and probably considerably less than that given limitations in data availability of private sector R&D activities (see Figure 9). This perspective has a bearing on the appropriate Federal role, areas of focus, and approaches to Federal and Federal-private sector collaborative R&D.

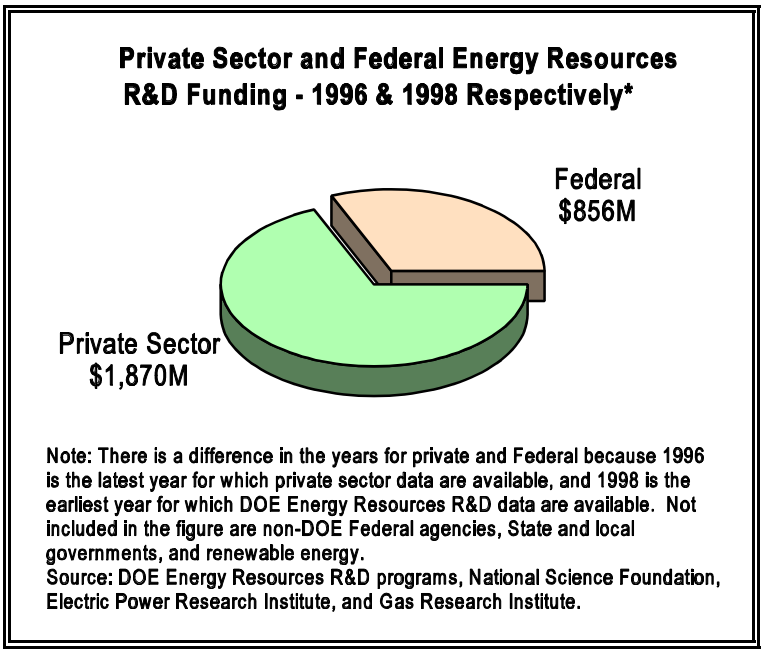


Figure 13

There are several considerations that are important for understanding the roles of the private sector and the Federal government in energy R&D. The private sector is very diverse, encompassing large companies, many of which are highly profitable, as well as areas containing mostly small start-up companies or not-yet profitable companies. Other factors include imperfections in the marketplace, the potential to affect national needs such as national security or environmental quality, the regulatory environment, and changes in R&D funding levels in

recent years—increasing in some industries and decreasing in many more. These all vary between industries and affect the prioritization and focus of DOE's R&D portfolio in each program area.

Typically, industry concentrates on near-term R&D and deployment of relatively mature technologies, while the DOE portfolio focuses more on mid-to long-term R&D—although there are exceptions in both cases. The ratio of Federal to private funding is much higher during the earlier and higher R&D risk stages and decreases during the innovation stages of product development and testing until, at the marketing and commercialization stages, it is essentially wholly a private sector undertaking. Another trend is the increasing collaboration and partnering between companies as well as between industries and DOE. The Department cost-shares with industry during the development stage.

The major energy producers (e.g., integrated oil and gas producers, refiners, and transporters) provide the largest portion of private sector energy R&D funding, representing $1.3 billion of the $1.9 billion private sector energy R&D total.[5] This is down from a peak of over $3 billion in 1991, and represents a considerable contraction of private sector funding for energy-related research, in part due to falling energy prices. Moreover, this R&D is aimed principally at improving the discovery, extraction, production, and refining of liquid, gaseous, and solid fossil fuels. Funding by the electricity industry has also declined significantly in recent years, in part due to uncertainties associated with restructuring of electricity markets.

There are significant limitations in our knowledge of the total energy R&D expenditures by the private sector and others. Most significant is in the area of energy efficiency. Much of the data are proprietary and not reported. Even more significant is that much of the R&D in this area is multi-purpose and advances in energy efficiency might be a secondary motivation for the R&D investment. For example, technological advances may be undertaken to improve industrial processes for better process quality control which at the same time increase energy efficiency. The development of new technology for a piece of equipment may be undertaken in such a way that the new product would have higher performance, more rapid throughput, and use less electricity at the same time. Hence, that portion of individual R&D activities associated with energy reduction cannot be isolated. The expenditures of this type are likely to be in the hundreds of millions of dollars, and if aircraft and military products were included, likely very much more.

For similar reasons, the R&D programs of non-DOE Federal agencies are not included in Figure 9. There also is energy research funding provided by some State governments and by the renewable energy industries that is not captured in the totals provided in Figure 9; however, the

[5] This estimate is based on the $1.3 billion reported by the National Science Foundation's *Survey of Industrial Research and Development for 1996*, plus an estimated $560 million by the Electric Power Research Institute and Gas Research Institute. The U.S. Energy Information Administration's Financial Reporting System reported total R&D expenditures of $2.7 billion in 1996, of which $1.6 billion was for "nonenergy" R&D (primary chemicals and petrochemicals). Given the differences in the survey methodology, these data correspond closely to the National Science Foundation survey.

ratio of DOE to other funding sources would not be significantly affected by inclusion of these expenditures.

Energy Resources R&D and Energy Services

The Energy Resources Business Line of the Department—the Offices of Fossil Energy; Nuclear Energy, Science and Technology; and Energy Efficiency and Renewable Energy—support both R&D programs and efforts providing other energy services. These energy service activities are beyond the definition of R&D in the rigorous sense as defined by OMB, and as utilized in this report. Research and development programs constitute approximately 60 percent of the DOE

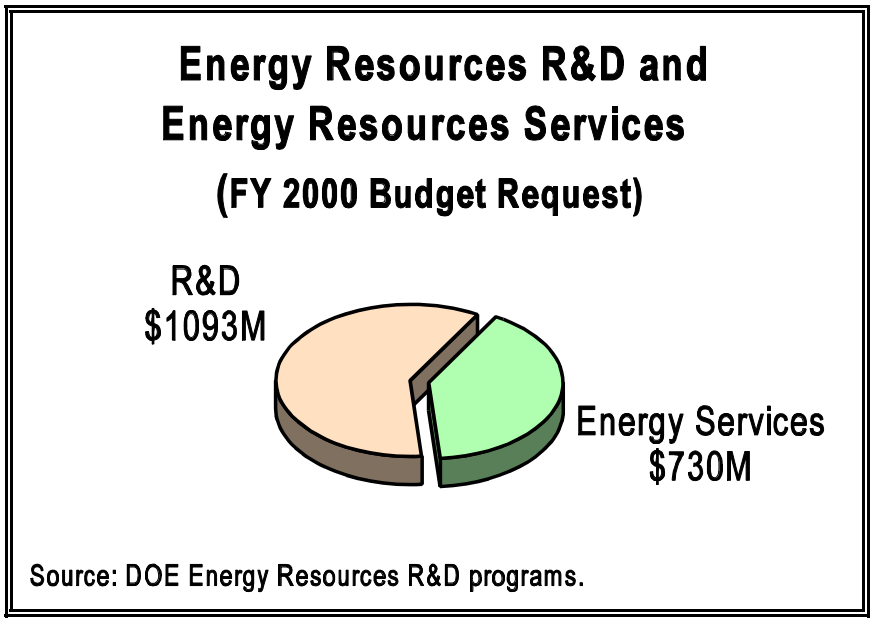


Figure 14

Energy Resources R&D budget and energy services represent the remaining 40 percent (see Figure 10).

Important examples of energy service activities include the Strategic Petroleum Reserve ($164 million) that provides a reserve supply of oil to support national security. Another large energy services program is the Weatherization Assistance program ($191 million), wherein the Department provides funding to State agencies which, when supplemented by State and other funding sources, finance energy efficiency improvements for low income households to help reduce their energy costs. Other examples include the development of appliance, equipment, and building codes and standards and consumer information.

DOE Energy Resources R&D Portfolio Budgets

The Energy Resources R&D Portfolio diagram (Figure 11) organizes the portfolio into three broad strategic areas.

- Reliable and Diverse Energy Supply

- Clean and Affordable Power
- Efficient and Productive Energy Use

These areas are particularly well-suited for communicating DOE's R&D activities because they follow a supply/conversion/end-use construct that is familiar to energy system stakeholders, and they create groupings where technology similarities are more easily identified. The budget

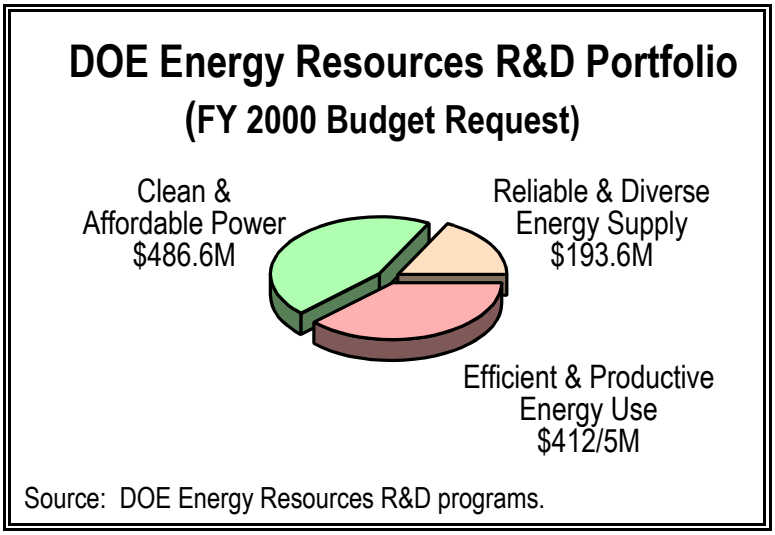


Figure 15

allocation to these strategic areas is displayed in Figure 11.

This resource allocation among the three strategic areas is reasonable when consideration is given to the number of R&D opportunities, associated R&D costs, and the appropriateness of a Federal role.

- Eighteen percent of the portfolio focuses on activities categorized as ***Reliable and Diverse Energy Supply***, that includes R&D to maintain and increase domestic production of oil, gas, and clean alternative fuels. Similar to many power technologies, technologies in this area are frequently characterized by large, complex systems. However, overall funding is lower because the timeframe associated with the development of hydrogen, liquid fuels from natural gas and coal, and some parts of the biofuels R&D portfolio are relatively longer-term. In addition, significant R&D is conducted by the private sector for oil and gas production, particularly activities directed toward near-term operational issues. This allows Federal efforts to focus on high benefit areas beyond industry's short-term focus.

- Funding for ***Clean and Affordable Power*** accounts for 44 percent of total portfolio expenditures. Faced with competitive pressures brought on by electric utility restructuring, industry-funded R&D has decreased from what were already relatively low levels, and were focused more on near-term operational issues. This adds even greater

importance to the Federal R&D role, which has traditionally focused on longer-term power systems opportunities across a broad range of resource and conversion technologies, from coal and gas-fired power plants to nuclear and renewable power systems. There are attractive advanced technology options in all of these areas. This area is also important because power production, which accounts for 36 percent of domestic energy consumption, is one of the most significant contributors to air emissions, including greenhouse gases, and other local/regional pollutants.

- Funding for ***Efficient and Productive Energy Use*** is 38 percent of total portfolio expenditures. Industry R&D in this area, particularly for industrial and building-related efficiency, has historically been low due to the fragmented nature of the industry and the difficulty of any one company capturing sufficient benefits from the R&D. This area has a very high national priority because efficiency not only brings immediate economic benefits, but also offers a relatively quick path for achieving significant air emissions reductions. There are hundreds of technologies in the energy efficiency portfolio (compared to dozens in power generation), reflecting the myriad number of R&D opportunities available. These activities range in size from small scale (electronic controls) to broad complex programs such as the advanced, ultra-high mileage vehicle (PNGV) program.

It should be noted that a nearly equivalent amount of funds support energy-related basic research that provides the scientific underpinnings of the applied energy research and development programs, and which are described in Chapter 10 and the companion Science Portfolio.

Figure 12 shows a breakout of the DOE budgets for the seven portfolio areas shown as the second row of the Energy Resources R&D Portfolio diagram for the FY 2000 request. This figure also shows the more important roles of each of the portfolio areas.

Budgets for 3 years, FY 1998, FY 1999, and the President's request for FY 2000, are provided in Figure 13. This figure indicates that the budgets for the seven different areas are fairly stable over these 3 years. These budget levels reflect the evolution and balancing of R&D opportunities and priorities, as well as the need for Federal support, in these portfolio areas over many years. For example, R&D in ocean thermal energy conversion has been dropped, as we have learned that this technology offers only minimal potential for the United States because of resource and technology performance limitations. On the other hand, developments in biogenetics and in gasification technologies have led to an increased emphasis on R&D of bioenergy technologies. Similarly, the Department is recommending increased nuclear energy R&D as a prudent action, in part, because of concerns over global warming. In addition, recent developments in the understanding of methane hydrates are leading to increased interest in the development of technologies for tapping those vast natural gas resources.

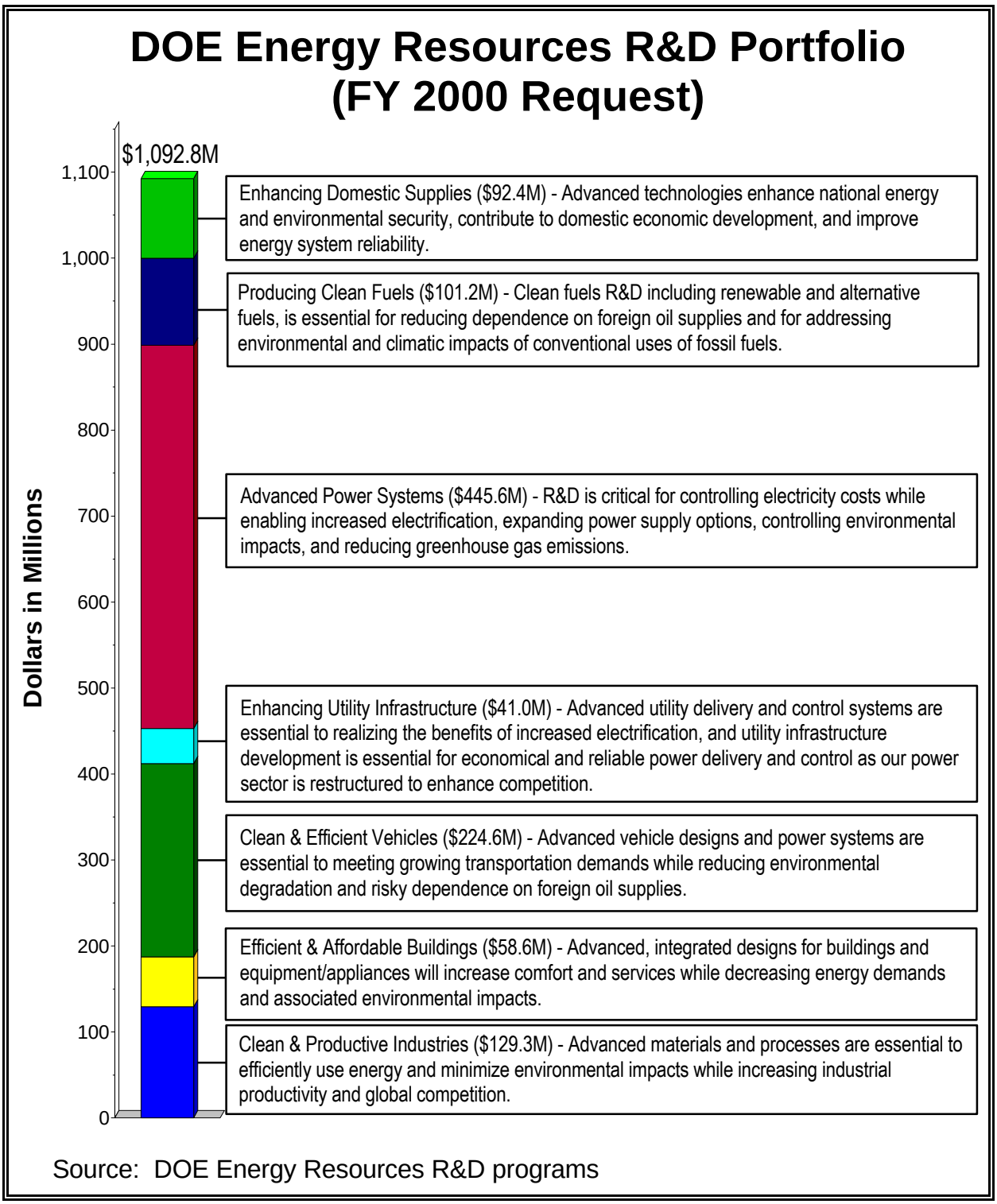

DOE Energy Resources R&D Portfolio
(FY 2000 Request)
$1,092.8M
Dollars in Millions
1,100
1,000
900
800
700
600
500
400
300
200
100
0
Enhancing Domestic Supplies ($92.4M) - Advanced technologies enhance national energy and environmental security, contribute to domestic economic development, and improve energy system reliability.
Producing Clean Fuels ($101.2M) - Clean fuels R&D including renewable and alternative fuels, is essential for reducing dependence on foreign oil supplies and for addressing environmental and climatic impacts of conventional uses of fossil fuels.
Advanced Power Systems ($445.6M) - R&D is critical for controlling electricity costs while enabling increased electrification, expanding power supply options, controlling environmental impacts, and reducing greenhouse gas emissions.
Enhancing Utility Infrastructure ($41.0M) - Advanced utility delivery and control systems are essential to realizing the benefits of increased electrification, and utility infrastructure development is essential for economical and reliable power delivery and control as our power sector is restructured to enhance competition.
Clean & Efficient Vehicles ($224.6M) - Advanced vehicle designs and power systems are essential to meeting growing transportation demands while reducing environmental degradation and risky dependence on foreign oil supplies.
Efficient & Affordable Buildings ($58.6M) - Advanced, integrated designs for buildings and equipment/appliances will increase comfort and services while decreasing energy demands and associated environmental impacts.
Clean & Productive Industries ($129.3M) - Advanced materials and processes are essential to efficiently use energy and minimize environmental impacts while increasing industrial productivity and global competition.
Source: DOE Energy Resources R&D programs

Figure 16

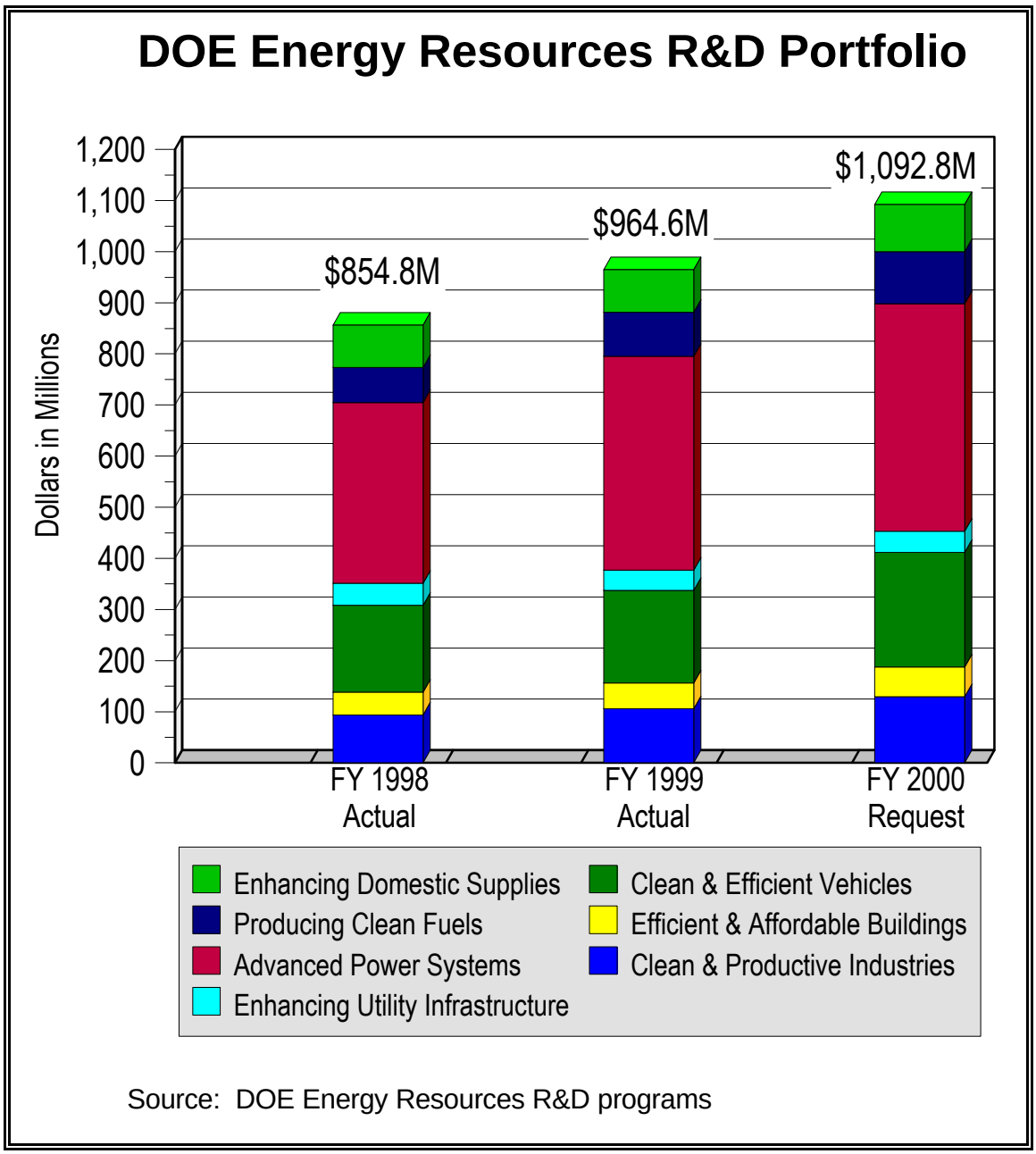


Figure 17

DOE Energy R&D Performers

The Department of Energy uses a broad range of performers in carrying out the Energy Resources R&D Portfolio, including industry, universities, National Laboratories, and other governmental agencies. The budget levels for each of these performers in FY 1998 are displayed in Figure 14.[6]

[6] Intramural refers to R&D performed by Federal employees at DOE or other Federal agencies.

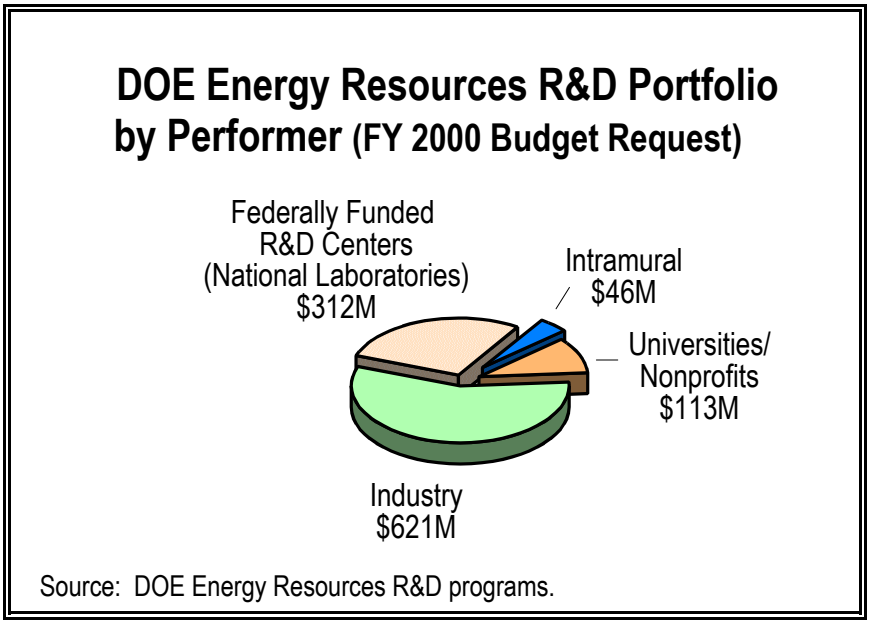


Figure 18

Industry plays the major role, reflecting the importance that the Department places on technology development in the private sector where these technologies must succeed, as well as a strong belief in the effectiveness of public-private research, development, and demonstration (RD&D) alliances which have also been recommended for energy R&D activities (see 11-Lab Report; PCAST; Yergin Report). Many of the R&D projects involving industry are cost-shared with industrial partners.

National Laboratories are used because of their extensive energy technology expertise, including world-class science and engineering staff who have conducted and managed R&D for more than 50 years. The National Laboratories have conducted much of the basic science research that provides the scientific underpinnings for many technology breakthroughs in energy and other areas. They also have a proven ability to successfully develop and evaluate advanced technologies, and they provide unique facilities for use by researchers from industry and academia, as well as by their own researchers, for the development of energy-related technologies.

University researchers contribute both new concepts and in-depth, specialized capabilities. They provide a wealth of scientific and engineering talent to undertake the cutting-edge research required to address the energy-related challenges facing the country. In addition to providing scientific resources, universities are the training ground for the future scientists and engineers needed to sustain a national effort to meet the energy goals contained in the Comprehensive National Energy Strategy.

Types of Energy R&D

The Department's R&D work in energy falls under three categories as defined by the Office of Management and Budget (OMB): basic research, applied research, and development (see

Figure 15). Basic research is defined as systematic study directed toward greater knowledge or understanding of the fundamental aspects of phenomena and of observable facts without specific applications towards processes or products in mind. Applied research is defined as systematic study to gain knowledge or understanding necessary to determine the means by which a recognized and specific need may be met. Development is defined as systematic application of knowledge toward the production of useful materials, devices, and systems or methods, including design, development, and improvement of prototypes and new processes to meet specific requirements.

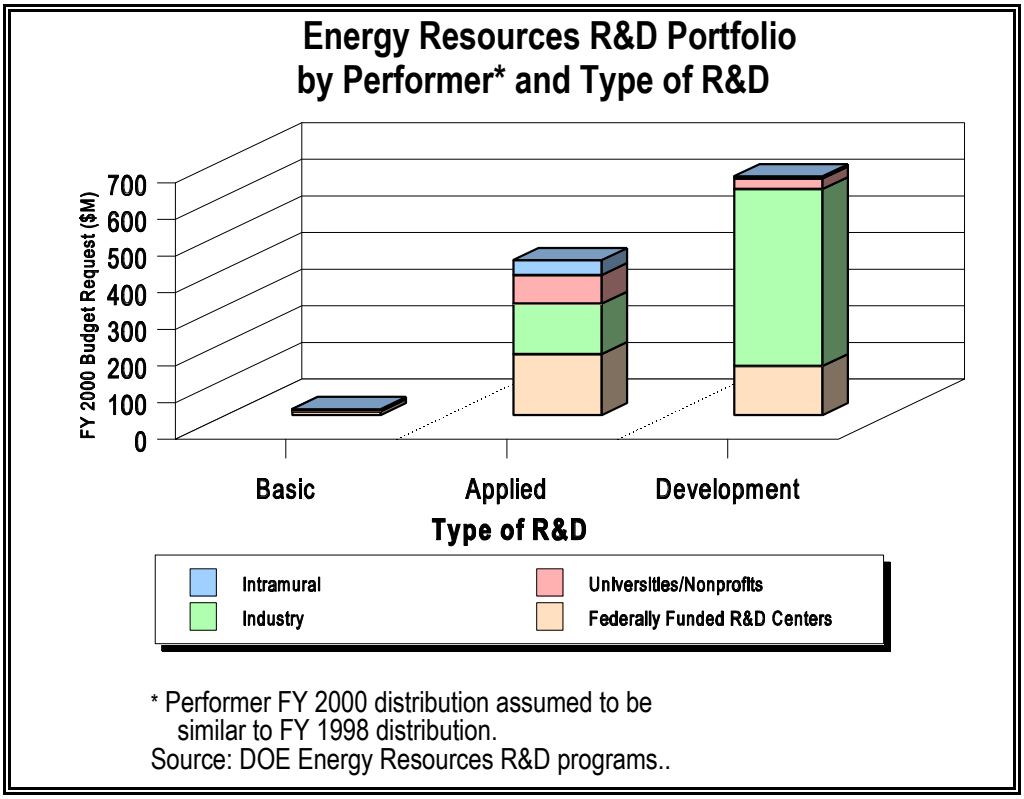


Figure 19

The majority of the Energy Resources R&D funding, 61 percent ($663 million), is devoted to technology specific developmental work, and the bulk of this work is performed by industry and National Laboratories (see Figure 16). This R&D generally attempts to produce a technological prototype that is at sufficient scale to convince industry to move to the commercialization stage. This is generally the most expensive precommercialization step, and because profit potential is emerging at this point, the Department seeks the greatest amount of cost share in this stage. As an example, an Office of Fossil Energy-led team including industry, a National Laboratory, and several government organizations is developing alternative diesel fuel via the Fischer-Tropsch (F-T) indirect liquefaction process. The fuel has been shown in preliminary engine tests to produce much lower emissions than its petroleum-derived counterparts, which has generated strong interest among the diesel engine manufacturers. The cornerstone to this development effort is the LaPorte, Texas, proof-of-concept facility where successes in the laboratory are

transferred into the production of fuel, as was demonstrated in the FY 1998 F-T operation where more than that fuel was produced in the advanced slurry reactor for further evaluation.

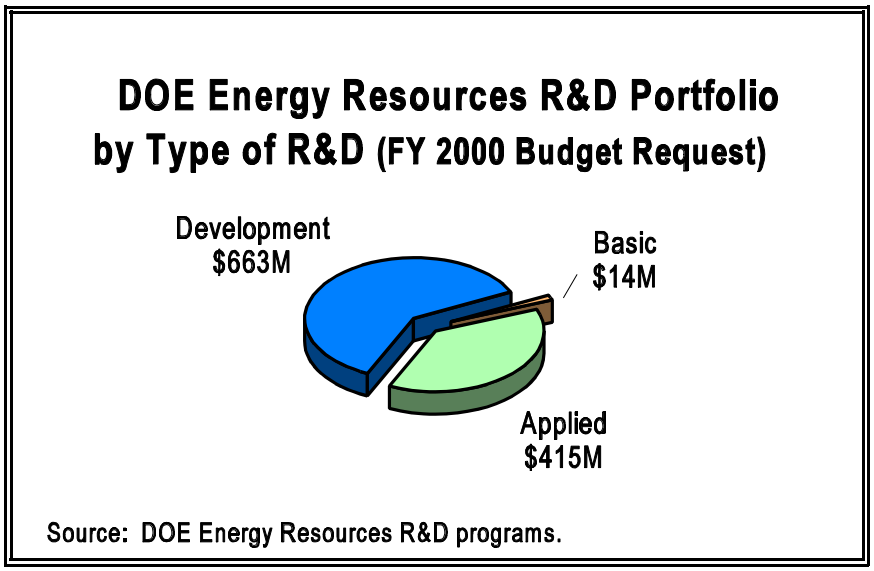


Figure 20

Approximately 38 percent ($415 million) of energy R&D is applied research. The Department's energy resources R&D places significant emphasis on applied work which helps bridge the gap between fundamental science and marketable technologies. In this effort, we seek to apply the capabilities of the National Laboratories, universities, and industry to the resolution of specific technical barriers to the use of cleaner, more efficient energy processes (see Figure 16). For example, fuel cell research for transportation applications places particular emphasis on applied research of fuel cell materials and components to achieve high efficiency, long life, and low manufacturing costs. This work is directed at component development, subsystem development, and technology integration and validation for stacks, fuel processors, and hydrogen storage. Methanol, ethanol, natural gas, and gasoline are being evaluated as fuels for on-board reforming for fuel use. Industry teams led by Chrysler-Pentastar, Ford, and General Motors are completing development of 10-50 kW fuel cell systems under cost-shared contracts. These projects include both methanol-fueled and direct hydrogen systems.

Only 1 percent ($14 million) of the Energy Resources R&D Portfolio is categorized as basic. The applied energy technology programs (fossil, nuclear, efficiency, and renewables) spend a very small fraction on basic research while relying on the Office of Science to carry out the basic research that provides the foundation necessary to understand the fundamental principles and mechanisms that govern energy technologies. Much of this work is carried out in collaboration with programs in the Office of Science, and the bulk of the research is performed by National Laboratories and universities (see Figure 16). This basic research focuses on areas such as novel methods to produce hydrogen from renewable resources or to fabricate high value carbons, especially those useful for hydrogen storage, membranes and catalysts for fuels processing, and production of high value chemicals from coal.

Energy Resources R&D Portfolio Relation to CNES Goals

The 5 major goals of the Comprehensive National Energy Strategy address the major energy issues discussed in section I. Figure 17 displays the relevance of the 7 Energy Resources R&D Portfolio areas to these 5 CNES goals. The purpose of this chart is to convey in general terms the degree of relevance of each of the seven portfolio areas to each of the CNES strategic goals. The indicators used were developed through a Delphian Technique. Because much of this energy R&D has a mid-to long-term focus, progress in these R&D areas toward CNES goal achievement will also be more substantial over a longer period and less likely in a shorter period such as 5 years.

Clearly, a key characteristic of the energy portfolio is its multi-dimensional interrelationships. More specifically, accomplishing any of the CNES goals requires progress in several of the 7 energy portfolio areas, and, conversely, each of these 7 areas contributes to achievement of several of the CNES goals. This multivariate relationship between strategic energy goals and the DOE Energy Resources R&D Portfolio results from a portfolio design that is intended to simultaneously address several issues, as well as reflecting the complexity and interrelationships of different parts of the energy economy. In short, the whole is greater than the sum of its parts.

Energy Resources R&D Portfolio Relevance to CNES Goals and Objectives

	Improve the efficiency of the energy system.			Ensure against energy disruptions.		Promote energy production and use in ways that respect health and environmental values.		Expand future energy choices.		Cooperate internationally on global issues.	
	Support competitive and efficient electric systems.	Significantly increase energy efficiency in the transportation, industrial, and buildings sectors by 2010.	Increase the efficiency of Federal energy use.	Reduce the vulnerability of the U.S. economy to disruptions in oil supply.	Ensure energy system reliability, flexibility, and emergency response capability.	Increase domestic energy production in an environ-mentally responsible manner.	Accelerate the develop-ment and market adoption of environmen-tally friendly tech-nologies.	Maintain a strong national knowledge base as the foundation for informed energy decisions, new energy systems, and enabling technologies of the future.	Develop technologies that expand long-term energy options.	Promote development of open, competitive international energy markets, and facilitate the adoption of clean, safe, and efficient energy systems.	Promote foreign regional stability by reducing energy-related environmental risks in areas of U.S. security interest.
Enhancing Domestic Supplies	◎			●	●	●	●	(1)	●	◎	(2)
Producing Clean Fuels	○	○		●	◎	●	●	(1)	●	◎	(2)
Advanced Power Systems	●		◎	○	●	●	●	(1)	●	◎	(2)
Enhancing Utility Infrastructure	●	○	○		●		●	(1)	●	◎	(2)
Clean and Efficient Vehicles		●	●	●	●		●	(1)	●	◎	(2)
Efficient and Affordable Buildings	○	●	●	○	○		●	(1)	●	◎	(2)
Clean and Productive Industries	◎	●	◎	○	◎	○	●	(1)	●	◎	(2)

● = Strong Relationship

◎ = Moderate Relationship

○ = Weak Relationship

(1) The majority of this research is basic science

(2) All R&D generically supports this objective.

Note: This chart reflects the relevance and degree to which the R&D activities are aligned with the CNES objectives. It does not predict the ultimate benefits or outcomes of the research and development.

Source: DOE Energy Resources R&D programs.

Figure 17

External Views on Energy Resources R&D Portfolios

An energy R&D program must provide the continuity necessary to bring R&D activities to fruition. At the same time, the Energy Resources R&D Portfolio must change over time to respond to changing national needs and market realities, technology opportunities, and the appropriate government responsibilities. DOE continually modifies its Energy Resources R&D Portfolio through portfolio planning and analysis, technology roadmapping, and budget planning activities. Even with these efforts, it is very appropriate to ask whether the current portfolio and the portfolio planning processes are appropriate.

There have been several studies in recent years that have provided important comments on DOE's Energy Resources R&D Portfolio. Overall, these studies provide a good benchmark for the portfolio. The first is the recently published *Federal Energy Research and Development for the Challenges of the Twenty-First Century* (November 1997). This study, conducted by an Energy R&D Panel appointed by the President's Council of Advisors on Science and Technology at the request of President Clinton, reports on a thorough review of DOE's Energy Resources R&D Portfolio. The study states that "energy R&D … is vital to the future of the United States and the world." It suggests that four criteria be applied in gauging the effectiveness of the work. These are:

- Strategic criteria—How well does the portfolio address energy related economic, environmental, and national security challenges, and how well does it strengthen science and technology leadership?

- Diversity criteria—How well is the portfolio balanced across technologies, time frames, and degrees of risk?

- Public-private interface criteria—How effectively does it provide potential payoffs to society that will justify bigger R&D investments than industry would likely make on the basis of private return on investment? What is the potential for leveraging and partnerships?

- Other project criteria—How well do the projects within the portfolio exhibit strong technical merit, well-defined goals, and appropriate attention to cost, schedule, and performance?

This review found that, in general, the R&D activities as addressed in the current DOE program are appropriate. While the study proposed a variety of changes within the program, including some specific reductions, redirections, and increases, **their most important recommendation was for a substantial increase in energy technology R&D**. They further recommended that DOE expand and emphasize the use of portfolio analysis as an integral part of R&D portfolio planning efforts in the future. This should include increased emphasis on setting goals for all technologies and measuring progress toward these goals as well as application of the criteria listed above.

A second important benchmark for evaluating the current DOE Energy Resources R&D Portfolio is the 1995 report *Energy R&D: Shaping Our Nation's Future in a Competitive World*. This report resulted from a study commissioned by the Secretary of Energy's Advisory Board, and was conducted by a Task Force on Strategic Energy R&D which included leading energy experts from industry, academia, and research. DOE's Energy Resources R&D Portfolio is well in line with the key program recommendations of that report. For example, the report "recommends that the Federal government continue to provide leadership, focus, and substantial financial support for energy R&D to ensure that the national goals of U.S. energy security, economic strength, environmental quality, and national leadership in science and technology are effectively achieved. Such support is essential to our Nation's future well-being." The report also recommends pursuit of a broad-based portfolio defined through a systematic portfolio planning and analysis process:

> *"The Task Force recommends that DOE develop an integrated strategic plan and process for energy R&D, and use this process to determine funding priorities and manage a diverse energy R&D investment portfolio through:*
>
> - *A balance of basic research and applied R&D (including industry co-funded demonstrations.*
> - *Near- and long-term R&D to provide continuing return on investment and to contribute to the health and vitality of domestic energy industries.*
> - *A continuing commitment to support energy efficiency and renewable energy."*

Another important frame of reference is *Technology Opportunities to Reduce U.S. Greenhouse Gas Emissions*. This 1998 study by 11 DOE National Laboratories identified 47 technology pathways that offer significant potential to reduce greenhouse gas emissions. These pathways were grouped according to "Energy Efficiency" (buildings, industry, transportation, agriculture, and forestry), "Clean Energy" (fossil resource development, fossil power generation, nuclear energy, and renewables) and "Carbon Sequestration." The first 2 of these groupings map directly into the first 4 CNES goals and objectives, while the third represents a narrowly focused technology R&D effort aimed at dealing with long-term fossil-energy-based greenhouse gas emissions. These technology pathways were reviewed for their likely time profile of contributions toward reducing U.S. greenhouse gas emissions through 2030 (low, medium, or high potential). The report recommends collaborative R&D efforts involving both the private sector, universities, and government. The study concludes that the current Energy Resources R&D Portfolio is largely consistent with development of the range of advanced energy technologies that represent the best opportunities for reducing greenhouse gas emissions over time, and recognizes that the portfolio also addresses the multiple CNES objectives.

It is interesting to note that some traditional energy companies are moving toward strategic development of broader energy portfolios. One of these is British Petroleum (BP). In a recent article by Robert Shelton (*Sustainable Development: The Technology Management Implications and Opportunities*, P. 51, in PRISM, A.D. Little, Q 4 1998), the author points out: "BP noted

that the world has moved from solid (e.g., wood, coal) to liquid fuels (i.e., petroleum-related) over the past several hundred years, and that the next fuel transition will be from liquids to gas, as liquids become more expensive and gas remains plentiful and relatively inexpensive. Eventually, BP sees the energy business moving toward renewable energy in order to become sustainable. For BP, the sustainable development vision has identified the need to change from an oil company (with a primary focus on petroleum-related technologies) to an energy company with a portfolio of alternative technologies."

In 1994, Royal Dutch Shell conducted a study of the evolution of the world's energy system, including development of contrasting scenarios for future global energy consumption. An important conclusion of their study is that, even under quite different consumption scenarios, future energy supplies are likely to be more diverse. While fossil fuels today contribute over 75 percent of the world's energy supplies, the Shell study projects their contribution will begin to decrease in about 3 decades. By the middle of the 21st century, the world will be utilizing a range of energy resources, including significant contributions from renewables and nuclear as well as continuing reliance on important contributions from hydro, petroleum, natural gas, and coal (Reference: *The Evolution of the World's Energy Systems*, Group External Affairs, Shell International Limited, 1996).

To summarize, there have been a number of direct and indirect external comments on DOE's Energy Resources R&D Portfolio which support its basic features:

- The portfolio should be broadly-based in terms of energy resources and technologies.
- The portfolio should be balanced with respect to areas of research and development.
- The portfolio should draw upon the expertise of industry, universities, and the National Laboratories in collaborative efforts.
- The portfolio priorities should be continually reviewed and re-focused based on strategic planning and portfolio analysis.

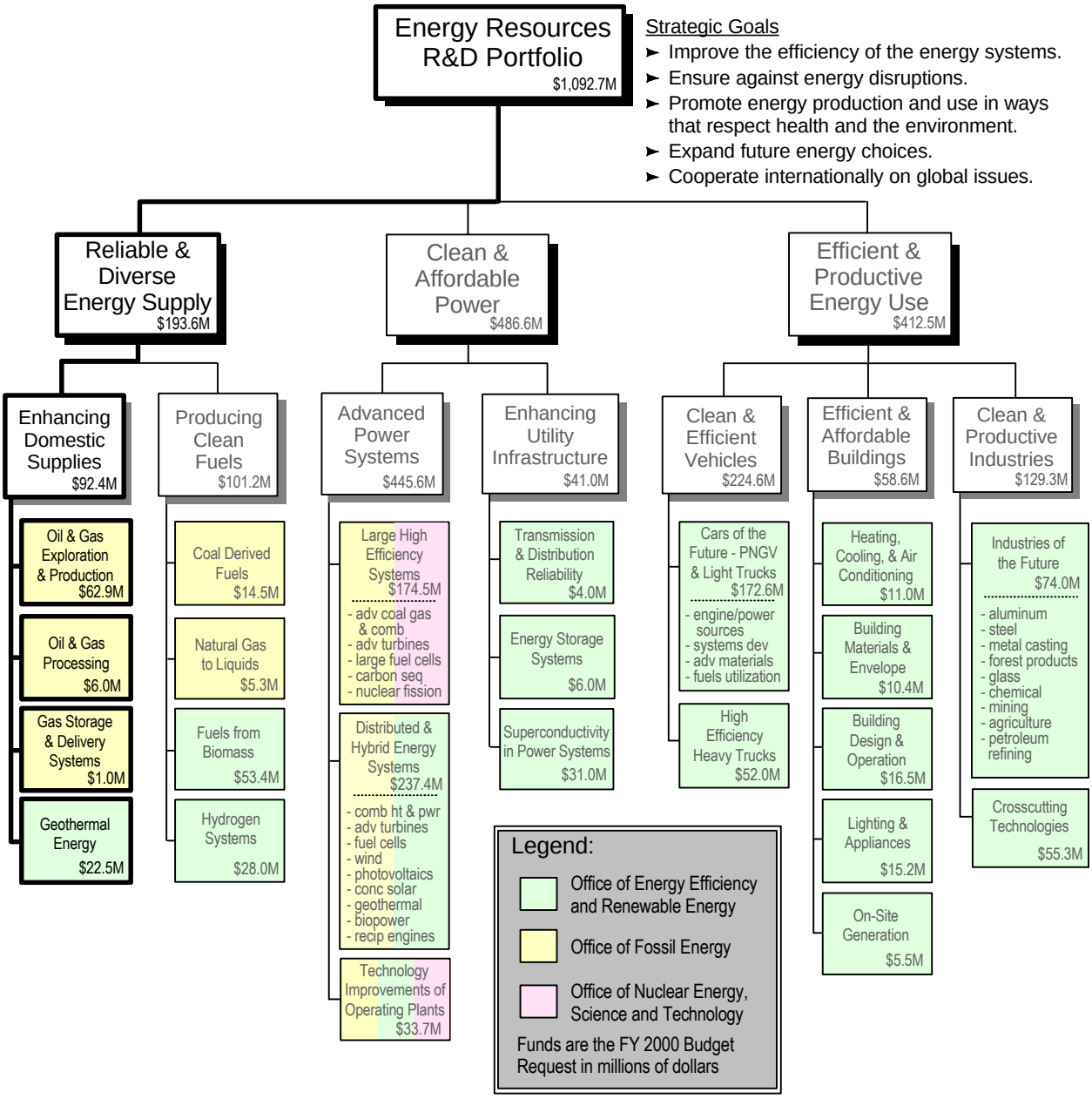
Next Steps

What is described herein and in the following chapters represents a comprehensive description of the DOE Energy Resources R&D Portfolio, including supporting basic research. The relevance of each part of the portfolio to the common-sense goal of maintaining available and reliable low-cost energy services in the context of enhancing national security and environmental quality is explained. This thorough presentation of the portfolio contents and their relevance to these national interests is an important first step in portfolio development and analysis, but it is only a beginning. This document indicates that the DOE portfolio meets multiple objectives and demonstrates robustness for an uncertain future, but continuing and expanded planning and analysis is needed to insure appropriate prioritization and efficient utilization of taxpayer funds applied to these efforts. Future steps should include expansion of current technology and

program roadmapping to all areas as well as portfolio analysis that models R&D outcomes relative to R&D investments.

Future changes to the portfolio will also occur because of new opportunities, such as natural gas hydrates or fossil fuel decarbonization with CO_2 sequestration. Technological developments, such as methods for efficient conversion of coal or gas resources to liquid fuels, or economical methods for directly producing hydrogen from sunlight, will also drive portfolio shifts. Finally, institutional changes such as electricity re-structuring and international developments are likely to influence changes to the focus of DOE's energy R&D. Thus, strategic planning and portfolio planning and analysis will continue apace with the R&D programs.

Chapter 3
Enhancing Domestic Supplies



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Enhancing Domestic Supplies

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Overview

Definition of Focus Area

The enhancing domestic supplies R&D portfolio address the Nation's need for stable and secure sources of domestic energy. Specifically, the R&D areas include oil and gas exploration and production (including environmental management), oil and gas processing, gas storage and delivery systems, geothermal energy, and preserving the Nation's critical energy infrastructure.

National Context and Drivers

A secure supply of reasonably priced energy is a prerequisite to U.S. strength in the global marketplace. Oil and gas account for two-thirds of the total U.S. energy consumption, and 97 percent of transportation fuels. Consumption of oil and gas will continue to increase (more than any other source of energy) despite energy efficiency improvements.

Oil security remains a prominent issue despite the relative tranquility in the market in recent years. Our economy is almost totally dependent on oil for its transportation needs. By 2015, it is projected that: (1) demand for petroleum in non-industrialized countries will nearly double; (2) the United States will consume more than 23 million barrels per day of oil and import more than 60 percent of it; and (3) the Middle East will control more than 62 percent of the world petroleum export market. This concentration of export market control will be greater than what existed in the 1970s and early 1980s when disruptions caused severe economic dislocations and fundamentally reordered U.S. and International Energy Agency (IEA) member nations' energy security program priorities.

Domestic natural gas consumption is expected to rise to more than 30 trillion cubic feet per year by 2015 (a one-third increase) because of its highly competitive cost and its cleanliness and efficiency. Gas can provide a low cost means to slow the rate of carbon dioxide emissions and be a bridge to a renewable energy future. Gas will be a significant energy source for moderating carbon emissions well into the middle of the next century. New resources of gas, such as methane hydrates, may prove to be a very large source of production worldwide.

Currently, the geothermal industry generates more than 16 billion kilowatt hours per year, supplies the residential electricity needs of about four million people in the United States, and displaces the emissions of 16 million metric tons of carbon dioxide. In addition, direct use of geothermal heat energy now contributes about 500 megawatts thermal (MWt) to displace additional carbon dioxide emissions. The U.S. geothermal industry has installed $3.0 billion worth of geothermal electrical generation projects overseas**,** and it has agreements for an additional $6.5 billion in foreign geothermal electric projects in the Philippines, Indonesia, and Latin America. The total of these foreign geothermal developments will generate an estimated additional 10 billion kilowatt hours per year and displace emissions of 10 million metric tons of carbon dioxide.

Linkage to CNES Goals and Objectives

The enhancing domestic supplies R&D areas support the following CNES goals and objectives:

- CNES Goal II, Objective 1 - Reduce the vulnerability of the U.S. economy to disruptions in oil supply.
- CNES Goal II, Objective 2 - Ensure energy system reliability, flexibility, and emergency response capability.
- CNES Goal III, Objective 1 - Increase domestic energy production in an environmentally responsible manner.
- CNES Goal IV, Objective 2 - Develop technologies that expand long term energy options.

Uncertainties

The United States is a mature oil-producing region, although domestic production is more difficult and more costly than overseas production. While an estimated two-thirds of all U.S. oil remains in the ground, much of it is located in deep, complex reservoirs or environmentally sensitive areas. High costs of operations and environmental compliance place U.S. producers at a competitive disadvantage with foreign producers.

An aging U.S. energy infrastructure raises concerns that tie to environmental issues. As local natural gas distribution systems continue to age, there is concern about methane leaks and the potential impact of this potent greenhouse gas.

Development of advanced oil and gas technologies is essential to efficiently maximize the production of domestic resources while preserving our environment. Advanced technologies are required to slow the decrease in domestic production of oil, to enable the processing and use of lower quality domestic crude, and to enhance the production and deliverability of natural gas.

Only ten percent of the U.S. hydrothermal (heated fluid) resources can be used commercially at this time, and none of the much greater conductive-geothermal (heated rock) resources can produce energy on a cost-competitive basis. The Department is developing more efficient technologies to reduce the risk and lower the cost of geothermal resource exploration and production for greater utilization of this energy resource.

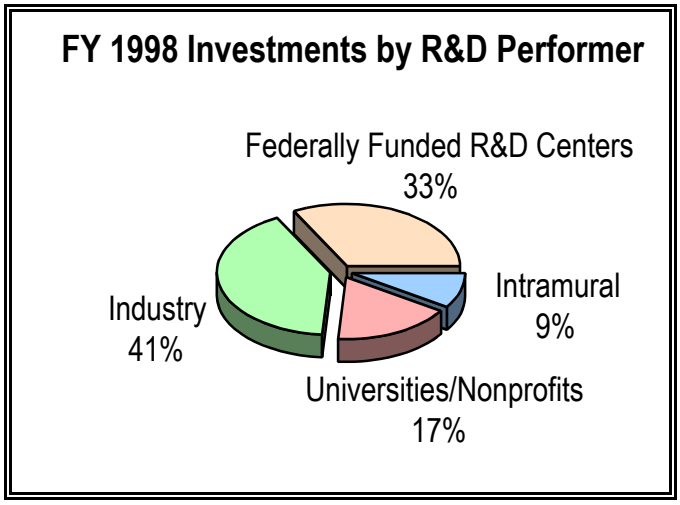
Declining R&D budgets, including the reduction in the Gas Research Institute's budget, have become a reality throughout the domestic energy industry. Electric utilities, in anticipation of increased competition, have already significantly reduced discretionary funding, including reductions of R&D by 30 percent in the past two years. The oil and gas industry has also reduced R&D applicable to domestic prospects by 29 percent, both in response to increased global competition and greater emphasis on overseas opportunities. Deficit-reduction has put increasing

pressure on DOE-supported R&D, which has decreased in real terms by about one-third since 1990. Within these spending constraints, important decisions must be made on the priorities and emphasis in DOE's energy R&D programs.

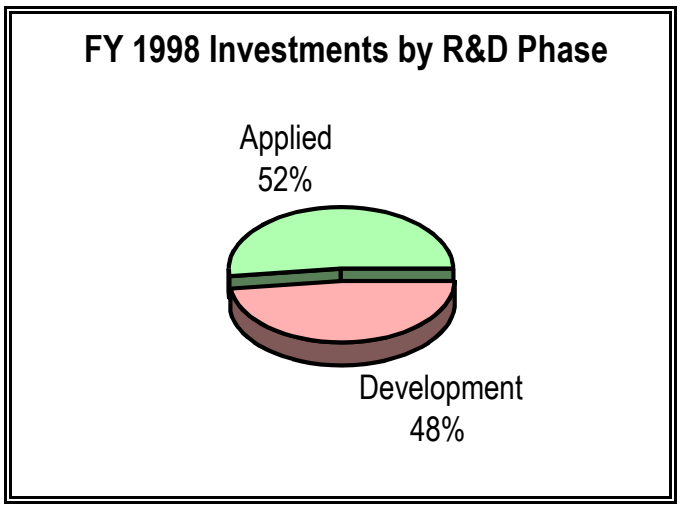
Investment Trends and Rationale

Oil and gas exploration and production R&D accounts for over 70 percent of the domestic supply budget at DOE. This is consistent with the large role that oil and gas currently plays in domestic supply, and the even larger role that it will play in the future. Geothermal exploration and development accounts for 20 percent of this budget area because of its important potential as a renewable energy source.

Over 40 percent of the research is performed by industry partners and over 30 percent is performed by the National Laboratories. However, a large portion of this work is actually done by teams of researchers that frequently includes university participants. In addition, it is anticipated that the role of universities will increase in the future as a result of the closeout of the management and operating contract in the oil program.



The type of research performed is evenly divided between applied and development. However, basic research that supports this technology portfolio is conducted in DOE's Office of Science.



Issues that may impact the direction of future budgets include:

- Should new R&D cost-shared initiatives be started to provide greater assurances of adequate natural gas supplies for the near- and mid-term (2005-2010), especially if driven by greenhouse gas mitigation targets?
- Should methane hydrate R&D be accelerated to provide earlier answers on feasibility, production safety, and environmental impacts?
- Should DOE invest in critical infrastructure protection for electric power and gas and oil production and storage?
- Should additional actions be taken to stop the decline in domestic oil production in light of the projected low prices for oil?

Federal Role

The Federal government role includes:

- Ensuring reliable energy supplies at reasonable costs.
- Providing strategic guidance for national energy policy.
- Supporting efficient and sustainable use of domestic energy resources.
- Protection of the environment and public safety.
- Enhancing the value of Federal lands.
- Enhancing global market opportunities for U.S. energy technologies.

- Contributing to U.S. science and technology leadership.
- Applying a unique national perspective to technology development that is independent of company-specific or State-specific interests.

DOE's Role in support of national goals includes efforts to:

- Enhance the efficiency and environmental quality of domestic oil and natural gas exploration, recovery, processing, transport, and storage operations.
- Focus on high risk technology that private companies alone won't undertake.
- Provide scientific and technological information and analysis to assist policymakers in their decision making.
- Contribute to science-based improvements in regulations to reduce uncertainties and costs while achieving optimal environmental protection.

Research needs are identified in combined workshops with Federal, industry, and research personnel. Competitive solicitations are used to identify qualified researchers. The applied research activities, supported by basic and enabling research, are managed by Federal personnel and performed by industry partners, National Laboratories, universities, and commercial research organizations. Centers of excellence and specialized expertise at National Laboratories support various elements of the program. In addition, cost-shared cooperative agreements and consortia are used as vehicles for joint funding of research with industry.

Key Accomplishments

Key accomplishments include:

The Oil Reservoir Class Program includes a total of 32 projects with a total DOE investment of $118 million and industry co-funding of $150 million (56 percent cost sharing). Successful demonstration of waterflooding in a high paraffin oil reservoir added 2.4 million barrels of oil to the region's reserves, resulting in over $12.7 million in taxes and royalties. Because of this demonstration, neighboring companies initiated 11 new waterfloods with more than 300 wells, which are expected to add 31 million barrels of oil and $160 million in Federal revenues. Because these 11 projects cover only 13 percent of the area, widespread application of waterfloods could double or triple the region's reserves and could increase Federal revenues to $500 million.

In the Natural Gas Program, new imaging technologies, including 3D seismic and vertical seismic profiling, were first utilized in the Texas Gulf Coast Basin and in the Fort Worth Basin. This work resulted in a substantial increase in reserve growth (estimated at 60 TCF) from established gas fields which were thought to be depleted.

A Risk Based Data Management System (RBDMS) originally developed for six States has proven so successful that 25 States have formed a users' group to help each other implement the system. The RBDMS is a PC based program that allows States to manage their underground injection data easily and use it to make risk based regulatory and operational decisions, such as where to assign inspectors for maximum effectiveness. The system enables States to generate reports quickly for the Environmental Protection Agency and the public.

Northern Indiana Public Service Company (NIPSCO) partnered with DOE and the Gas Research Institute (GRI) to demonstrate the use of geological modeling and seismic survey techniques to optimize the development and operation of gas storage fields. Based on the results of this integrated study, NIPSCO drilled a horizontal well at the Royal Center field in Indiana. Initial flow tests indicate that the well will significantly enhance deliverability from the field and allow the utilization of gas from an area of the storage field that was not accessible from the existing vertical wells.

The Department conducted initial design and testing of PDC drill bits now used in about 40 percent of drilling worldwide, an industry with annual sales in excess of $200 million. In addition, the program developed high-temperature drilling muds, high-temperature elastomers for downhole motors, advanced drilling fluid flow instrumentation, high-temperature memory logging tools; and fostered the use of slimhole drilling as an exploration tool for geothermal energy saving 30 to 50 percent of exploration drilling costs.

Industry and the Department of the Interior estimate that new discoveries in the Gulf of Mexico, an area with little exploration activity just a few years ago, may yield as much as 18 billion barrels of oil—more than Prudhoe Bay, Alaska. Technological innovations in subsalt imaging, reservoir characterization, and drilling technologies enhance the ability to discover such potential reserves.

Air motors based on DOE horizontal drilling technology are now being used for most new wells drilled in eastern gas formations. Horizontal drilling techniques, that use air in place of mud to drive and cool the downhole bit motor and remove drilling debris, have vastly improved the efficiency of drilling in Appalachian reservoirs, where mud use causes formation swelling and fracture blockage.

Production improvements at the earliest U.S. wells stimulated by CO_2/sand fracturing were so significant, that DOE received the 1994 Hart's Oil and Gas World Award for introducing the "Best New Technology in the Northeast."

Oil and Gas Exploration and Production

Budget: FY98-$59.9M, FY99-$60.4M, FY00-$62.9M

Background

Even though remaining U.S. oil and gas reserves are substantial, they are becoming more difficult and expensive to discover and produce. Past technology has recovered only an estimated one-third of the oil in place, leaving two-thirds of the U.S. oil resource base—about 350 billion barrels—still in the ground. Yet high operating costs are resulting in the abandonment of more than 16,000 U.S. oil wells each year. With the rising costs of environmental compliance, U.S. oil and gas producers and processors can face competitive disadvantages relative to operators in other areas of the world. These competitive disadvantages contribute to the fact that many major companies are concentrating their new exploration and production investments overseas.

Historical data demonstrate that technology advances are key to keeping energy prices low for consumers and to maintaining the profitability and long-term survival of the domestic industry. Since the 1980s, because of 3-D seismic, advanced drilling systems, and fracturing technologies, our Nation has seen a 14 percent increase in its gas production, despite a 50 percent decline in wellhead prices. Higher gas production in 1994 was achieved with fewer than 9,000 well completions, as compared to 14,250 completions in 1985. Further, success rates of exploratory wells have increased from 29 percent to 38 percent since the 1980s, while costs have substantially decreased. These technology advances, coupled with incentives such as deepwater royalty relief, have made the Gulf of Mexico one of the most active oil and gas exploration areas in the world.

Linkage to CNES Goals and Objectives

The oil and gas exploration and production R&D area supports the following CNES goals and objectives:

- CNES Goal II, Objective 1 - Reduce the vulnerability of the U.S. economy to disruptions in oil supply. *(by stabilizing domestic production)*

- CNES Goal III, Objective 1 - Increase domestic energy production in an environmentally responsible manner. *(by increasing domestic gas production, recovering oil with less environmental impact, and developing cost-effective renewable technologies)*

- CNES Goal IV, Objective 2 - Develop technologies that expand long term energy options. *(such as the production of gas from methane hydrates and deep gas formations)*

The program's efforts focus on enhancing the efficiency and environmental quality of domestic oil and natural gas exploration and production. Improved technology and information are required to boost production of natural gas, a clean and abundant domestic fossil fuel that is an

increasingly important component of our Nation's energy portfolio, and to extend the life of domestic oil fields, many of which are marginally economic and operated by independent producers. Specific goals are to find and exploit new resources through resource- and reserve-base expansion, increase recovery through wellbore improvements, extend the life of domestic energy resources and reduce well abandonments, minimize any potential environmental damage from oil and gas operations, and improve understanding/industry cooperation in environmental compliance

Program Description

Technology advances can further the trend toward more cost-effective recovery of domestic oil and gas, particularly from geologically-complex deeper reservoirs. Such advances will enable domestic producers to continue exploring for and recovering oil and gas from reservoirs that would otherwise be economically unviable.

By reducing the costs of domestic oil and gas production, advanced technologies can help to maintain reliable domestic supplies of these vital fuels at competitive prices—a goal of strategic importance to our Nation.

Diagnostics and Imaging

Budget: FY98-$19.9M, FY99-$20.4M, FY00-$20.1M

Description, Objectives, and Performers. Advanced imaging is an increasingly powerful tool for discovery and insight in medicine, engineering, and many other fields. In the oil and gas industry, sophisticated diagnostics and imaging technologies can be used to cost effectively locate and produce our reserves. The program supports the development and use of advanced technologies for reservoir characterization and risk based decision making, preserves and provides access to subsurface data, and develops analytical tools to perform the analyses required for accurately quantifying oil and gas resources and reserves.

R&D Challenges. Although the Nation's largest, most easily identified reservoirs have been discovered, potentially substantial reserves still exist, both onshore and offshore, in geologically complex settings or in deeper and smaller compartmentalized reservoirs. With advanced diagnostics and imaging technology, the costs and risks of exploring for these reservoirs can be significantly reduced.

The Department of Energy's emphasis on diagnostic and imaging technology RD&D has greatly increased over the past 10 years in parallel with industry interest in putting new technologies to work. This growing interest is driven by the need to reduce risk and uncertainty in a low product price environment; the need for improved resolution to define smaller, more compartmentalized and deeper reservoirs; and the understanding that reservoir heterogeneity impacts all recovery processes, an observation made in the late 1970s and early 1980s during enhanced oil recovery projects.

In the future, newly developed imaging and modeling technologies can enable production from tight, inaccessible, and fractured reservoirs, that contain major portions of our Nation's

future oil and gas resources. Such reservoirs include fractured shale, fractured tight gas reservoirs in the Rocky Mountain region, deeper parts of producing basins, and reservoirs in deep water or below salt in the Gulf of Mexico.

R&D Activities. Program activities include:

- Improve seismic and other geophysical acquisition, processing, and interpretation technologies to provide increased resolution and accuracy, with emphasis on single-well, crosswell, and novel surface methods.

- Increase the understanding and measurement of rock and fluid properties, rock-fluid interactions, and fluid flow, and develop techniques to monitor reservoir and production processes that are not currently measurable using, for example, multi-frequency crosshole electromagnetic technology or accelerometer based, multi-level receiver systems for seismic monitoring.

- Increase the accuracy and performance of geologic and reservoir modeling and simulation, especially fast, user friendly, PC-based techniques to mathematically simulate flows, predict the production from a reservoir, and assess the technical and economic viability of development.

- Develop and demonstrate techniques to predict, locate, and exploit reservoir fractures for improved production from low permeability reservoirs. These techniques may include high resolution aeromagnetic surveys to locate structural anomalies, integrated modeling methodology to identify targets, and direction drilling technology to optimize recovery.

- Improve industry knowledge of and access to reservoir characterization technologies.

  – Develop methodologies for the quantitative description and prediction of reservoir characteristics, including fractures and diagenesis, through laboratory analysis of the lithology, in-situ stress, and fracture conductivity.

  – Transfer reservoir characterization data, models, and tools to industry.

- Increase the accuracy of present and future oil and gas resources and reserves estimates, and industry access to them.

  – Work with industry and State and Federal agencies to preserve irreplaceable subsurface geologic data.

  – Provide industry, government, and academic customers with accurate, unbiased, and timely current and predicted future estimates of U.S. resources and reserves.

Accomplishments. Ongoing simulator development has led to the recent release of BOAST3, a new version of the Department of Energy's three-dimensional, three-phase "Black Oil Applied Simulation Tool." Over 2,000 copies of BOAST versions have been distributed, primarily to independent producers, for use in designing waterfloods and other improved recovery projects.

A prototype system was developed that reduces the time needed for crosswell imaging to one-fifth the time of conventional technology and provides a 10 percent cost savings when used for monitoring fracture treatments.

Industry and the Department of the Interior estimate that new discoveries in the Gulf of Mexico, an area with little exploration activity just a few years ago, may yield as much as 18 billion barrels of oil - more than Prudhoe Bay, Alaska. Technological innovations in subsalt imaging, reservoir characterization, and drilling technologies enhance the ability to discover such potential reserves.

Drilling Completion and Stimulation

Budget: FY98-$9.1M, FY99-$7.5M, FY00-$7.6M

Description, Objectives, and Performers. Of the entire exploration and production effort, drilling is the moment of truth for oil and gas producers. Drilling tests the validity of geological, geophysical, engineering, and mechanical theories on the existence of new oil and gas reservoirs, and demonstrates whether subsurface analyses have, in fact, succeeded in pinpointing productive pay zones. Sizable investments ride on the results.

DOE's Advanced Drilling, Completion and Stimulation Systems Program focuses on the development of sophisticated technologies and methodologies that can encourage investments in producing new oil and gas plays, and that can increase production from existing plays. Technology advances in this field have already succeeded in reducing costs per foot drilled in the United States by 8 percent over the last 10 years, and the potential for further improvements is significant. Future advances are most likely to result from addressing the full drilling system, not just individual components, with a focus on increasing the net present value of the entire investment. This program will by 2010 contribute the following economic and technological improvements:

- Reduced total drilling costs of 0.5 to 2.0 percent per year.
- Reduced development drilling costs of 10 to 20 percent.
- Reduced stimulation costs of 20 to 30 percent.
- Reduced operating costs of 1 percent per year.
- Reduced dry hole rates of 5 percent.
- Increased reserves per well of 5 to 10 percent.

- Reduced skin factor of 40 to 70 percent.

R&D Challenges. Risks have always been inherent in drilling for oil and gas. Today, the technology challenges are becoming even greater for producers in the United States. Much of our remaining oil and gas is locked away in geologically complex formations that necessitate deeper drilling and penetration of harder rock, and the increasing application of such techniques as underbalanced directional drilling, slimhole drilling, and multilateral configurations. Drilling challenges often make investment in domestic exploration and production less attractive than investment in easier-to-produce overseas reservoirs.

R&D Activities. Technologies under development can increase the value of the exploration and production effort in several ways. First, by increasing the rate of penetration or by lengthening bit life, new methods can enable producers to drill faster, farther, and longer, resulting in reduced rig time. These technologies include the development of steerable air percussion drilling systems, advanced mud hammers, and high pressure downhole pumps for jet assisted drilling. Improved drilling and completion technologies also reduce formation damage, helping to maintain high well productivity. New stimulation technologies can be more effective than current methods in reviving well productivity after the well production rate declines to below economic levels. New methods also more effectively preserve the integrity of the wellbore over time, including the use of under balanced drilling fluids such as air, nitrogen, or foam. Finally, cost savings and increased environmental protection are also possible by reducing the volume of fluids needed in drilling and stimulation.

Carbon dioxide/sand fracturing technology was introduced into the United States by DOE for low permeability gas bearing formations. This non-damaging technology, which uses a sand-laden liquid CO_2 slurry to extend fractures, has the potential to significantly outperform traditional stimulation approaches. To encourage industry evaluation of the technology, DOE and its partner, Petroleum Consulting Services, have been working with industry to apply CO_2/sand fracturing, along with other stimulation methods, to newly-drilled wells of similar design and geological setting.

Accomplishments. Air motors based on DOE horizontal drilling technology are now being used for most new wells drilled in eastern gas formations. Horizontal drilling techniques, that use air in place of mud to drive and cool the downhole bit motor and remove drilling debris, have vastly improved the efficiency of drilling in Appalachian reservoirs, where mud use causes formation swelling and fracture blockage.

Improved environmental protection is an important benefit. Some advanced drilling, completion, and stimulation technologies promise to reduce drilling wastes. Others use a closed system approach that recycles and reuses materials that previously would have been treated as wastes. Other methods, such as directional drilling, can prevent the disturbance of wetlands and sensitive surface environments. Another important environmental contribution is the smaller amount of acreage impacted, thanks to the greater longevity and productivity of existing wells when advanced technologies are used.

Production improvements at the earliest U.S. wells stimulated by CO_2/sand fracturing were so significant, that DOE received the 1994 Hart's Oil and Gas World Award for introducing the "Best New Technology in the Northeast."

Reservoir Life Extension

Budget: FY98-$21.2M, FY99-$23.3M, FY00-$24.2M

Description, Objectives, and Performers. In partnership with the U.S. oil and gas industry, the Department supports the development of innovative and cost-effective technologies that can extend the productive life of domestic reservoirs. By encouraging advances in oil and gas recovery technologies and facilitating their transfer to producers, DOE can help slow the rate of premature abandonment of U.S. oil and gas wells and reduce our reliance on energy imports.

R&D Challenges. Production at most petroleum reservoirs includes three elements: primary, secondary, and tertiary recovery. Tertiary oil recovery is also known as improved oil recovery (IOR) or enhanced oil recovery (EOR). Primary recovery refers to production when energy stored in the reservoir is sufficient to drive the oil through reservoir rock into a wellbore. As reservoir pressure declines along with oil production rates, much additional oil can still be recovered using secondary recovery techniques. One such technology, waterflooding, displaces the oil and drives it to the wellbores of the producing wells.

Oil displacement in the reservoir is incomplete, however, even with secondary recovery processes. Tertiary oil recovery technologies such as thermal, gas-miscible, chemical, or microbial methods, can provide additional production. Such technologies could potentially recover about half of the 350 billion barrels of "discovered but unrecovered" oil in the United States. These technologies included polymer-augmented waterfloods and polymer-gel profile modification; continuous steam injection and in-situ combustion techniques; continuous gas injection, cyclic, and water-alternating-gas injection; and micellar surfactant and alkaline surfactant polymer flooding. Current U.S. oil production is 6.4 million barrels per day. Of this amount, 63 percent is produced by secondary and tertiary recovery.

In-situ combustion attempts to recover oil by heating it through the burning of a portion of in-place crude. Air or oxygen is injected to facilitate burning. The process is very complex, involving multi-phase flow of flue gases, volatile hydrocarbons, steam, hot water, and oil. Its performance in general has been insufficient to make it economically attractive to producers.

Polymer flooding involves injection into the reservoir of a small slug of surfactant solution, followed by polymer-thickened water, and then brine. Despite its very high displacement efficiency, micellar-polymer flooding is hampered by the high cost of chemicals and excessive chemical losses within the reservoir.

Even though improved oil recovery technologies have significant potential to extend reservoir life, and have been successfully demonstrated in the laboratory and in the field as early as the 1960s, their historically high cost has limited their widespread application. In the

last decade, however, dramatic improvements in analytical and assessment tools including integrated reservoir description methods, have led to a greater understanding of the geology of reservoirs and the physical and chemical processes governing flows in porous media. This understanding has led to the development of new technologies that have potential for reservoir life extension.

The problems associated with more complete gas recovery are somewhat different. Research conducted by the Texas Bureau of Economic Geology, on behalf of the Gas Research Institute and DOE, has demonstrated that current production practices fail to recover a large portion of the gas in place. Even after 50 years of commercial production, substantial infield reserve growth exists in bypassed, incompletely drained, and untapped reservoir compartments, not to mention deeper pool potential in many fields.

R&D Activities. To demonstrate that today's reservoir life extension technologies are a highly cost effective alternative to abandonment in many real life situations, DOE launched the Reservoir Class Field Demonstration Program. This area represents the opportunity for in-the-field application of many improved and new reservoir life extension technologies.

The technological premise of the Reservoir Class Program is that reservoirs with a common geologic origin often have common producibility problems. These problems should respond similarly to reservoir life extension technologies. As new or advanced technologies are ready to be demonstrated in the field, a group of producing oil wells often spanning multiple States, are chosen as likely candidates for the demonstration. The wells are chosen because their reservoirs share similar geology, belonging to one of the three reservoir classes selected for demonstrations.

A commitment on the part of all program partners to technology transfer has been a critical factor in the program's success to date. Oil producers (including both small independent companies and major producers), universities, State agencies, service companies, and consultants, in partnership with DOE, team up for development, application, and transfer efforts. Project results are also being fed into a national petroleum technology transfer network. A revised strategy calls for revisiting the three classes and analysis of lessons learned.

In the Natural Gas Recovery Program, the focus is on a more complete characterization of complex heterogeneous reservoirs to afford a more precise placement of new wells and recompletions in existing wells.

Accomplishments. The Oil Reservoir Class Program includes a total of 32 projects with a total DOE investment of $118 million and industry co-funding of $150 million (56 percent cost sharing). Successful demonstration of waterflooding in a high paraffin oil reservoir added 2.4 million barrels of oil to the region's reserves, resulting in over $12.7 million in taxes and royalties. Because of this demonstration, neighboring companies initiated 11 new waterfloods with more than 300 wells, which are expected to add 31 million barrels of oil and $160 million in Federal revenues. Because these 11 projects cover only 13 percent of the

area, widespread application of waterfloods could double or triple the region's reserves and could increase Federal revenues to $500 million.

In the Natural Gas Program, new imaging technologies, including 3D seismic and vertical seismic profiling, were first utilized in the Texas Gulf Coast Basin and in the Fort Worth Basin. This work resulted in a substantial increase in reserve growth (estimated at 60 TCF) from established gas fields which were thought to be depleted.

Drilling and Production Environmental Management

Budget: FY98-$9.6M, FY99-$8.7M, FY00-$9.0M

Description, Objectives, and Performers. The Department of Energy is working closely with industry to stem the rising costs of environmental protection, and to enable the domestic oil and gas producers to operate more efficiently, contributing fuels, jobs, and economic value to the Nation. DOE and industry are using the best information and science available to find new ways to address our Nation's environmental concerns, and to demonstrate that the needs of a strong economy and a healthy environment can be fully compatible.

Working with industry, DOE's Office of Fossil Energy is helping to ensure that environmental protection approaches make technical, environmental, and economic sense. DOE is well positioned between industry and regulators to champion balanced cost-effective approaches to environmental protection. DOE's environmental program pursues improvements to the regulatory process, supports development of new technologies, and exercises key responsibilities for energy policies that encourage efficient recovery and ensure adequate secure energy supplies.

R&D Challenges. Can the needs of a vital, growing U.S. economy be balanced with our Nation's commitment to a healthy environment? Nowhere is this question more pointed than in the domestic oil and gas industry. The economic contributions of the domestic oil and gas industry are being endangered by rising environmental compliance costs. Higher costs could cause valuable domestic oil and gas resources to become uneconomical to produce, potentially raising imports and increasing the trade deficit. Gas supply could be constrained, preventing natural gas from filling its role as the environmentally-preferred fuel.

In recent decades, environmental concerns led to numerous Federal and State regulations being imposed on oil and gas operations in the United States. While these regulations provided the framework for many environmental improvements by the industry, compliance has become costly and increasingly complex. Currently, the petroleum industry, including refining, spends as much on environmental protection as it spends searching for new domestic supplies of oil and natural gas—9 cents for each gallon of gasoline Americans buy. That amounts to $10 billion a year, nearly twice the budget of the United States Environmental Protection Agency.

As in other industries, the oil and gas industry has become subject to overlapping, duplicative, and sometimes unnecessary or outdated regulatory requirements. Although these regulations were created with the best of intentions, the time has come to focus on implementing regulations with greater flexibility and efficiency, and achieving optimal levels of environmental protection at the lowest possible cost.

The higher cost of meeting environmental regulations places a substantial economic burden on industry. The burden is magnified by the economically-marginal condition of a large percentage of domestic oil wells, and a growing share of domestic natural gas wells. Over two-thirds of domestic oil wells produce, on average, less than three barrels per day, making them highly sensitive to increasing costs.

R&D Activities. To support more informed regulatory decision making, DOE facilitates dialogue among Federal officials, State regulators, industry personnel, and other stakeholders. Through its program activities, DOE can provide assessments of costs or risks, lending an independent voice to the debate. DOE also characterizes problems and possible alternative solutions, catalyzing and contributing to the process of achieving common sense approaches.

Many times, more cost effective environmental approaches hinge on the development of new technologies. DOE supports such development, focusing on beneficial technology investments that could not be justified by a single company or small group of companies. Some of these technologies have longer term payoffs or high risks; others may have widely diffused benefits that a single company could not capture, but that will accrue to the Nation.

DOE brings unique capabilities to its role, including the scientific capabilities of its National Laboratories, and modeling/analysis tools developed specifically to address energy policy questions. A fundamental commitment to outreach and technology transfer—putting information and new techniques into the hands of those who can use them—enables DOE's efforts to generate maximum benefits for the Nation.

DOE is currently conducting over 60 environmental research and analysis projects. Some projects are national in scope and others are regional in nature, addressing specific technology needs or environmental constraints. Whether a project is initiated at a single site or in a handful of States, technology transfer is an integral part of the program approach. Once a project proves successful, the program focuses on transferring the results nationwide.

Accomplishments. A Risk Based Data Management System (RBDMS) originally developed for six States has proven so successful that 25 States have formed a users' group to help each other implement the system.

The RBDMS is a PC based program that allows States to manage their underground injection data easily and use it to make risk based regulatory and operational decisions, such as where to assign inspectors for maximum effectiveness. The system enables States to generate reports quickly for the Environmental Protection Agency and the public.

Gas Hydrates

Budget: FY98-$0.0M, FY99-$0.5M, FY00-$2.0M

Description, Objectives, and Performers. Methane production from hydrates could contribute low cost natural gas to satisfy domestic demand. As much as 200,000 trillion cubic feet (TCF) of methane may exist in hydrate systems in the U.S. permafrost regions and surrounding waters, which is hundreds of times greater than the estimated conventional U.S. gas resource base of 1,400 TCF. Even if actual reserves prove to be only a small fraction of these estimates, methane hydrate production could alter U.S. and world patterns of energy supply and consumption. Gas production from hydrates will also contribute to energy security and Federal revenues from royalties and lease rentals in the Outer Continental Shelf.

Methane hydrate is a methane bearing, ice-like material that occurs in abundance in marine and arctic sediments and stores immense amounts of methane. A cage of water ice molecules surrounds the gas molecule allowing high methane concentrations–one unit volume of methane hydrate can contain over 160 volumes of gas and less than one unit of water at surface pressures and temperatures. Methane hydrates are found on land in permafrost regions (Alaska) and within ocean floor sediments around the United States.

In the past year, a renewed interest in methane hydrates has been driven by:

- Growing recognition of the need for increased supplies of cleaner domestic fuels in the middle 21st century.
- Expanded industry activities in the Arctic and deep offshore that have increased awareness and interest in hydrate formation, occurrence, and stability.
- Concern about global climate change has emphasized the need to understand the role of hydrates in global carbon cycles.
- Technological progress over the past few years indicates that research will proceed more rapidly than previously expected and with increased expectations of commercial production.
- Increased international activity and significant spending in Japan and India points out the expectation of commercial production in the not-too-distant future.

This program can produce the knowledge and technology necessary for commercial production of methane from hydrates by 2015 and address associated environmental and safety issues.

R&D Challenges. In order to turn the potential hydrate resource into gas reserves while developing technologies to assure safe petroleum operations in hydrate areas, and defining the role of methane hydrates in global climate, the following must be addressed:

- Determine the location, sedimentary relationships, and physical characteristics of methane hydrate resources to assess their potential as a domestic and global fuel resource (Resource Characterization).

- Develop the knowledge and technology necessary for commercial production of methane from oceanic and permafrost hydrate systems by 2015 (Production).

- Develop an understanding of the dynamics and distribution of oceanic and permafrost methane hydrate systems sufficient to quantify their role in the global carbon cycle and climate change (Global Carbon Cycle).

- Develop an understanding of the hydrates system in near-seafloor sediments and sedimentary processes, including sediment mass movement and methane release so that safe, standardized procedures for hydrocarbon production and ocean engineering can be assured (Safety and Seafloor Stability).

R&D Activities. Activities include the preparation of a strategy for methane hydrate R&D and an implementation plan.

Accomplishments. A ten-year program, starting in 1982, at the Department of Energy (DOE) Morgantown Energy Technology Center (now the Federal Energy Technology Center, FETC) supported methane hydrate studies that: established the existence of hydrates in Kuparuk Field, Alaska; completed studies of 15 offshore hydrate basins; developed production models for depressurization and thermal production of gas from hydrates; and built the Gas Hydrate and Sediment Test Lab Instrument. The program was canceled as government policy shifted from long-term, high risk R&D to near-term exploration and production R&D. Although DOE funding stopped, work has continued at the United States Geological Survey (USGS), universities, other laboratories, and overseas.

Oil and Gas Processing

Budget: FY98-$5.5M, FY99-$6.2M, FY00-$6.0M

Background

Throughout many of our western States, there are gas reserves containing high levels of contaminants, which render these reserves economically unmarketable in most instances. Finding ways to utilize such unmarketable gas resources has become essential to sustaining a reliable domestic supply of gas and liquid fuels as our Nation's most accessible and economical supplies are depleted.

In the last decade, environmental regulations have had a far-reaching impact on both the processes and products of the U.S. refining industry. Refineries must comply with increasingly stringent emissions and discharge limits on their processes. At the same time, they must meet demands for lighter, high value finished products, such as gasoline, diesel fuel, jet fuel, and petrochemical feedstocks, whose composition and quality have changed markedly to meet environmental standards. The Clean Air Act Amendments of 1990 have required the production

and use of reformulated gasoline, for example. This and other projected changes in the product slate will result in higher storage and transportation costs, added capital expenditures, and product exchange complications.

According to a recent study by the National Petroleum Council, between 1991 and 2010 environmental compliance costs are projected to exceed $150 billion, including $36 billion for capital equipment. Since 1994 alone, the refining industry has committed over $20 billion to capital equipment for improving environmental performance. Such equipment has absorbed between 75 and 90 percent of total capital expenditures.

Linkage to CNES Goals and Objectives

The program supports the following CNES goal and objective:

- CNES Goal III, Objective 1 - Increase domestic energy production in an environmentally responsible manner. *(by increasing domestic gas production, recovering oil with less environmental impact, and developing cost-effective renewable technologies)*

Program Description

New processing technologies can equip the oil and gas industry to prevent pollution and protect the environment more efficiently than is possible with today's costly retrofit approaches, to handle the challenges posed by lower quality domestic feedstocks, and to produce the more complex, purer, high value product slates that the market now requires. By gathering the scientific information that is essential for sound regulatory decision making as well as developing processing technologies that increase efficiency, decrease costs, and enhance environmental performance, the industry may continue to be profitable in a highly global market place.

Low Quality Gas Upgrading

Budget: FY98-$1.1M, FY99-$1.9M, FY00-$1.6M

Description, Objectives, and Performers. In partnership with the U.S. oil and gas industry, the Department of Energy seeks to advance technologies and processes that will enable gas reserves with high contaminant levels to be upgraded to market specifications using gas purification technologies. Pursuing advanced processes to collect and utilize the methane released during underground coal mining would harness this greenhouse gas and prevent it from being vented into the atmosphere.

R&D Challenges. Approximately one-third of our Nation's natural gas resource is low quality gas that does not meet market specifications for pipeline shipment. Typical specifications call for gas with no more than: 2 percent carbon dioxide; 4 percent total carbon dioxide, nitrogen, and other inert gases; and 4 parts per million of hydrogen sulfide gas. Some low quality gas can be blended with higher quality gas to meet market requirements. But much of our low quality gas must be upgraded through gas purification technologies that eliminate or substantially reduce inert and hazardous contaminants. Current technologies can be costly and, in some cases, cost prohibitive. In situations where the cost

of upgrading would make producing the gas uneconomical, the gas is simply shut in. Advanced upgrading technologies under development will improve purification techniques while significantly lowering costs.

Methane, a greenhouse gas considered at least 20 times more harmful to the atmosphere than carbon dioxide on a unit basis, is released naturally from coal and surrounding strata in the course of underground coal mining. Most of this methane is currently exhausted to the atmosphere through the mine's ventilation system.

R&D Activities. Low quality gas upgrading program efforts target two technology areas. The first is the development of organic and inorganic membranes that screen and separate gas components. Membranes offer high component selectivity and overall gas throughput. The second area of technology development is gas-contaminant absorption and adsorption systems that have rapid regeneration capability. Both areas of technology development have the potential to significantly reduce gas upgrading costs compared to current technologies.

Coal mine methane R&D efforts focus on the demonstration of available methods to economically collect and utilize this methane for pipeline sales, small-scale electric power generation, and other uses. The goal is to expand the number of mines that utilize emitted gas instead of passing it into the atmosphere.

Accomplishments. A DOE-sponsored project is focused on the development of more efficient and compact physical solvent systems for the upgrading of natural gas with high carbon dioxide and/or hydrogen sulfide content. Researchers at the Institute of Gas Technology are working with representatives from the Gas Research Institute, Shell Oil Company, Michigan Consolidated Gas Company, and others to develop the advanced system designs required to enable the separation processes to proceed using structured packing and/or rotating solvent-gas contactors in place of traditional large absorber towers with many sets of contactor trays. The new designs would allow a five-fold or greater reduction in the size of gas upgrading plants. Such size reduction is particularly valuable for platform-scale upgrading in the Gulf of Mexico.

Air Emissions Detection and Control

Budget: FY98-$4.4M, FY99-$4.3M, FY00-$4.4M

Description, Objectives, and Performers. Environmental regulations have resulted in the closing of a number of smaller, less efficient U.S. refineries that have been unable to afford the required capital expenditures. These regulations make the construction of new refineries in the United States unlikely. While larger refining operations are expected to remain viable, recent studies suggest that another 10 percent of U.S. refineries may close. With U.S. refineries already operating at near maximum utilization rates, such a loss in capacity exposes U.S. consumers to gasoline price spikes caused by interruption of operations at any one refinery.

R&D Challenges. Crude oil supplied to refineries is becoming heavier with more sulfur, nitrogen, and heavy metals, while the market requires a product slate that is lighter, with less

sulfur and nitrogen, and more oxygenates. Using present technology, the processing of heavy crude yields unacceptably high levels of low value residual oils, coke by-products, and wastes.

Environmental regulations, particularly the Clean Air Act Amendments of 1990, are forcing refineries to devote substantially more of their budgets to environmental compliance at the expense of their technology development efforts. The impending fine particulate ($PM_{2.5}$) regulations have caused concern within the industry because of the lack of data about origin and formation of this fine particulate matter. Data must be produced that will allow science-based implementation of this proposed regulation.

R&D Activities. This program serves the Nation's environmental objectives by providing sound science for improved regulation and develops fundamental scientific data to facilitate the development of effective refining technologies to prevent pollution formation.

Accomplishments. A recent success story concerns the measurement of emissions from heavy oil storage tanks. In complying with the Clean Air Act Amendments of 1990, which regulate emissions from heavy oil storage tanks, the California Air Resources Board had planned to use existing data on emissions from light oil storage tanks. But these data would probably over-estimate actual emissions by a significant degree because heavy oil has less volatile components than light oil. The project data will enable the State to issue regulations that are based on the more specific and appropriate risks of vapor from heavy oil.

Gas Storage and Delivery Systems

Budget: FY98-$1.0M, FY99-$1.0M, FY00-$1.0M

Background

The natural gas storage system provides a vital link between production and end use. Gas storage is the primary means of managing fluctuations in supply and demand. Gas from storage can supply up to 30 percent of daily gas demand in winter and summer months for heating and power. Storage enables greater system efficiency by allowing more level production and transmission flows throughout the year. Without this leveling effect, the amount of transmission pipeline would need to be increased by 50 percent to connect the producing regions to the marketplace.

Linkage to CNES Goals and Objectives

The program supports the following CNES goal and objective:

- CNES Goal II, Objective 2 - Ensure energy system reliability, flexibility, and emergency response capability. *(oil and gas transportation and storage)*

Program Description

DOE is working with industry to ensure that the gas delivery and storage system continues to provide a reliable, cost-effective supply of natural gas well into the next century.

Gas Storage and Delivery Systems

Budget: FY98-$1.0M, FY99-$1.0M, FY00-$1.0M

Description, Objectives, and Performers. This program includes cooperative efforts that will increase gas system deliverability, and contribute to our Nation's energy security, economic competitiveness, and environmental goals. Through its Gas Storage Program, DOE supports the development of advanced technologies and methods to enhance deliverability, increase efficiency, and reduce the costs of operation and maintenance. Program drivers include:

- Federal Energy Regulatory Commission (FERC) regulatory changes increased system deliverability requirements.
- Projected increased gas demand in the South Atlantic and New England Regions and gas production shifting towards the western producing basin create a critical need for delivery and storage system expansion.
- The aging delivery and storage system infrastructure requires re-engineering for increased operational flexibility.

R&D Challenges. Depleted oil and gas reservoirs are used for interim storage of natural gas primarily to meet the large increase in natural gas demand during the winter. Each reservoir has characteristics that determine the limits of injection and withdrawal rates and total storage capacities that can be achieved. Improved methodologies and technologies must be developed through rigorous R&D to prevent the loss of deliverability from these fields and to better remediate lost deliverability when it occurs. Natural gas storage is a critical segment of the Nation’s overall energy system, and innovative gas storage methods are required to meet the projected increase in gas demand, especially in the power generation sector and in areas where conventional underground storage-depleted oil and gas reservoirs are unavailable (South Atlantic and New England Regions).

R&D Activities. DOE, in collaboration with industry, is conducting storage research in the following areas:

- Advanced storage technologies that will meet the specific storage needs of new and growing industrial and power generation markets, specifically the short-term or hourly requirements of the power generation sector.
- Novel and advanced fracture simulation technologies and improved remediation treatments that will increase storage reservoir deliverability and help to offset the reported 5.2 percent annual loss in deliverability.

- The development of improved gas flow metering (such as ultrasonic metering) and energy measurement technologies that will provide real time, automated monitoring of pipeline gas flow and energy content, increasing system deliverability and optimizing gas sales to customers.

- Re-engineering underground gas storage reservoirs to increase operational flexibility, extend the useful life of underground storage reservoirs using horizontal wells, and lower costs for storage.

Development of advanced technologies that meet industry needs would result in a more efficient natural gas storage system and benefit both industry and consumers. The gas storage industry would benefit from improved storage efficiency through increased deliverability, decreased deliverability revitalization costs, and increased operating efficiency. Local distribution companies would gain from improved system reliability and flexibility. Industrial and power generation end users would benefit from advanced storage concepts, and residential customers would benefit from lower costs for service.

Accomplishments. Program accomplishments include:

- Northern Indiana Public Service Company (NIPSCO) partnered with DOE and GRI to demonstrate the use of geological modeling and seismic survey techniques to optimize the development and operation of gas storage fields. Based on the results of this integrated study, NIPSCO drilled a horizontal well at the Royal Center field in Indiana. Initial flow tests indicate that the well will significantly enhance deliverability from the field and allow the utilization of gas from an area of the storage field that was not accessible from the existing vertical wells.

- Universal Well Services, located in Wooster, Ohio, pumped the first ever CO_2/sand fracture stimulations in a gas storage field to determine the applicability of a totally nondamaging fracturing fluid. The deliverability from two underground storage wells at the Galbraith field in Pennsylvania, operated by National Fuel Gas Supply Company, increased by 600 percent.

Geothermal Energy

Budget: FY98-$16.9M, FY99-$16.0M, FY00-$22.5M

Background

The accessible geothermal resource is the thermal energy contained in the rocks within the top three miles of the Earth's crust. This heat energy is carried by naturally occurring hot water or steam brought to the surface through deep wells, and the fluid is used to drive turbine-generator systems to produce electricity (see Geothermal Conversion Systems under Advanced Power Systems) or heat is used directly for industrial, agricultural, or domestic purposes.

Linkage to CNES Goals and Objectives

The program supports the following CNES goal and objective:

- CNES Goal III, Objective 1 - Increase domestic energy production in an environmentally responsible manner. *(by increasing domestic gas production, recovering oil with less environmental impact, and developing cost-effective renewable technologies)*

Program Description

The Department is working with industry to solve the major R&D challenges in the exploration, drilling, and reservoir management of geothermal resources. The goals are to reliably detect producing fractures in hydrothermal systems; to efficiently drill and complete wells under conditions of high temperature, hard rock, and corrosive fluids; and to economically operate production and injection wells for the maximum energy yield as a sustainable resource.

Geothermal Exploration

Budget: FY98-$5.6M, FY99-$5.5M, FY00-$7.0M

Description, Objectives, and Performers. To improve the detection of producing zones in geothermal reservoirs, the Department in partnership with the geothermal industry is augmenting the technology for 3-D seismic surveys and electromagnetic logging.

R&D Challenges. The major challenge in exploration for geothermal resources is the detection of producing zones deep in the subsurface so that drill holes can be directed from the surface to intersect them. Lower well costs would result in expanded use of geothermal power by making this environmentally-preferred alternative more economical.

Present exploration techniques are not specific enough to identify producing zones, and their application results in too many dry wells, driving up development costs. The industry needs better geological, geochemical, and geophysical techniques to identify and characterize the geothermal reservoirs. Technology improvements are needed to reduce the cost of drilling into hard rock at high temperatures which contain corrosive formation fluids, and cements must be developed to maintain well integrity in acidic conditions and high temperature.

R&D Activities. The geothermal reservoir contains steeply dipping faults and fracture zones which provide the high permeability pathways for geothermal fluid production, and the opposing rocks may have only a slight contrast in seismic velocity. Shear-wave generators are being tested to determine the best technique to provide the seismic energy needed for characterization of the geothermal production zones. Geophone array configurations will be tested in mathematical models to determine the optimal design for increased accuracy of location and decreased biasing of the data.

To increase the success of exploration wells intersecting productive fractures, joint Department-industry research is developing a deep-penetration electromagnetic logging tool. The initial activity will be development of the theoretical basis for the electrical response and

the mathematical procedures for interpretation of the measurements. The major challenge will be the construction of a tool that will have sufficient signal strength and receiver separation distance to allow the imaging of potential producing fractures within a radius of 100 feet from the exploration well.

Accomplishments. Development of better interpretation methods for imaging logs have revealed the evolution of faults and fractures in relation to regional stresses in the Earth, and this has led to knowledge of the local control of fracture permeability in the geothermal reservoir. Research on surface electromagnetic survey methods has resulted in improved geothermal field definition with greater instrument reliability and more credible interpretation mathematics. Fluid inclusion studies of secondary alteration minerals from geothermal systems allow developers to determine the changes in salinity and temperature of geothermal fluids with time.

Geothermal Drilling and Completion

Budget: FY98-$6.9M, FY99-$5.0M, FY00-$7.5M

Description, Objectives, and Performers. Geothermal drilling R&D consists of two key components over the next 5-years: incremental improvements for geothermal drilling technology and a high-speed diagnostics-while-drilling (DWD) system.

R&D Challenges. Geothermal wells cost 35-50 percent of the costs of a typical geothermal electric power project. Geothermal well costs can be significantly reduced by improving the technology used in geothermal drilling. Reduced drilling costs is the key to the expansion of geothermal power from traditional hydrothermal resources to hot dry rock, the next generation of geothermal power.

R&D Activities. Activities include the application of advanced techniques, materials and equipment including: a core-tube data logger to collect downhole data while drilling; advanced hard rock polycrystalline diamond compact (PDC) drill bits to drill harder rock; a dewared pressure/temperature/spinner logging tool to provide data in high-temperature wells; and development of slimhole drilling to reduce exploration costs by about 50 percent. The second involves the conceptual work, technology development, field testing necessary, and possible commercialization for the use of a high-speed DWD system. Real-time drilling and logging data, analyzed and used in real-time to control the drilling process, will result in dramatic improvements in drilling performance and reductions in well costs.

Accomplishments. Conducted initial design and testing of PDC drill bits now used in about 40 percent of drilling worldwide, an industry with annual sales in excess of $200 million. In addition, the program developed high-temperature drilling muds, high-temperature elastomers for downhole motors, advanced drilling fluid flow instrumentation, high-temperature memory logging tools; and fostered the use of slimhole drilling as an exploration tool for geothermal energy saving 30 to 50 percent of exploration drilling costs.

Geothermal Reservoir Production

Budget: FY98-$4.4M, FY99-$5.5M, FY00-$8.0M

Description, Objectives, and Performers. Collaboration between the Department and industry in the areas of reservoir modeling, tracer technology, and the study of water absorption is the major focus of geothermal reservoir production.

R&D Challenges. The development of geothermal energy systems requires improved computer methods for modeling heat-extraction and water injection strategies from geothermal reservoirs. An entire suite of chemical tracers are needed to track the migration of injected water through the geothermal reservoir to the production zone to avoid premature breakthrough of cooled production fluid. It is necessary to quantify the relative permeabilities of water and steam in the geothermal reservoir to develop the best strategy for injection of cold water to avoid reservoir pressure loss. A knowledge of adsorption of water on mineral surfaces is important in low-pressure geothermal reservoirs to determine the amount of fluid reserves available for production.

R&D Activities. The possibility of water adsorption on mineral surfaces as a significant source of fluid in low-pressure geothermal reservoirs is being investigated by collaboration between Lawrence Berkeley National Laboratory and Stanford University through measurements of mass change in rocks as a function of water saturation in steam. This research will have important ramifications for the operating pressure of a geothermal reservoir and for the optimum conditions during water injection.

Collaboration between the Department and industry is enabling the development of chemical tracers that are compatible with the environment, do not react with the reservoir rocks, are thermally stable at reservoir temperatures, and can be detected in minute quantities. These tracers show the path of injection water through the reservoir, and they provide a measurement of transit time for a chemical front between injection and production wells. Operators can avoid the temperature drop that would result from rapid breakthrough of cold injection water into the production zone of the reservoir. When cold injection water is used properly to maintain reservoir pressure, geothermal energy is sustainable over long periods of time.

Basic experimental laboratory studies are being conducted to determine the relative permeabilities of reservoir rock to steam and hot water. Empirical evidence has shown that the different phases travel through the reservoir at different rates, and this fundamental property is required for accurate reservoir modeling. Testing of potential tracers is continuing because different tracers are needed to identify the water from each injection well in an operating geothermal field with a large number of production and injection wells.

Accomplishments. Program accomplishments include:

- Demonstrated the application of reservoir modeling to geothermal systems to predict longevity and total energy recovery. Model improvements are underway to incorporate mineral precipitation in the prediction of reservoir permeability.

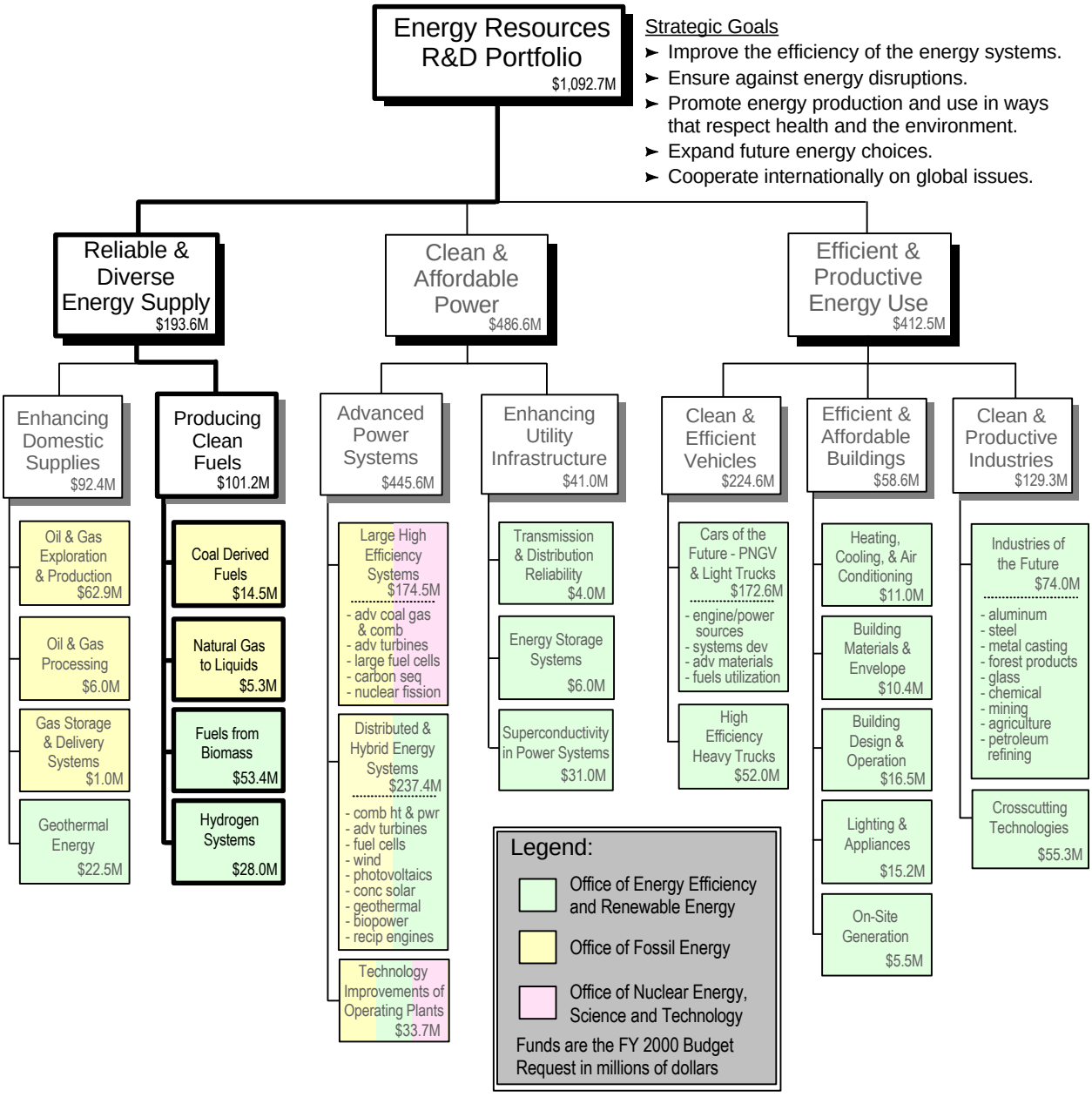
- Identified and tested chemical tracers for monitoring flow of injected water through geothermal reservoirs.

- Analyzed causes of reservoir pressure decline at the Geysers Geothermal Field and developed effective injection strategies to sustain reservoir productivity.

Summary Budget Table (000$)

Enhancing Domestic Supplies Research Areas	FY 1998 Appropriated	FY 1999 Appropriated	FY 2000 Request
Oil and Gas Exploration and Production	**59,800**	**60,400**	**62,900**
Diagnostics and Imaging	19,900	20,400	20,100
Drilling, Completion, and Stimulation	9,100	7,500	7,600
Reservoir Life Extension	21,200	23,300	24,200
Drilling and Production Env. Management	9,600	8,700	9,000
Gas Hydrates	0	500	2,000
Oil and Gas Processing	**5,500**	**6,200**	**6,000**
Low Quality Gas Upgrading	1,100	1,900	1,600
Air Emissions Detection and Control	4,400	4,300	4,400
Gas Storage and Delivery Systems	**1,000**	**1,000**	**1,000**
Geothermal Energy	**16,887**	**16,000**	**22,500**
Geothermal Exploration	5,600	5,500	7,000
Geothermal Drilling and Completion	6,900	5,000	7,500
Geothermal Reservoir Production	4,387	5,500	8,000
Total	**83,187**	**83,600**	**92,400**

Chapter 4
Producing Clean Fuels



Chapter 4

Producing Clean Fuels

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Overview

Definition of Focus Area

The Department's clean fuels R&D portfolio responds to important energy security and environmental challenges by providing the technical basis for a clean fuels industry capable of producing transportation fuels from non-petroleum, domestic resources. These "clean fuels" produce very low emissions of regulated pollutants, and can be derived from carbon-based feedstocks such as coal, natural gas, biomass, or any combination. Use of biomass feedstocks to produce hydrogen and other fuels greatly reduces net emissions of carbon dioxide, the primary greenhouse gas associated with climate change. Further, there is the potential to eliminate carbon dioxide emissions through the use of hydrogen from non-biomass renewable sources, or by combining processes using carbon-based feedstocks with carbon sequestration.

National Context and Drivers

The U.S. transportation sector is 97 percent reliant on liquid fuels, and in spite of current low oil prices and abundant supply, past history suggests that there are credible scenarios where oil security is a concern. For example, the Energy Information Administration (EIA) 1998 International Energy Outlook forecasts that, by 2020:

- U.S. petroleum imports, already over 50 percent of the 18 million barrels per day consumed, will increase to 65 percent of the projected 24.4 million barrels per day consumed.

- Worldwide oil dependence will continue at nearly 40 percent of total energy consumed, and total petroleum imported by all countries will double.

- OPEC states, many in politically unstable regions, will be the source of the ever increasing amounts of oil imported by the United States and other countries.

There are also fuels-related environmental concerns. Vehicles currently account for a large portion of urban air pollution, including 81 percent of carbon monoxide, 49 percent of nitrogen oxides, and 37 percent of volatile organic compounds. The transportation sector also contributes over one-third of U.S. carbon dioxide greenhouse gas emissions which, absent new reduction initiatives, are projected to increase more than 40 percent by 2020. In coming decades, increasing public health and environmental concerns will likely lead to new environmental regulations that may be difficult or impossible to meet with petroleum-based fuels.

The clean fuels that are the focus of this paper can be produced in abundance from indigenous resources, are environmentally superior to conventional petroleum-based fuels, and are well-suited for advanced, clean, high efficiency engines. With essentially none of the impurities found in petroleum based fuels, they permit ready use of advanced emission control technologies in all types of vehicular engines. With these new fuels, even diesel engines are capable of meeting future California Air Resources Board (CARB) standards for gasoline engines.

A clean fuels industry could take on different forms, including a series of plants that co-produce electric power, transportation fuels, and chemicals. These plants would operate in a deregulated gas and electric utility environment and their co-production capabilities and product flexibility would provide a robustness not available in single purpose plants. Co-production of high value products would act synergistically to reduce the costs of all energy products while further reducing the use of imported petroleum-based feedstocks.

Linkage to CNES Goals and Objectives

The primary outcome of clean fuels R&D is to make available, during the 2008-2020 period, a suite of competitive fuels that can be used in transportation and other applications to reduce conventional pollutants and greenhouse gases, and displace oil imports. These activities strongly support CNES goals and objectives dealing with energy/oil security and environmental protection. In particular:

- CNES Goal II, Objective 1 - Reduce the vulnerability of the U.S. economy to disruptions in oil supply. *(longer-term replacement of imported oil with clean fuels)*

- CNES Goal III, Objective 1 - Increase domestic energy production in an environmentally responsible manner. *(all clean fuels offer environmental advantages)*

Uncertainties

Developmental clean fuels face uncertainties that will affect the timing and extent of market penetration. All must successfully meet R&D challenges (discussed later) in order to significantly reduce product costs from the current state-of-the-art. Furthermore, the marketplace may be reluctant to embrace these fuels if there is the perception that oil prices could be low (e.g., under $20/barrel) for sustained periods. However, any future incentives to reduce greenhouse gas emissions would affect the relative attractiveness of these fuels. In addition:

- If greenhouse gas reduction is a priority, large-scale production of coal-derived liquid fuels would need to be combined with methods (some are currently under investigation) to significantly reduce carbon emissions during processing stages.

- The timing for domestic markets is uncertain for large volume production of natural gas-to-liquids. While it appears that new liquid sources could be needed in about a decade to maintain a viable Trans-Alaska Pipeline, new oil discoveries could delay the conversion of North Slope gas to fuel liquids.

- A key question for biofuels is regulatory and policy uncertainties for ethanol used as a transportation fuel. Several States have enacted legislation encouraging the use of ethanol, such as requiring ethanol to be used in State motor vehicle fleets and establishing minimum statewide oxygenate levels. Other States have passed laws or instituted legislation restricting the use of ethanol, such as limiting oxygenate levels or evaporative

emissions limits. Although the tax incentive for ethanol was extended through 2007, some uncertainty remains with respect to the magnitude of the incentive over this period.

- A significant hydrogen industry exists that produces hydrogen centrally in large plants and transports liquid hydrogen to the marketplace. The ultimate goal of achieving a distributed gaseous hydrogen storage and distribution system, however, is subject to a chicken-and-egg phenomenon. Hydrogen use will require establishment of a new fueling infrastructure with a set of codes and standards that are acceptable to the community. However, the development of such an infrastructure requires cost-competitive plants.

Investment Trends and Rationale

The clean fuels portfolio is designed to respond to both energy security and environmental drivers over the mid- to longer-term time frame. Fuels from coal and natural gas enjoy a high level of compatibility with the existing infrastructure, and could provide environmental benefits due to their suitability for use in advanced, high-efficiency vehicle engines. Biofuels, and ultimately hydrogen fuels, provide renewable options with very low environmental impacts, although there will be infrastructure challenges. Several trends are evident in the portfolio:

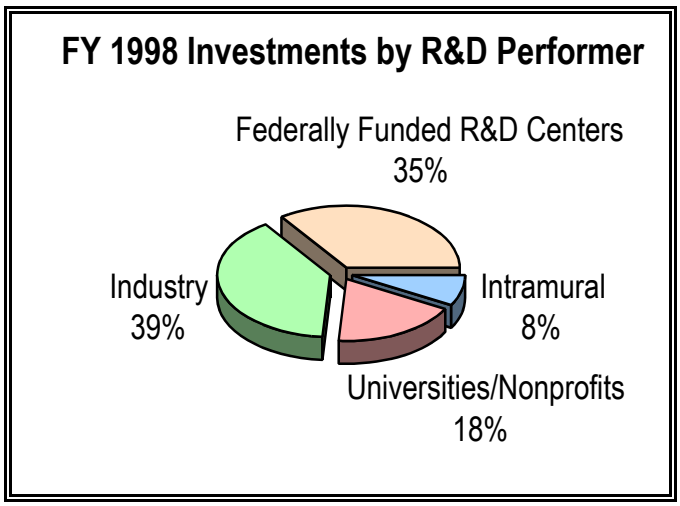
- For coal-derived fuels, there is increasing emphasis within current funding levels on reducing greenhouse gas emissions through strategies such as blending coal with biomass, and incorporating natural gas and waste products into the feed stream.

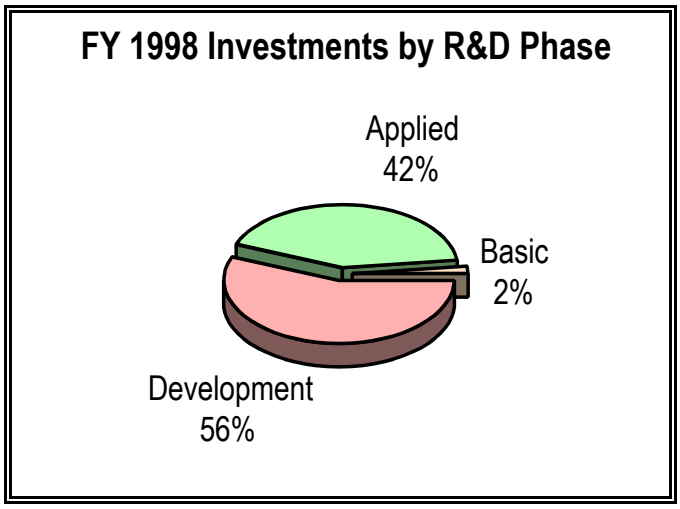
- Increasing funding for biofuels emphasizes lowering the cost of ethanol production technology through advances in pretreatment, cellulase enzymes, and fermentation.

- Increasing funding for hydrogen fuels emphasizes infrastructure-related activities such as development of molecular hydrogen storage and distribution technologies that will be demonstrated as hydrogen refueling stations for fleet vehicles and mass transit buses.

The figures below show how funding for clean fuels programs are distributed by R&D performer and R&D phase. Relatively little basic research is carried out within the clean fuels portfolio, although there is basic research carried out in crosscutting programs, e.g., materials programs in the Office of Energy Efficiency and Renewable Energy (EE) and the Office of Fossil Energy (FE), and particularly in the Office of Science (SC), that could contribute to these programs.

R&D performers tend to reflect the maturity and origins of the technologies. For example, technologies in the latter stage of the development, such as some of those in the coal fuels program, will normally have more industry participation. Other clean fuels areas that are less mature have greater university and National Laboratory (which appears in the figures under Federally Funded Research and Development Centers) participation. The significant “intramural” activity for coal fuels reflects in-house R&D at the Federal Energy Technology Center, which is staffed by Federal employees.





Federal Role

Based on the environmental and security-related concerns associated with our current fuels mix, the Federal Government is investing in clean fuels where the industry believes that the risk is too high to profitably recover the costs of the long-term and/or high-cost R&D required to develop those technologies, or where the Government has unique R&D capabilities.

While global concern over the environmental impacts associated with transportation demands is growing, the low price of conventional transportation fuels makes it difficult to change current fuel use patterns. There is little immediate market incentive for investment in cleaner fuels, especially for longer-term options. Accordingly, there is a significant gap between the level of advanced clean fuels R&D that the market will support and the level needed to address current and future concerns about impacts of conventional fuels. The Department's clean fuels research and development portfolio is designed to help bridge that gap.

Key Accomplishments

The Clean Fuels program has made significant progress toward meeting its goal and objectives. Broad accomplishments include:

- Coal liquids R&D has reduced the crude oil equivalent cost to approximately $30 per barrel, versus $60 per barrel in the late 1970s.
- Recent breakthroughs in air separation via ceramic membranes have created the potential for reducing the cost of liquids from natural gas at least 25 percent below conventional technology and significantly reducing costs from coal-based synthesis gas.
- Over the last 2 decades, the predicted cost of biomass-derived ethanol has been reduced by at least 50 percent, and commercial production of biomass ethanol from low cost feedstocks is expected to begin by 2002. Biodiesel is produced today from agricultural crops, such as rapeseed and soybeans, and from recycled restaurant grease.
- Experimental results achieved on a Sorbent Enhanced Reformer validate expectations for a system that will reduce the cost for the production of hydrogen by 25 percent from conventional steam reforming methods.

Coal-Derived Fuels

Budget: FY98-$15.8M, FY99-$15.5M, FY00-$14.5M

Background

Historically, the obstacle to producing coal-based liquid fuels has been cost. In particular, the costs of the various processes used to convert coal to liquids have not been able to compete with conventional oil production and refining, especially when relatively low-cost oil from the Middle East and elsewhere has kept crude oil prices below the $20 per barrel mark. Today, however, a decade of research and development on a new generation of synthetic fuel technologies has brought about dramatic drops in the cost of substitute liquid fuels. Where once in the late 1970s, for example, the projected cost of coal liquids approached $60 per barrel, today's technology has brought down the cost to about $30 per barrel. Moreover, the prospects of additional process breakthroughs has created the probability that costs, by 2015, can be lowered even further, to the EIA projected reference price of $21 per barrel for crude oil.

An estimated 2 to 3 billion tons of coal “fines”—microscopic coal particles—lie in waste impoundments at coal mines and washing plants around the country. This discarded “waste” contains the energy equivalent of 8 to 12 billion barrels of oil, as much as a massive oil field. Moreover, each year, mining operations dispose of as much as 30 million tons of coal as waste, and utilities discard millions of tons of unburned carbon along with fly ash in power plant landfills. Technologies are required to utilize these carbon resources, including co-firing applications with a diverse group of energy sources ranging from wood, agribusiness wastes, and landfill materials (municipal and animal waste, plastics, rubber, etc.) that are discarded in the United States, as well as fast-growing “energy crops.”

While over half of U.S. power currently comes from coal, environmental concerns (e.g., emissions of hazardous air pollutants and greenhouse gases) could affect future use of the Nation's most abundant fossil fuel resource. Development of pre-combustion technology can address these issues.

Linkage to CNES Goals and Objectives

There are two main goals for coal-derived fuels:

- By 2010, develop technology to permit continued use of our abundant coal resources in a cost-effective, environmentally-benign manner, including:
  - An alternative source of coal-derived liquid transportation fuels that is cost-competitive with equivalent petroleum products.
  - Technologies that utilize low-cost waste coal resources and significantly lower power plant emissions, including carbon dioxide, by reducing pollutant-forming species in all coal resources and preparing suitable blends of coal with biomass/wastes.
- By 2015, develop technologies for the cost effective production of premium carbon products and feedstocks from coal.

These program goals support multiple CNES goals and objectives:

- CNES Goal II, Objective 1 - Reduce the vulnerability of the U.S. economy to disruptions in oil supply. *(coal-derived liquids represent a potentially large supply of domestic transportation fuels)*
- CNES Goal III, Objective 1 - Increase domestic energy production in an environmentally responsible manner. *(production of these fuels in combination with carbon management would be ideal for advanced, high-mileage, low emission vehicle engines)*
- CNES Goal I, Objective 1 - Support competitive and efficient electric systems. *(coal's main domestic use is for power production, and efforts to recover waste coal, reduce emissions, and produce high-value carbon-related products would enhance the overall economics of coal power)*

Program Description

Coal, our country's most abundant fossil resource, provides much more than just raw fuel to be burned. The carbon and hydrogen in coal are a rich source of molecular "building blocks" that can form a diversity of liquid fuels and valuable commercial chemicals as historically exemplified by the coke and tar products industry. The Department of Energy's Office of Fossil Energy is focusing on developing processes that produce premium liquid fuels from coal, natural gas, wastes, and renewables that offer enhanced engine performance and produce significantly

lower emissions than conventional petroleum-derived fuels. One such process, referred to as indirect liquefaction, utilizes synthesis gas, a mixture of carbon monoxide and hydrogen that can be produced from the gasification of a wide range of carbonaceous feedstocks. The synthesis gas can then be converted to a specific, high value product slate depending on the catalyst and reactor conditions. A partnership has been established among the Offices of Coal and Power Systems (FE), Oil and Gas (FE), and Transportation Technologies (EE) to support a cost-shared research program with industry to develop premium transportation fuels and vehicles which would have significantly greater efficiency and produce ultra-low environmental emissions. In view of the current economics for fuel production, Fossil Energy is also pursuing an initiative termed the "Vision 21 Early Entrance Plant" to assist industry with the integration of power and fuels co-production at a single facility that would be operational by 2007. Co-production could provide major economic and environmental benefits over production of fuels and power at separate plants.

Transportation Fuels and Chemicals

Budget: FY98-$10.0M, FY99-$8.7M, FY00-$8.3M

Description, Objectives, and Performers. Two approaches are being pursued for bringing advanced technology for the manufacture of liquid fuels from coal into the marketplace. One is the direct process, which converts the complex organic chemical structures found in coal directly by hydrogenation. Another approach is indirect liquefaction, where coal is gasified and the molecules catalytically recombined into liquid products. Fuels from indirect liquefaction (e.g., gasoline, diesel, jet) constitute a "new generation" of transportation fuels that have no aromatic or sulfur compounds and exhibit very low toxicity. These technologies will be particularly attractive when integrated with advanced power production technologies, permitting the economic co-production of electricity, transportation fuels and premium chemicals. The objective of these activities is to develop fuels that will: be compatible with the existing infrastructure; exceed future transportation fuel emission requirements; increase the efficiency of the current gasoline-fueled fleet from 22 percent to 40 percent by using newly developed light diesel engines with performance that is environmentally superior to today's conventional gasoline and diesel fuels; and be competitively priced. The R&D is being performed by 13 organizations, including 7 industrial companies that comprise about one-half the program funding, 2 universities, 2 National Laboratories and 1 Fossil Energy field laboratory.

R&D Challenges. The primary challenge is to simultaneously drive down costs and reduce environmental emissions. Improved techniques for synthesis gas and hydrogen production , hydrogen separation and purification, achieving greater reactor throughput, and the creation of higher value products can all lead to better marketability through lower product cost and environmental performance that leads to the DOE goal of "zero-emissions."

R&D Activities. Fossil Energy's transportation fuels and chemicals program is multi-faceted and focused on developing technologies that will lead to specific high-value products, including diesel, gasoline and jet fuels and a range of premium chemicals. This market emphasis presents very clear economic and environmental targets that in turn drive the research activities. As an example, an FE-led teaming among industry, a National Laboratory

and several government organizations is developing alternative diesel fuel via the Fischer-Tropsch (F-T) indirect liquefaction process. The fuel has been shown in preliminary engine tests to produce much lower emissions than its petroleum-derived counterparts, which has generated strong interest among the diesel engine manufacturers. The cornerstone to this development effort is the LaPorte TX proof-of-concept facility where successes in the lab are transferred into the production of fuel, as was demonstrated in the FY 1998 F-T operation where several barrels of product were produced in the advanced slurry reactor for further evaluation.

The indirect conversion laboratory research is emphasizing continued improvements in the three-phase slurry reactor technology where technology advances have shown the productivity, i.e, product per unit volume of reactor, is moving far beyond what was anticipated. Low cost iron-based catalysts are being developed for the slurry reactor, especially for their application and suitability to feedstocks that are low in hydrogen content such as coal, wastes and petroleum coke. Additionally, a major thrust is also directed at developing the next generation of premium fuels that will be needed in order to meet increasingly stringent emissions regulations. An example includes work on preparing liquid, high-cetane number, ultra-clean oxygenates that would be compatible with the existing petroleum-based fuel infrastructure.

There is considerable interest in the Peoples Republic of China (PRC) in establishing a direct liquefaction industry to reduce that country's reliance on imported oil. The U.S. technology is considered to be highly competitive to those that have been developed in other countries. Because of this large potential market, efforts are being focused on providing test and engineering data at a scale that will enable definitive comparisons with competing systems and provide the market push needed to implement the establishment of this technology in the PRC.

Extensive life cycle analyses will continue to identify those areas of fuel conversion processing that offer the best opportunities for CO_2 mitigation. Concurrently, novel R&D is underway to include methods to reduce production of greenhouse gases through process improvements and utilization of multiple feeds such as waste material or biomass.

Accomplishments. Since the mid-1980s, advanced transportation fuels and chemicals technologies which would provide environmentally superior fuels and strategic chemicals, accompanied by significant reduction in product cost, have been developed from the laboratory and bench scale to current proof-of-concept activity. For example, the Liquid Phase Methanol Technology, has been successfully developed through the research and development program, and is now being commercially demonstrated at the Eastman Chemicals plant in Kingsport, TN with support from DOE's Clean Coal Technology Program.

Solid Fuels and Feedstocks

Budget: FY98-$5.1M, FY99-$5.1M, FY00-$4.0M

Description, Objectives, and Performers. Activities provide for the environmentally-responsible utilization of the vast U.S. coal resource as well as the increased utilization of non-fossil resources such as biomass and waste. The objective is to provide for the development and deployment of technologies to produce environmentally acceptable, efficient, and affordable carbon-based solid fuels and feedstocks that can compete with those from alternate energy sources, including oil. In addition to ensuring low-cost environmentally acceptable supply of solid fuels for energy production, the activities will ensure a supply of quality feedstocks for specialty applications. The program currently involves fourteen participants, including three private sector consortia. These encompass a broad range of organizations including coal producers and technology developers, electric utilities, State and Federal agencies and universities.

R&D Challenges. R&D is needed to: (1) reduce the environmental impacts associated with the generation of hazardous air pollutants from the utilization of coal, particularly the pre-combustion removal of mercury; (2) reduce the generation of greenhouse gases (i.e., CO_2) associated with the utilization of coal; (3) enable and encourage the recovery of previously lost carbon raw materials from waste (culm piles/ponds); (4) permit greater recoveries of the useful energy of mined coal; (5) decrease the reliance of the carbon products industry on increasingly dirty (high-sulfur and -metals) imported petroleum; (6) support the development of technology for the production of new premium carbon and industrial products for U. S. Strategic industries necessary for national security and growth of the economy; (7) enable the co-utilization, with coal, of historically discarded biomass and waste materials, therefore, better utilizing domestic energy resources

R&D Activities. R&D specifically focuses on the development of advanced technologies for the recovery and dewatering of fine coal now lost as waste or already disposed of in waste ponds and discard coal piles/culms; the processing of coal, biomass, and/or waste materials to produce new solid fuels for the generation of power and heat and to mitigate emissions of CO_2 and other greenhouse gases; the pre-combustion removal of trace elements for the reduction of hazardous air pollutants (HAPs) from coal-fired power plants; the production of value-added, premium-quality carbon products (such as light-weight, high-strength carbon fibers, and composites and electrodes) from anthracite, bituminous, and subbituminous coals; the production of solid feedstocks from coal, biomass, and/or waste for producing premium transportation fuels, low-smoke fuels, electricity, and chemicals; and improvement in the handleability and transportability of various solid fuels.

Accomplishments. This activity has enjoyed notable successes. For example, the Microcel flotation column coal cleaning technology, developed by Virginia Polytechnic Institute with DOE support, has had significant commercial success in coal and minerals applications worldwide. The ENCOAL and Rosebud projects are successfully demonstrating technologies for converting low quality coals to cleaner, higher-value solid and liquid fuels.

Advanced Research

Budget: FY98-$0.7M, FY99-$1.8M, FY00-$2.2M

Description, Objectives, and Performers. Advanced Research (AR) explores new concepts and ideas that lead to technologies that significantly enhance the economics and reduce the environmental consequences of coal conversion and utilization. Surveying and evaluating new ideas allows AR to bridge the gap between basic research and line programs and provides the technical foundations which serve as the basis for advanced process development. AR is carried out by Federal laboratories, academia, National Laboratories, and industry through various mechanisms and financial support vehicles.

R&D Challenges. Key to the concept of the "hydrogen economy" is the low cost production of high purity hydrogen, preferably without the emission of carbon dioxide. Regardless of the source of the hydrogen (e.g., fossil, biomass, photoelectric, photochemical, etc.), storage, in a fashion that would provide a high enough energy density for it to be used as a vehicular fuel, is problematical and rife with concerns of safety and infrastructure compatibility. This area presents the current and most difficult R&D challenge.

R&D Activities. R&D focuses on areas such as novel methods to co-produce hydrogen and high value carbons, especially those useful for hydrogen storage; coprocessing of coal and biomass; advanced, clean burning diesel fuels; and production of high value chemicals and non-traditional carbon products from coal.

Accomplishments. Many of the present coal conversion technologies now in use were developed through the AR program. These include low-cost, high-efficiency catalysts for direct and indirect liquefaction processes, advanced synthesis gas technologies which will serve as the fuels building blocks for future Vision 21 co-production facilities, coal-waste co-processing technologies, and development of unique analytical methods and protocols suitable for characterization of coal-derived products.

Natural Gas-to Liquids

Budget: FY98-$6.3M, FY99-$6.8M, FY00-$5.3M

Background

Despite being discovered 30 years ago, the vast natural gas reserves in Alaska's North Slope remain largely unproduced, without access to urban markets. Pipeline construction to an ice-free port, enabling physical conversion and tanker export of the gas as LNG to Asian markets, has long been seen a possibility. However, this option has been stymied by less costly foreign competition. An alternative production and marketing route for the gas would be for it to be chemically converted into a liquid that is more easily transported via an existing oil pipeline and tankers to market. Similar gas-to-liquids (GTL) conversion processing also could be used on offshore platforms or barges in the Gulf of Mexico and in many remote locations worldwide to facilitate oil and gas production from wells that do not have pipeline access.

Converted gas from Alaska's North Slope could be transported through the underutilized Trans-Alaska Pipeline System, which carries crude oil from the Prudhoe Bay field on the North Slope to Valdez for tanker shipment to markets. Production from that field is declining at a rate of about 10 percent per year. Even with additional production from newer, more marginal fields, pipeline flow will eventually fall below the minimum volume needed for viable pipeline operation, cutting short final North Slope oil recovery.

The investment hurdles of present natural GTL technology are formidable, and the gas conversion industry in the United States is in its infancy. Recent breakthroughs in ceramic air separation, however, have created the potential for meeting conversion technology cost goals.

Linkage to CNES Goals and Objectives

The main goal of the gas-to-liquids program is to develop, for deployment by 2008, breakthrough technology to convert unmarketable Alaskan and other remote natural gas to high quality, cleaner transportation fuels and premium chemicals at costs 25 to 35 percent below current technology. As a potentially large source of fuels suitable for advanced, high-mileage, low emissions vehicle engines, liquids derived from natural gas could:

- CNES Goal II, Objective 1 - Reduce the vulnerability of the U.S. economy to disruptions in oil supply.

- CNES Goal III, Objective 1 - Increase domestic energy production in an environmentally responsible manner. *(transportation applications)*

Program Description

GTL R&D is focusing on several key technical areas, the most prominent being advanced Fischer-Tropsch (F-T) conversion technology. F-T usually involves two major processing steps: generation of an intermediate process gas (“syngas”) composed of hydrogen and carbon monoxide, and synthesis of the intermediate gas over a special catalyst to a hydrocarbon liquid, which also can be followed by separate steps of catalyst/liquid separation and liquid finishing to exact product specification. The major capital plant investment required is for the first step of syngas generation, and this is where DOE’s research emphasis is currently placed. At the same time, technology advances are being sought for the second step conversion of the syngas to paraffin hydrocarbon liquids, chiefly in the diesel fuel range. Other DOE work addresses the problem of unmarketable natural gas through development of physical liquefaction technology that is economic at smaller-scale than typical giant LNG trains of today, handling upwards of 500 mmcfd of natural gas.

By furthering the advancement and validation of economical GTL conversion processes, the Federal program can serve not only as a technical facilitator for the public-private Alaskan decision making needed to utilize our large Alaskan gas resources, but one exceedingly helpful in opening up a significant supply of highly desirable, clean-burning liquid transportation fuels. The three areas of GTL research are as follows:

Ceramic Membrane Reactor Systems for the Conversion of Natural Gas to Syngas

Budget: FY98-$4.8M, FY99-$5.5M, FY00-$4.0M

Description, Objectives, and Performers. This research seeks major cost reductions by using a novel ceramic membrane capable of integrating oxygen separation from air, and methane partial oxidation in a single step. This process would eliminate the need for expensive oxygen produced by cryogenic means to make the intermediate syngas product of carbon monoxide and hydrogen, which then can be readily converted to the desired hydrocarbons. Other cost reductions in F-T processing are being investigated in cooperation with the Coal-Derived Fuels program through development of high-volume slurry reactors and delineation of characteristics of productive catalysts for syngas conversion to liquids. Liquid product optimization for Alaska pipeline transport is also a subject of GTL. The overriding objective of all of these F-T efforts is to develop, advance and identify optimum gas conversion technology to enable timely and economic conversion of presently unmarketable Alaska North Slope natural gas to quality liquid motor fuel stock.

The major work element of GTL research, ceramic membrane reactor system development, is being conducted on a significant cost-shared basis by a competitively selected, industrial research consortium headed by Air Products and Chemicals, Inc., with team partners including DOE National Laboratories, major gas holding oil companies, ceramic producers, and others. Federal funding is provided by FE's GTL program (75 percent) and EE's hydrogen program (25 percent).

R&D Challenges. Critical to the success of the novel membrane system will be the ability of the ceramic to allow oxygen ion and reverse electron flow at steady rates (flux) while maintaining strength, durability and chemical stability, all in the face of significant pressure and temperature differentials. Metal-ceramic seals likewise will be a challenge, particularly as the process moves from laboratory confirmation scale to extended, high volume commercial module scale, able to weather normal operating interruptions and accompanying temperature swings of several hundred degrees Centigrade.

R&D Activities. Early ceramic membrane system research is focused on ceramic and metal-seal development and testing, leading to fabrication plans for bench and pilot process operations. Numerous reactor design options will be evaluated, followed by careful trial and scaleup of the preferred design under a full range of anticipated GTL operating conditions. The final scaleups of the membrane reactor will be linked with comparably scaled, continuous operating liquid conversion units to make target, ultra clean-burning motor fuels and feedstock.

Accomplishments. Accomplishments thus far are reports considered to be the premier references on the subject. The membrane underpinning of the syngas project builds on pre-project exploratory ceramic work sponsored by the GTL program and also DOE's Small Business Innovation Research program in the mid-1990s. Preliminary design evaluations are expected in the Spring of 1999.

Thermoacoustic Natural Gas Liquefaction

Budget: FY98-$0.5M, FY99-$0.6M, FY00-$0.6M

Description, Objectives, and Performers. This process, designed for small-scale liquefied natural gas (LNG) manufacture at remote offshore and onshore locations, uses direct gas burning to generate sound waves to drive an orifice pulse tube refrigerator. The liquefier has no moving parts and requires no electric power. The objective is to develop a process for small-scale liquefaction of natural gas that achieves one-half the cost of traditional small-scale refrigeration at a scale of 10,000 gallons per day (gpd), or about 1 million cfd. Conceived by researchers at the Los Alamos National Laboratory, and also the National Institute of Standards and Technology, the *"Thermoacoustic Sterling Hybrid Engine Refrigerator"* (TASHER) is now entering the cost-shared prototype development phase led by Cryenco, a division of Chart Industries Inc. and a leading equipment maker for the cryogenics industry.

R&D Challenges. Economic viability of the TASHER concept for LNG manufacture will require liquefaction efficiency in the 80 percent range. This compares with large scale unit efficiency of 90 percent and experimental TASHER results of 60 percent to-date.

R&D Activities. Near-term plans call for a pre-commercial scaleup to 500 gpd, gas well-site liquefaction testing, and trial use for LNG-servicing of small LNG-powered truck fleets (funded by EE's Transportation Technology Program). Subsequent scaleup and demonstration with participating industry users is planned at the 10,000 gpd scale or higher.

Accomplishments. Small-scale production at a rate of 100 gallons/day of LNG has been achieved for several hours duration in an experimental unit. Efficiency of 60 percent was 30 times the original laboratory runs.

Novel Conversion Processes

Budget: FY98-$1.1M, FY99-$0.7M, FY00-$0.7M

Description, Objectives, and Performers. Novel exploratory routes are being pursued to convert natural gas to other intermediate products such as ethane, ethylene, acetylene, and oxygenates for direct use or subsequent conversion to valuable liquid products. The objective is to develop catalytic and non-catalytic alternative approaches to gas conversion that are more direct than the multi-step syngas route. Exploratory conversion work is currently underway at Lawrence Berkeley and Idaho Engineering and Environmental National Laboratories, Oklahoma University, a Canadian government laboratory, and at Fossil Energy's Federal Energy Technology Center.

R&D Challenges. Methane is an extremely stable molecule, and breaking it down to separate hydrogen and carbon components without full oxidation is extremely difficult. Reaction thermodynamics must be tightly controlled for success in any 'reconstitution' process.

R&D Activities. Research areas currently under investigation include electrochemical conversion, plasma conversion, novel hydrogen separation reactor technology, and photochemical conversion.

Accomplishments. While selected novel conversion reactions and products have been achieved, sustainable processes remain elusive. Explorations continue, however, at a measured pace.

Fuels From Biomass

Budget: FY98-$30.3M, FY99-$41.8M, FY00-$53.4M

Background

The existing ethanol production capacity is approximately 1.7 billion gallons per year from corn kernels and the average production cost is nearly $1.10 per gallon. Approximately 30 million gallons of biodiesel capacity is available in the United States today, with production costs ranging from $1.60/gal to $2.30/gal. However, market price is substantially higher because of volume related marketing and distribution costs. Beginning in the 2001-2004 period, ethanol plants using cellulosic biomass that are currently under construction or being designed, will start up and will be competitive with those using corn. This market value allows investors to obtain the high rates of return needed for initial production facilities. Cellulosic ethanol costs are expected to decrease by over 40 percent over the next 12 years thanks to ongoing research and development funded by the private sector, DOE and the United States Department of Agriculture (USDA). With California and possibly other States contemplating the phasing out of MTBE as an oxygenate, the demand for ethanol as a replacement is expected to grow sharply. Several companies are aggressively engaged in commercial development of biomass ethanol utilizing niche feedstocks, including municipal solid wastes, bagasse, and rice straw.

There are three Midwest biodiesel producers using soy oil (one of which is combining soy oil with recycled grease); two firms producing biodiesel from recycled grease in the eastern United States, and at least one firm producing biodiesel from tallow and other low cost feedstocks in South Carolina. Several producers are working with urban planners to build new facilities, primarily recycled grease biodiesel plants. By focusing on new nonedible, nonindustrial oil seeds, future biodiesel costs could be reduced to about $1.00/gal by 2010.

Linkage to CNES Goals and Objectives

The goal of biomass fuels activities is to reduce transportation petroleum use and carbon emissions by using renewable resources such as agricultural and forest residues beginning in 2001, higher value agricultural residues beginning in about 2005, and finally, crops grown specifically for use as energy feedstocks beginning in 2010. As a potentially large-volume, renewable source of transportation fuels, biomass fuels could:

- CNES Goal II, Objective 1 - Reduce the vulnerability of the U.S. economy to disruptions in oil supply.

- CNES Goal III, Objective 1 - Increase domestic energy production in an environmentally responsible manner. *(transportation applications)*

Program Description

DOE conducts research on a variety of feedstocks and conversion processes to produce a wide menu of biofuels for the future. The near-term focus is on biofuels that can be deployed in niche markets for solving environmental problems associated with large quantities of waste material, such as ethanol from rice straw, forest residues, municipal solid wastes, and other low value biomass. Two companies, in partnership with DOE, are exploiting the use of "concentrated acid hydrolysis" processes that can handle a broad range of waste materials. A third industry partner is focusing on the use of dilute acid processes to produce ethanol from sugarcane bagasse. Several companies are commercializing biodiesel technology that will be able to utilize waste oils and greases from restaurants and other commercial operations.

DOE laboratories and university partners will continue to improve the cost effectiveness of ethanol production. This research has two major emphases: the development of enzymes capable of efficient release of sugars from biomass, and the development of microorganisms capable of high yield conversion of all available sugars in biomass.

At the same time, DOE is supporting research on biomass feedstocks. Farmers are already sitting on a huge potential resource for ethanol—agricultural residues. Corn farmers leave tons of residue on the field after the harvest. Understanding how much of this residue can be safely and cost effectively removed offers a way to create a new co-product for the farmer. Using these residues will give farmers new sources of income, while allowing the ethanol industry to expand without competing for new farm acreage. "Waste" biomass has its limits. Therefore, it is important to expand the resource base for ethanol production. Ultimately, dedicated energy crops will provide another source of biomass, and DOE is supporting the development of trees and grasses with characteristics that will ensure their successful deployment as energy crops.

DOE analysis shows that standard vehicles using blends of 10 percent ethanol in gasoline could require several billion gallons per year before 2015. In addition, hundreds of thousands of flexible fuel vehicles are already available today. These can handle blends of up to 85 percent ethanol in gasoline.

Both biomass ethanol and biodiesel reduce greenhouse gases (80 percent for ethanol and 78 percent for biodiesel), on a total fuel cycle basis. When used as a low blend, both fuels are readily blended with petroleum fuels used in conventional vehicles, and require minimal changes to the existing fuel distribution infrastructure. Collaboration with USDA and their research units at land-grant universities allows us to tap into a unique combination of Federal and academic expertise in biomass R&D. Partnerships with industry help transfer Federally funded technologies from the Government research organizations to the private sector, thereby reducing the biofuels production costs and accelerating their market entry.

Feedstock Production

Budget: FY98-$2.5M, FY99-$2.8M, FY00-$5.5M

Description, Objectives, and Performers. Studies are carried out in the areas of wood energy species, herbaceous energy species, environmental research, systems integration and analysis, and market development factors. The current DOE program focus is on switchgrass, hybrid poplars, and willows. Switchgrass will be among the first of the dedicated energy crops to made available. Bioethanol producers using waste feedstocks should begin to supplement their resource base with switchgrass by around 2005 based on availability near conversion facilities. The objective is to develop and demonstrate environmentally acceptable crops and cropping systems for producing large quantities of low-cost, high-quality biomass feedstocks to support future large-scale deployment of lignocellulosic-based ethanol in many parts of the country. Sixty percent of the funding is for R&D work being performed by universities, USDA research organizations, private research companies, and forest products companies. The Oak Ridge National Laboratory conducts some R&D in-house, and also coordinates the work done at the institutions cited above.

R&D Challenges. While past R&D has enabled biomass yield per acre to increase significantly, additional yield improvements will directly benefit the economics of biomass production. The variety of soils and climates dictates the need for additional varieties of switchgrass and woody crops, and for numerous test sites throughout the country in order to maximize the likelihood of cost-effective deployment on a large scale. Biomass harvesting technologies need to be refined and demonstrated in partnership with industry. Three basic areas for information are being collected to better define research needs. Water quality, regulated by the Environmental Protection Agency, including non-point source pollution from agricultural practices, is becoming of increasing concern to both regulators and the public. Soil sustainability is of major concern to producers and users of energy crops as well as to environmental groups that take a national view of environmental issues. Biodiversity, particularly wildlife diversity, is a top priority environmental issue because of the continued loss of habitat both nationally and internationally.

R&D Activities. Biofuels feedstock development activities focus on planting genetically transformed poplars in commercial fields, expanding switchgrass breeding and testing in the North Central region, and identifying locations for potential low-cost perennial crop establishments. Poplar R&D involves an integrated portfolio of R&D in genetics, breeding, physiology, and/or biotechnology to allow for continued progress towards the development of a single model wood energy crop. The switchgrass research plan for 1998 and beyond focuses on promoting advanced breeding, facilitating scale-up and commercial utilization, obtaining long-term yield data, and understanding the microbial ecology affecting longer term carbon and nitrogen cycles which sustain switchgrass production.

Accomplishments. More than 125 tree and nonwoody species have been screened and a limited number of model species for development as energy crops have been selected. The pulp and paper industry deployed over 70,000 acres of hybrid poplars in the Northwest based in part on DOE's development of new faster-growing clones. A number of new switchgrass varieties have been tested successfully at several university and USDA test sites.

Ethanol Production

Budget: FY98-$25.0M, FY99-$36.0M, FY00-$37.4M

Description, Objectives, and Performers. The major research effort in biofuels production is the development of technologies for producing ethanol. Continued improvements will make biochemical conversion of biomass to ethanol a more efficient and economical route to renewable fuels production. By 2004, at least three ethanol plants will be in operation, using biomass wastes, and a partnership with the corn ethanol industry will complete pilot scale work on ethanol production from corn stover. The ultimate objective is to reduce the cost of producing ethanol from biomass residues and dedicated crops and trees that will allow the displacement of nearly 5 percent of projected gasoline use by 2020 with 11 billion gallons of ethanol.

The National Renewable Energy Laboratory (NREL), leads the development of improved technology in collaboration with industry and selected universities. Specific targets for technology improvement have been established. The improvements targeted lean heavily on biotechnology tools such as metabolic engineering and gene shuffling. NREL conducts R&D in-house, but subcontracts out a large chunk of its budget in order to utilize unique expertise in academia and industry. Some industry pioneers are in various stages of partnership formation and financing in terms of building the first generation of biomass ethanol production plants. There is currently considerable interest in the western States whose forests have too much residue which could lead to devastating fires. Several communities, environmental groups, and local government organizations are assessing the feasibility of using the excess residues as feedstocks for producing ethanol fuels on a commercial scale.

R&D Challenges. Specific improvement targets have been identified to reduce the cost of ethanol from biomass by over 40 percent over the next 12 years. This will be accomplished by the development of improved enzymes, fermentation microorganisms, and pretreatment processes through collaboration with industry and academia in partnerships that are driven by industry's needs.

R&D Activities. In order to expand the available resource base, the program focuses on non-starch, non-food-related biomass such as trees, grasses, and waste materials. The three largest components of biomass are cellulose, hemicellulose and lignin. Cellulose and hemicellulose contain sugars that can be converted to ethanol. Lignin is a biopolymer rich in phenolic components, which provides structural integrity to plants.

Key R&D areas include pretreatment of feedstocks, fermentation micro-organisms, cellulase enzymes and lignin utilization. A pretreatment process is used to reduce the feedstock size, break down the hemicellulose to sugars, and open up the structure of the cellulose component. New pretreatment processes, such as the countercurrent dilute acid technology, will make the biomass more amenable to subsequent bio-processing. The greatest promise for improvement lies in biotechnology. By combining computer technology, robotics and genetic engineering, researchers can generate mutant strains that can be rapidly screened and selected for improved enzyme performance. As with enzymes, fermentation organisms can be improved through a variety of genetic engineering tools.

Accomplishments. Over the last 2 decades, the predicted cost of biomass-derived ethanol was reduced by at least 50 percent. Technology developers are partnering with DOE to commercialize bioethanol technology. Using the technology as it exists today, these entrepreneurial partners are exploiting niche markets and unique investment opportunities. While the list of improvements developed in biomass technology is extensive, one of the most important advances has been in the development of new fermentation organisms that are now available. Today these patented organisms are at the heart of the first commercial plants that are scheduled to start up in the early 2000s.

Biodiesel Production

Budget: FY98-$0.8M, FY99-$0.8M, FY00-$1.0M

Description, Objectives, and Performers. Biodiesel can be used as a blend in any proportion with diesel fuel, or used as a pure fuel without major vehicle modifications, with excellent efficiency and performance characteristics. The use of biodiesel reduces hydrocarbons, particulates, carbon monoxide, and carbon dioxide emissions. Production costs for biodiesel from recycled grease are approximately $1.60/gal, but further cost reductions are desirable. Nonfeedstock operating and capital costs represent a very small portion of biodiesel production costs. Reducing feedstock cost is the key to reducing biodiesel costs.

Some micro algae species produce oils which can be used to make biodiesel. R&D investments will be required to reduce algae oil costs for commercialization purposes. Other research programs focus on edible/industrial oil seeds. The high value which markets placed on edible and industrial oils makes these oils too expensive for biodiesel production. The current focus is on identifying and optimizing an oil seed that has an inedible, nonindustrial, low-value oil (<$0.10/lb) suitable for high quality biodiesel, and a meal (or residue) that has a high value (>$0.20/lb) industrial use.

The biodiesel industry is likely to expand from 30 million gallons to 75 million gallons per year by 2004, with the majority of the new capacity using recycled greases. By 2005, new oil seeds should be ready for commercial demonstration by the seed processing and chemical industries. The objective is to reduce the production cost to $1 per gallon by 2010, and provide new crops for rotation in the Great Plains and other agricultural regions.

Most of the DOE/NREL biodiesel research will be conducted through subcontracts and partnerships with industry. Partnerships with other Federal agencies, universities, biotechnology firms, chemical industries, and agricultural companies will provide unique expertise and resources that will be crucial for near-term success.

R&D Challenges. Recycled grease and some animal fats (tallow and lard) are available, but in limited quantities, and are price sensitive to increased demands. Large supplies of trap and sewage grease are available in urban areas but these free feedstocks require production technology improvements with respect to eliminating contaminants and improving yields and quality control.

R&D Activities. Research projects in fuel quality include consumer education on fuel quality parameters and emissions, support of research needed to establish fuel standards, and research to identify fuel-specific characteristics that may explain high NO_x emissions from biodiesel. NREL is also supporting industry-led research to determine if biodiesel emissions are significantly less toxic and harmful than diesel emissions. Other activities have included a life cycle study of biodiesel and diesel, and a publication of a report summarizing the last five years of biodiesel research in the United States. Development of new oil seeds that produce inedible, non-industrial oil, and industrial chemicals will require R&D on a few species with a high probability of near-term success. Production R&D will focus on integrated technologies that crush oil seeds and co-produce biodiesel and other high value co-products.

Accomplishments. The U.S. Department of Agriculture and DOE have jointly completed a life cycle inventory of petroleum diesel and biodiesel that provides information on all of the energy and environmental flows associated with raw materials extracted from the environment, energy resources consumed, and air, water, and solid waste emissions. Several manufacturers of biodiesel are using waste greases as their feedstocks. A draft waste grease assessment is now available for review. A draft report on oxidative stability test methods is also available and will be used in developing a fuel standard for biodiesel.

Regional Biomass Energy Program

Budget: FY98-$2.0M, FY99-$2.3M, FY00-$3.5M

Description, Objectives, and Performers. The Regional Biomass Energy Program (RBEP) seeks to increase the use of biomass energy resources through activities related to technology transfer, industry support, and matching local resources to conversion technologies. Its major focus is to transfer current, reliable information to potential biomass users, with emphasis on technologies best suited to near-term use. The program provides a strong complement to the other biomass activities by bringing in 5 regional offices and a network of 49 State biofuels and biomass contacts. Partners include universities, industry, local and State governments, and other stakeholders.

R&D Challenges. The program's challenges are partly technical, and are also associated with ensuring cost-effective and timely technology transfer in view of the diverse portfolio of the RBEP bioenergy applications and the unique needs and opportunities of each region.

R&D Activities. The program is funding the pilot-testing of a continuous stirred reactor/separator system for ethanol production, and demonstration of biodiesel use in heavy trucks. Active industry partners are working with RBEP on a 200,000 mile demonstration of a long haul diesel truck which includes performance and emissions testing. Several other efforts focus on cost-shared field demonstrations of a spectrum of biofuels technologies and on overcoming market barriers.

Accomplishments. Numerous successes have allowed the leveraging of almost twice the programs's resources through contributions from private industry and States, and enabling bioenergy technologies to be used in solving environmental and other problems.

Integrated Bioenergy Technology R&D

Budget: FY98-$0.0M, FY99-$0.0M, FY00-$6.0M

Description, Objectives, and Performers. Coordination and integration of biomass related activities are critical to the future economic viability of biomass-based products such as fuels, chemicals, and electricity. Increased collaboration among industry partners, stakeholders, DOE programs (e.g., biomass fuels, biomass power, etc.), and DOE laboratories will result in a convergence toward an industry R&D agenda, will lay the foundation for accelerating the development and use of diverse biomass feedstocks, and enhance the Nation's capability for turning out a variety of products in response to market demands.

R&D Challenges. The integration of diverse biomass activities on a national scale in order to achieve synergy is a challenging task and will require close coordination among DOE, industry, and various stakeholders.

R&D Activities. A total systems analysis will be conducted, with industry participation, to support the goal of optimizing the integration of bioenergy feedstocks, equipment, and end products for biomass energy systems. High priority technologies and processes will be identified and a roadmap will be developed for R&D needs. Existing and planned technology projects will be re-evaluated and enhanced to allow for integrated processing of diverse feedstocks and options for a variety of products.

Accomplishments. Executives and senior representatives from industry and other stakeholder groups participated in a recent meeting with DOE management to initiate discussions of this integration process.

Hydrogen Systems

Budget: FY98-$15.8M, FY99-$22.3M, FY00-$28.0M

Background

Hydrogen is a carbon-free energy carrier that has the potential to replace fossil fuels in every sector of the economy. For longer-term transportation applications, hydrogen may be produced in a central facility and then stored on-board, resulting in a zero-emission vehicle. In the nearer term, hydrogen can be produced on-board from liquid fuels such as methanol or gasoline. The changing electricity supply industry presents an opportunity for fuel cells for distributed electric generation, cogeneration, and the production of hydrogen for vehicles. Hydrogen feedstock for the fuel cell can be produced from either natural gas or coal, with the option of carbon sequestration, or directly from renewable resources to eliminate greenhouse gas emissions. At the same time, the use of hydrogen permits increasing use of domestic resources for transportation fuels.

The Proton Exchange Membrane (PEM) fuel cell is becoming a reality. The automobile industry is expected to be producing commercial buses by 2002 and tens of thousands of cars annually by 2004 that employ the PEM fuel cell. The electric generation industry has also recognized the potential for PEM fuel cells to deliver clean, quiet, and cost-effective premium electricity. GPU International has formed a joint venture with Ballard Power Generation to produce 250 kW PEM

fuel cells by 2002. Several industry consortia plan to commercialize 5 kW residential PEM fuel cells in the same time frame.

There are other types of fuel cells commercially available and being developed by DOE, all of which use hydrogen (for example, Phosphoric Acid and Solid Oxide). Moreover, there are a number of very aggressive companies pursuing the fuel cell market. These companies include Teledyne Brown Engineering, Energy Partners, H-Power, Detroit Edison, Idaho Power, General Electric, Schatz Energy Research Center, Northwest Power, Plug Power, and International Fuel Cells, to name a few.

Linkage to CNES Goals and Objectives

The goal of the Hydrogen Program is to conduct research and development for the purpose of making hydrogen systems cost-effective for use with fuel cells for the production of electricity for deployment beginning around 2004, and for transportation applications for deployment beginning around 2008. As a potentially large-volume, renewable source of fuels for transportation and other applications, hydrogen use could:

- CNES Goal II, Objective 1 - Reduce the vulnerability of the U.S. economy to disruptions in oil supply.

- CNES Goal III, Objective 1 - Increase domestic energy production in an environmentally responsible manner.

Program Description

The Hydrogen Program has four strategies: (1) expand the use of hydrogen in the near-term by working with industry, including hydrogen producers, to improve the efficiency, lower the emissions, and lower the cost of technologies that produce hydrogen from hydrocarbons and to introduce renewable-based production options; (2) work with fuel cell manufacturers to develop hydrogen-based electricity storage and generation systems that will enhance the introduction and penetration of distributed, renewable-based utility systems; (3) coordinate with the Department of Defense and the DOE's Office of Transportation Technologies to demonstrate safe and cost-effective fueling systems for hydrogen vehicles in urban non-attainment areas and to provide onboard hydrogen storage systems; and (4) work with the National Laboratories to lower the cost of technologies that produce hydrogen directly from sunlight and water. Concerning transportation applications, the Federal role concentrates on the hydrogen refueling infrastructure, onboard vehicle storage of hydrogen, and the cost effectiveness of the hydrogen fuel. On the utility side, a key program need is the demonstration of integrated renewable and hydrogen systems to provide increased operational and peaking generation flexibility.

Hydrogen Production

Budget: FY98-$4.7M, FY99-$6.3M, FY00-$8.5M

Description, Objectives, and Performers. Current hydrogen production processes are based on the thermal conversion of fossil and biomass fuels, or the electrolysis of water. Thermal

processes use heat and steam to convert carbonaceous feeds such as natural gas, coal, biomass, and municipal solid waste into hydrogen and carbon dioxide. Several advanced processes that improve the efficiency and lower the temperature of the reaction are being investigated to reduce the cost of production of hydrogen by 25 to 30 percent. The objective is to reduce the production costs of thermal processes from fossil and biomass resources to $6 to 8/million BTU and the cost from electrolytic and biological processes to $10 to 15/million BTU.

Industry support is provided by traditional hydrogen producers in the research and development of low temperature thermoconversion processes for distributed applications. Universities are contributing to research in this area. The National Renewable Energy Laboratory, with university support, is leading the activities associated with biomass to hydrogen conversion systems, and the photoelectric and photobiological production of hydrogen.

R&D Challenges. Key challenges include the development of low-cost processes using thermoconversion to enhance the separation of carbon and hydrogen streams; and producing hydrogen directly from water.

R&D Activities. R&D of thermoconversion systems for natural gas, coal and biomass feedstocks are being pursued. R&D for advanced electrolysis systems is being addressed for utilization in solar/electrolysis and wind/electrolysis systems. Hydrogen produced directly from sunlight and water by biological organisms and by using semiconductor-based systems similar to photovoltaic is also receiving attention.

Accomplishments. Program accomplishments include:

- In the Sorption Enhanced Reformer process at Air Products and Chemical, Inc., a single reactor demonstrated over 85 percent conversion of natural gas to produce a product stream with 98 percent purity prior to conventional cleanup via pressure swing absorption.

- In the Plasma Reformer process, a hydrogen production system demonstrated power densities of 10kW(H_2 HHV)/liter of reactor with low CO content (3 to 5 percent).

- In the Biomass to Hydrogen via Fast Pyrolysis process, hydrogen yields of 80-90 percent of stoichiometric amount in a fixed bed experiment were achieved.

- In the Photoelectrochemical (PEC)-based Direct Conversion Systems project, a PEC water splitting system was operated with a world-record solar-to-hydrogen efficiency of 12.4 percent.

Hydrogen Storage and Use

Budget: FY98-$2.2M, FY99-$2.8M, FY00-$5.6M

Description, Objectives, and Performers. The storage, transport and delivery of hydrogen are important elements in a hydrogen energy system. With intensive interest in mobile applications, and as the amount of intermittent renewable electricity increases, hydrogen storage becomes an essential element of these systems. The objective of this activity is to develop hydrogen storage options that will cost less than 50 percent of production costs and be more than 5 percent weight hydrogen systems.

With the advent of the Proton Exchange Membrane fuel cell, hydrogen utilization should increase significantly in electric generation and transportation applications. The objective is to develop low-cost manufacturing approaches for fuel cell and reversible fuel technologies, and enable the development of more reliable, less expensive hydrogen sensors.

Hydrogen storage and use activities are carried out primarily by three industrial partners (Thiokol, Thermo Power Systems, Energy Conversion Devices) four National Laboratories (Sandia National Laboratories, Oak Ridge National Laboratory, National Renewable Energy Laboratory, and Lawrence Livermore National Laboratory), and the University of Hawaii.

R&D Challenges. Key challenges are to facilitate the use of hydrogen as a vehicular fuel, develop lower cost storage technologies and demonstrate their competitiveness in integrated renewable energy systems, and develop a low-cost fuel cell and reversible fuel cell.

R&D Activities. High pressure, liquid, hydride, and carbonaceous storage systems are being investigated to achieve technical and cost goals that include measures for volumetric and gravimetric density. Hydrogen use activities include fuel cell research focused on the development of inexpensive, easy-to-manufacture membrane electrode assemblies, and the development of reversible fuel cells for stationary applications

Accomplishments. Program accomplishment include:

- Designed and fabricated lightweight pressure vessels that represent >7 wt percent tanks.
- Measured dehydrogenation rates at temperatures as low as 100°C and rehydrogenation to >5 wt percent at 170°C for a metal hydride.
- Successfully tested lithium hydride and calcium hydride for potential use in hydride slurries.
- Began testing a short stack of a low-cost fuel cell with significantly less than 10 percent parasitic power loss.

Technology Validation

Budget: FY98-$6.4M, FY99-$11.0M, FY00-$11.4M

Description, Objectives, and Performers. This activity supports industry in the development and demonstration of hydrogen systems in the utility and the transportation sectors. Concerning transportation applications, the barriers to the introduction of the hydrogen option include the lack of a hydrogen refueling structure, onboard vehicle storage, and affordability. On the utility side, a key program need is the demonstration of integrated renewable and hydrogen systems to provide increased operational and peaking generation flexibility. In addition there is support (outside of the Hydrogen Program) of projects for small fuel cells for remote and village power systems. Some of the industry that is participating in the 50/50 cost-share efforts on the renewable hydrogen systems are Proton Energy, Energy Partners, Inc., and Energy Conversion Devices. Other industry include Teledyne Brown, Stuart Energy, NRG and other companies to be selected for the hydrogen infrastructure program. Teledyne Brown, Hydrogen Burner Technologies, Schatz Energy Research Center, Energy Partners, Plug Power and Northwest Power are all involved in the remote power element. Sandia National Laboratory contributes technically and programmatically to this program area.

R&D Challenges. Challenges include demonstrating: (1) renewable hydrogen systems for niche markets; (2) cost-effective hydrogen refueling and generation systems; (3) >5 wt percent and cost-effective onboard storage of hydrogen on vehicle systems; and (4) fuel cells for remote applications.

R&D Activities. Activities include Concentrating Solar, Wind, and Photovoltaic/Hydrogen systems for islands and remote areas, and reversible fuel cells with a wind system. Several refueling station concepts will be demonstrated. They will include an electrolysis system, co-production of hydrogen and electricity from a PEM fuel cell, advanced thermoconversion systems, and a renewable system. In addition, vehicles that use natural gas/hydrogen mixtures and extended range electric vehicles will be demonstrated at the refueling sites.

Accomplishments. Program accomplishments include:

- Successfully demonstrated a Crown Victoria vehicle with a natural gas/hydrogen mixture.
- Successfully demonstrated 47 percent indicated thermal efficiency in an optimized Internal Combustion Engine, with near zero NO_x levels.
- Initiated a research and deployment program to accelerate the commercialization of hydrocarbon reformed hydrogen PEM fuel cells for remote residential utility systems. Fully automated residential PEM fuel cell utility systems operating on diesel reformate will be deployed in a remote arctic location in 2000.

Analysis and Outreach

Budget: FY98-$2.5M, FY99-$2.2M, FY00-$2.5M

Description, Objectives, and Performers. Analyses will be performed to ensure that Federal R&D investments in hydrogen production, storage, distribution, and end-use technologies will provide maximum value. Distributed Utility Associates, Directed Technologies, and Energetics support the program with analyses. Also, the National Renewable Energy Laboratory and Princeton University perform key evaluations.

R&D Challenges. Challenges include identifying and evaluating key market segments and market entry conditions for hydrogen utilization, and developing and applying metrics to measure the program's contribution to attaining national strategic energy goals and market share in key market segments.

R&D Activities. The focus is on analyses that support the program in making informed decisions in research and development and demonstration activities, including portfolio analysis, market segment and market entry analyses for technology validation projects, and techno-economic analyses of hydrogen research and development projects to define key goals.

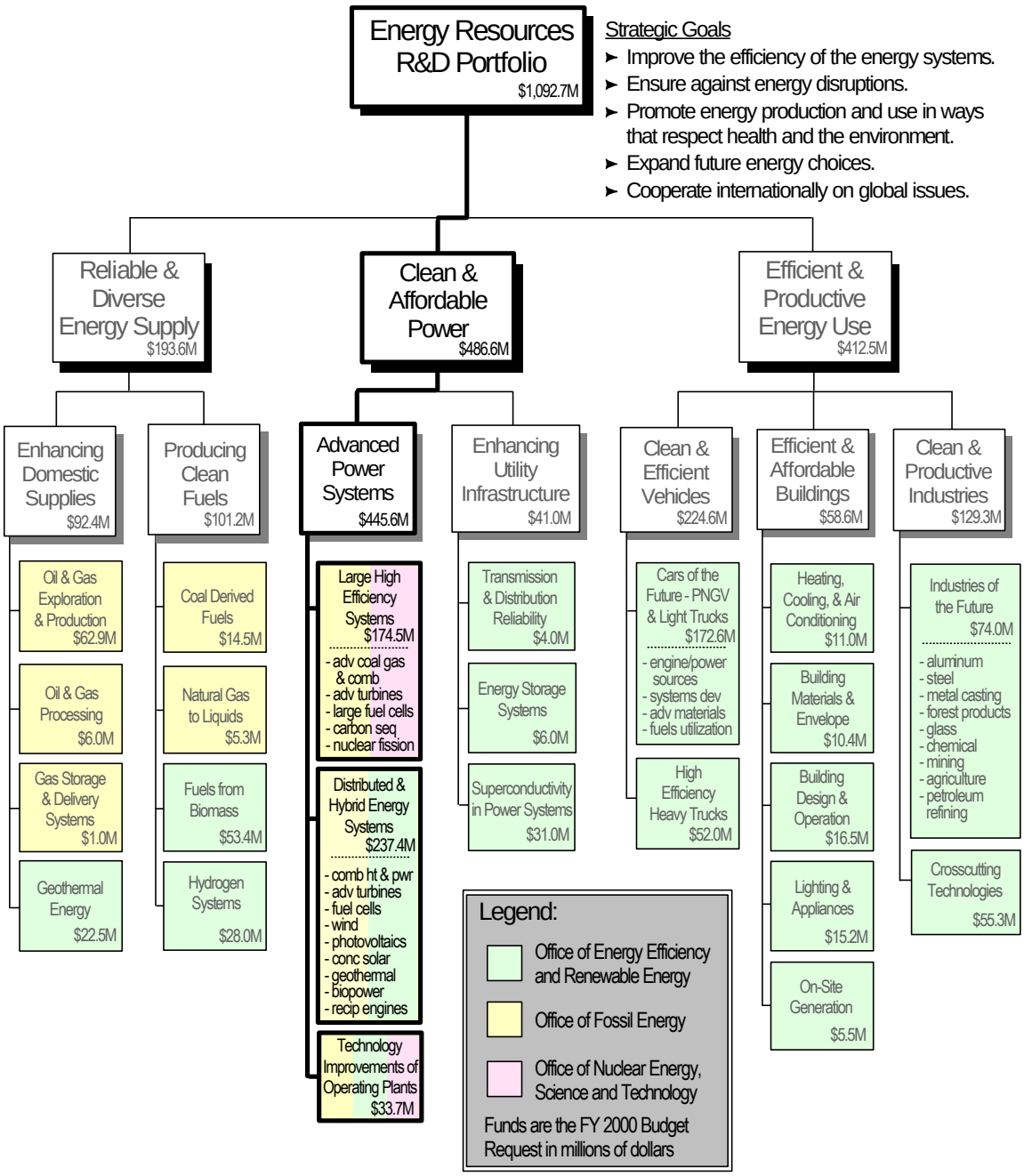
Accomplishments. Program accomplishments include:

- Analyzed the cost advantages of the co-production of electricity and hydrogen at a refueling station.
- Compared four biomass to hydrogen options and identified two of the systems as being able to meet program goals.
- Completed an analysis of village remote power systems for electricity generation and cogeneration of heat.
- Compared the cost effectiveness of photoelectrochemical production of hydrogen to PV electrolysis systems. Identified research areas necessary to improve the performance of these systems.

Summary Budget Table (000$)

Producing Clean Fuels Research Areas	FY 1998 Appropriated	FY 1999 Appropriated	FY 2000 Request
Coal-Derived Fuels	**15,844**	**15,528**	**14,500**
Transportation Fuels and Chemicals	10,039	8,650	8,300
Solid Fuels and Feedstocks	5,064	5,097	4,000
Advanced Research	741	1,781	2,200
Natural Gas-to-Liquids	**6,297**	**6,784**	**5,302**
Ceramic Membrane Reactor Systems	4,785	5,500	4,000
Thermoacoustic Natural Gas Liquefaction	458	600	600
Novel Conversion Processes	1,054	684	702
Fuels from Biomass	**30,327**	**41,750**	**53,441**
Feedstock Production	2,500	2,800	5,500
Ethanol Production	25,027	35,950	37,441
Biodiesel Production	800	750	1,000
Regional Biomass Energy Program	2,000	2,250	3,500
Integrated Bioenergy Technology R&D	0	0	6,000
Hydrogen Systems	**15,806**	**22,250**	**28,000**
Hydrogen Production	4,737	6,259	8,510
Hydrogen Storage and Use	2,238	2,829	5,590
Technology Validation	6,361	10,993	11,420
Analysis and Outreach	2,470	2,169	2,480
Total	**68,274**	**86,312**	**101,243**

Chapter 5
Advanced Power Systems



Chapter 5

Advanced Power Systems

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Overview

Definition of Focus Area

The Department's advanced power systems research and development portfolio is comprised of a broad range of power generation technology options that utilize fossil fuels, renewable energy resources, and nuclear power in both large, high efficiency energy systems and in distributed and hybrid energy systems to deliver affordable, reliable, and clean electric power. The work is principally applied R&D which is cost-shared with industry, supported by basic and enabling research activities, managed by Federal personnel, and performed primarily by industry, National Laboratories, and universities. Longer-term R&D includes a modest investment in carbon sequestration and a more significant investment in the Science and Technology program in nuclear fusion.

National Context and Drivers

The electric power sector is the largest direct consumer of energy in the United States. It used 36 percent of all primary energy consumed in the country in 1996, while providing power worth approximately $200 billion annually to fuel myriad essential functions in our homes, businesses, and industries. Most energy projections show the United States requiring an increase of 100,000 to 200,000 megawatts of additional power generation capacity between now and the year 2010.

About 68 percent of the electrical power generated in the United States is fueled by coal, natural gas, and oil; the balance is provided by nuclear (20 percent), hydroelectric, and renewable technologies. Due to the reliance on fossil fuels, power generation currently contributes substantially to the pollutants and greenhouse gas emissions in the United States, at a time when world concern continues to grow regarding global climate change. Meeting the projected significant increase in demand for electric power without compromising the Nation's environmental standards is therefore essential to sustaining the Nation's economic growth while at the same time protecting human health and the environment.

Nearly 95 percent of the electricity consumed annually in the United States is generated by large (greater than 30 megawatt) power plants. Because of the significant capital investment in large plants, the existing residential, commercial, and industrial infrastructure connected to the plants, and the Nation's dependence on the large amounts of electricity they produce, large plants will continue to produce the majority of the Nation's electric power for the foreseeable future.

Under current market and regulatory trends, coal and, increasingly, natural gas, will continue to be the primary fuels for large systems, well into the 21st century. No significant new additions of nuclear, hydroelectric, or oil capacity are expected, and existing nuclear plants in the United States are expected to be retired over the next 50 years.

However, many power generators, either in response to public pressure or State and Federal regulatory trends, are seeking to diversify their fuel choices and add renewable energy resources to their fuel mix. Environmental concerns, ample supplies of cheap natural gas (the cleanest

fossil fuel), current and potential constraints of large system power transmission and distribution, and technological advances are causing distributed and hybrid systems and technologies such as combined heat and power systems, gas turbines, photovoltaics, wind turbines, and solar, geothermal, and biomass systems gradually to augment and sometimes to replace conventional, large-scale generating technologies.

Linkage to CNES Goals and Objectives

There are three strategic ends for advanced power R&D:

1. Ensure the availability of large-scale, advanced technologies to: (1) reduce both fuel use and the volume of pollutants and greenhouse gases emitted per unit of useful electric power produced; and (2) maintain an adequate, reliable and affordable supply. This end supports:

- CNES Goal I, Objective 1 - Support competitive and efficient electric systems. *(improve the efficiency of the energy system)*

- CNES Goal III, Objective 1 - Increase domestic energy production in an environmentally responsible manner.

- CNES Goal IV, Objective 2 - Develop technologies that expand long-term energy options.

- CNES Goal V, Objective 1 - Promote development of open, competitive international energy markets, and facilitate the adoption of clean, safe, and efficient energy systems.

2. Ensure the availability of a portfolio of advanced power technologies utilizing renewable and hybrid energy systems that will increase the flexibility, capacity and reliability of the U.S. power system. This end supports :

- CNES Goal II, Objective 2 - Ensure energy system reliability, flexibility, and emergency response capability.

- CNES Goal III, Objective 1 - Increase domestic energy production in an environmentally responsible manner.

- CNES Goal III, Objective 2 - Accelerate the development and market adoption of environmentally friendly technologies.

- CNES Goal IV, Objective 2 - Develop technologies that expand long-term energy options.

- CNES Goal V, Objective 1 - Promote development of open, competitive international energy markets, and facilitate the adoption of clean, safe , and efficient energy systems.

3. Protect the Nation's investment in existing baseload power plants through the development of improved information management systems, sensors and controls, aging management, and regulatory compliance programs. This end supports:

- CNES Goal I, Objective 1 - Support competitive and efficient electric systems. *(improve the efficiency of the energy system)*

- CNES Goal V, Objective 1 - Promote development of open, competitive international energy markets, and facilitate the adoption of clean, safe , and efficient energy systems.

Uncertainties

Renewable energy sources, nuclear power, and fossil fuel with sequestering (direct or indirect) are insurance against the possible occurrence of climate change. Government investment at this time is prudent as the country and the world face major environmental and energy security challenges and domestically the electrical power sector is dealing with the issues of restructuring.

The following major planning assumptions are implicit in the attainment of our strategic goals.

- Robust U.S. Economy Depends on Low Cost Energy.
  The continued strength of the U.S. economy depends on the availability of low-cost energy. It is virtually assured that there will be continued growth in demand for electricity and transportation fuels. Fossil fuels will meet much of the demand.

  Americans want secure energy supplies, and the associated economic benefits, achieved in an environmentally responsible manner. The public supports ongoing efforts to reduce the environmental impacts of fossil energy production, transportation, and use. The combined benefits of a secure energy supply and environmental stewardship can be achieved by the use of advanced, more efficient power generation and conversion systems.

  Changes in electricity prices have significant effects on the economy. For example, an increase in the cost of electricity of 4 to 5 cents per kilowatt-hour (more than a 50 percent increase in the national average delivered price) leads to the same inflationary impacts as a 30-cent-per-gallon rise in gasoline price (about a 25 percent increase in delivered price.) Therefore, low cost electricity is essential to economic growth.

- Electric Utility Deregulation Leads to Competition.
  Deregulation of the electric utility industry and the resultant increase in competition will lead to lower electric bills for large consumers. This is evidenced by the Comprehensive Electricity Competition Plan (CECP), a proposal published by the Administration that is expected to result in lowered prices for electricity and a cleaner environment. Cost savings of $10 billion per year and greenhouse gas emissions reductions of 25 to 40 million metric tons are anticipated.

These lower costs could increase demand. In the near term, most new capacity will be characterized by the lower-capital-cost technologies that use natural gas. In the longer term, this demand will be satisfied by using clean and efficient technologies being developed by the Department and others.

- Public Wants Environmental Issues Addressed.
  Significant environmental issues have been, are being, and will be addressed. Sulfur dioxide (SO_2) emissions have been capped. It is expected that permissible nitrogen oxide (NO_x) emissions will be lowered. Allowable levels of particulate and hazardous air pollutants (HAPs) emissions will be further reduced because of health considerations. Limitations on land use will increase pressure to reduce the quality of waste generated.

- International Community Urges the United States to Reduce Greenhouse Gas Emissions.
  The effort to reduce greenhouse gas emissions, principally carbon dioxide (CO_2), will continue to increase. A major driver for the Office of Fossil Energy's research program is a reduction of CO_2 emissions with the vision of zero emissions in order that fossil fuels can be used in a greenhouse gas constrained economy. Nuclear power can provide electrical power on a large scale without harmful air pollutants. The Office of Nuclear Energy, Science and Technology is charged with maintaining the viability of this important technology.

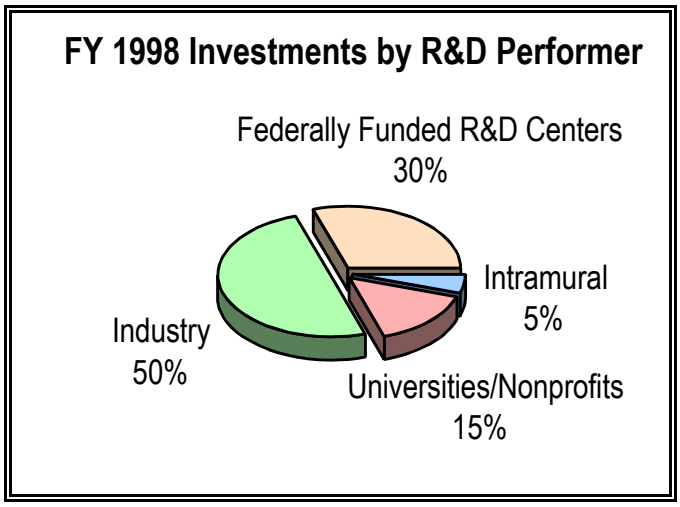
- Imported Oil Remains a National Security Issue.
  National security concerns will be exacerbated by the ever-increasing reliance on potentially unstable, non-domestic sources of oil. The technology to produce alternate transportation fuels (e.g., coal-based) at competitive prices can reduce this concern and ensure national security.

Investment Trends and Rationale

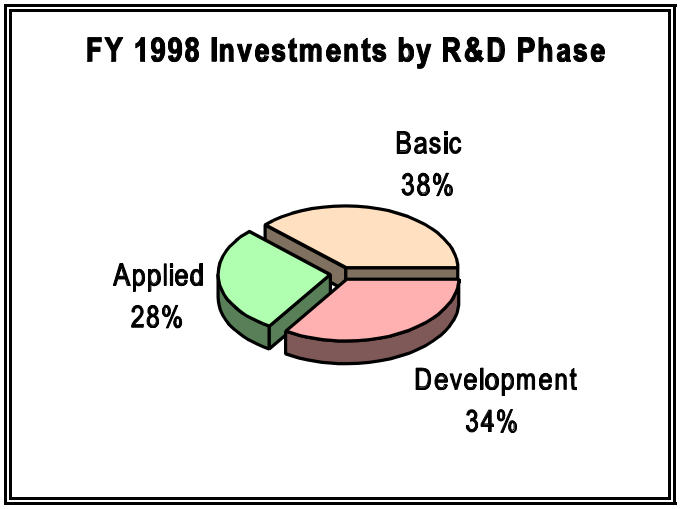
Domestic utilities are perceived to be in a "wait-and-see" mode, given the uncertainties associated with the restructuring of the power generation industry, uncertainties about recovery of new expenditures during the transition to retail deregulation, and competition from other entities such as independent power producers (IPPs) and energy service companies. It is expected that reserve margins will shrink before new facilities will be built. Utilities are currently pursuing life extension and asset management to optimize utilization of existing capacity, thereby delaying the need for new generating capacity. Under current conditions, these utilities foresee an extended period of operation for older units over the next two decades.

Utilities are concerned about proposed, tougher environmental regulations for NO_x, SO_2, particulates, and HAPs. They also are concerned about the treatment of assets in which they invested as a "regulated" industry. The trend in the industry is to focus on the "market clearing price" rather than the "obligation to serve." In the preparation for competition, some are planning to provide other energy services, shed assets, or enter into joint ventures. These competitive pressures and uncertainties, as well as the lack of demand for additional baseload capacity, limit U.S. private-sector R&D investment in advanced power systems.

As a response to the above, the Department spends $350 million on advanced power systems. Advanced power R&D is performed cooperatively with industry, National Laboratories, universities, and State/local governments. The percentage split among these organizations is shown in the chart below.



The next chart shows the investment by R&D phases, that is, the type of R&D. The chart includes fusion from Science and Technology. Fundamentally, fusion accounts for the basic research performed in advanced power systems.



In FY 1998, the Department invested 42 percent, 53 percent, and 5 percent of the $350 million dollars for advanced power systems in large high efficiency systems, distributed and hybrid systems, and technology improvements of operating plants, respectively. These proportions don't change materially in FY 1999 and FY 2000. However, the year to year funding increases

are approximately 18 percent and 5 percent for FY 1998 to FY 1999 and FY 1999 to FY 2000, respectively. Additionally, there are no foreseen factors that would alter substantially the current mix of R&D performers and types of R&D. In large high efficiency systems, the investment is in coal- and gas-fired systems (including sequestration).[1] The Department does not invest in advanced oil-fired power systems because no large oil-fired facilities are expected to be constructed in the United States in the foreseeable future. As work in other coal combustion systems is completed, the early stages of the concept for the Vision 21 PowerPlex will begin. Approximately $53 million for the Vision 21 PowerPlex concept will be spent in FY 2000. The Vision 21 PowerPlex seeks to integrate advanced systems in order to achieve higher efficiency, product flexibility, reduced emissions, and lower cost. In distributed and hybrid systems, wind energy, photovoltaic, and bio-power receive more focus and resources. These alternate electricity sources present choices in meeting the challenges offered by a restructured power industry and the goals in the CNES.

Federal Role

Regulated utilities have traditionally invested significantly in power generation R&D, either individually or through industry R&D organizations like the Electric Power Research Institute. However, the U.S. electric power industry is restructuring in response to changes in State and Federal regulations requiring increased competition in the industry. In response to increased competitive pressures, utilities and other companies that traditionally have invested in research have reduced or eliminated their R&D budgets.

Moreover, while global concern over the environmental impact of power generation is growing, most U.S. power generation facilities are in compliance with existing environmental regulatory requirements. At the same time, the prices of fossil fuels, particularly oil and natural gas, are at historic lows. There is little immediate market incentive for investment in cleaner power generation technologies. To the contrary, an increasingly competitive market in power generation could well accelerate the decline in private sector investment in power generation R&D in the United States.

Concern for the environment and electric industry restructuring create a significant public interest challenge: how can the Nation mitigate and possibly eliminate the adverse environmental impact of power generation while ensuring the availability of affordable electricity to continue to grow our economy? An appropriate Federal role in addressing this challenge is to invest in advanced power generation technologies where the market will not support industry's incurrence of all of the costs of the long-term, high-risk, and/or high-cost R&D required to develop those technologies, or when the Government has unique R&D capabilities.

Accordingly, there is a significant gap between the level of advanced power generation R&D that the market will support and the level needed to address current and future concerns about the steady increase in the demand for electricity worldwide and the resulting impact of power

[1] In addition, the Department, in the Science and Technology budget, is proposing $223 million for both FY 1999 and FY 2000 in the fusion program.

generation on human health and the environment. The Department's advanced power systems research and development portfolio is designed to help bridge that gap.

Key Accomplishments

Considerable progress has been made through DOE support toward achieving the advanced power systems goals:

- A new generation of higher-efficiency, cleaner, coal-fueled technologies is currently being demonstrated (e.g., integrated gasification combined cycle) that will also be attractive in hybrid applications when combined with ongoing advances in coal power R&D, turbines, and fuel cells.

- R&D has continued to reduce the cost of renewable systems suitable for distributed applications:

  – Biomass power is being demonstrated at scales from 10-75 MWE for dedicated feedstocks and for co-firing with coal.

  – Recent advancements in geothermal technology have reduced costs by increasing power plant efficiency 5-10 percent for certain key resources.

  – Concentrating solar power has been combined with thermal storage to produce more competitive levels of cost.

  – The cost of producing photovoltaic modules has decreased 50 percent since 1991, making it cost-competitive in certain applications.

  – The cost of wind power has decreased by 85 percent since 1980, making it competitive in some areas that have good wind resources.

- Fuel cells and turbines have reached the stage where they are expected to achieve significant deployment in distributed and hybrid applications in the next decade:

  – Phosphoric acid fuel cells are commercially available, and molten carbonate fuel cells are being successfully tested at full scale.

  – An advanced, cleaner, higher-efficiency industrial turbine is nearing commercial readiness, including a 1999 demonstration.

- Numerous technologies have been deployed/demonstrated and actions taken to help protect the Nation's investment in existing power plants:

  – Test data has been used to help shape environmental regulation.

- Reductions have been achieved in sulfur dioxide, nitric oxides, fine particulates and associated trace toxic substances.
- New alloys and ceramics have increased equipment life.
- Research on hydropower turbines is improving the understanding of advances needed to incorporate "fish-friendly" features.

- Fusion research has continued to raise the power achieved in test reactors (the Princeton Tokamak reached 10 MW in 1996) and increased the understanding of how to control plasma conditions and improve energy confinement.

Large High Efficiency Systems

Budget: FY98-$148.0M, FY99-$182.1M, FY00-$174.5M

Background

Out of a total of about 750,000 megawatts of generating capability in the United States, large electric utility generating capability totaled about 710,000 megawatts in 1996. Coal and natural gas fueled about 65 percent of this capacity.

Large Plant Generating Capacity in 1996

Primary Energy Source	**Capacity** (Megawatts)	**Percent of Total Capacity**
Coal	322,000	45.6
Gas	131,000	18.6
Nuclear	109,000	15.4
Conventional Hydroelectric	76,000	10.8
Petroleum	62,000	8.8
Renewable and Waste Heat	6,000	0.8

Large systems will continue to be needed to satisfy the majority of the Nation's increasing demand for electricity, and fossil energy-based systems are expected to continue to predominate the market. Conventional fossil plants, however, are extremely fuel inefficient, wasting as much as 70 percent of the energy that is used in the generation process. Moreover, these systems create the vast majority of the environmental impacts resulting from power generation in the United States.

Nuclear power plants do not emit air pollutants or greenhouse gases such as carbon dioxide, and are the largest non-emitting electricity supply technology used in the United States. These plants currently produce about one-fifth of the Nation's electricity. The country, however, is at a critical juncture with regard to the continued operation of its nuclear power plants. While many of the 105 existing nuclear power plants will continue to produce electricity well into the next century, licenses for existing U.S. nuclear power plants will begin to expire in large numbers in 2010. However, nuclear plants can be re-licensed for an additional 20 years under current regulations. Two plants have already applied for an extended license and expect approval from the Nuclear Regulatory Commission within the next 2 years. Also, competitive pressures resulting from electricity deregulation could result in the premature closure of some nuclear power plants with relatively high production costs. There have been no new orders for nuclear power plants in the United States since the 1970s, and this is likely to remain the case unless issues of plant economics, spent fuel disposal, and safety and proliferation are successfully

addressed. As a result, nuclear units are projected to provide one-tenth of total electricity generation in 2015.

Linkage to CNES Goals and Objectives

The Department invests in large, high efficiency systems to ensure the availability of large-scale, advanced technologies to (1) reduce both fuel use and the volume of pollutants and greenhouse gases emitted per unit of useful electric power produced, and (2) maintain an adequate, reliable and affordable supply. These ends support:

- CNES Goal I, Objective 1 - Support competitive and efficient electric systems.
- CNES Goal III, Objective 1 - Increase domestic energy production in an environmentally responsible manner.
- CNES Goal IV, Objective 2 - Develop technologies that expand long-term energy options.
- CNES Goal V, Objective 1 - Promote development of open, competitive international energy markets, and facilitate the adoption of clean, safe, and efficient energy systems.

Program Description

The Department invests in the development of a number of large, high-efficiency systems including coal and natural gas power generation technologies and systems, as well as nuclear fission and fusion systems. Nuclear energy's continued role in electricity production provides for our economic and energy security, and is a critical element of our Nation's global climate change responsibilities. Nuclear power plants currently produce about 20 percent of all U.S. utility-generated electricity without emitting carbon dioxide, a greenhouse gas, and sulfur and nitrogen oxide pollutants associated with the combustion of fossil fuels.

For coal and natural gas systems, a program called "Vision 21" aims for the upper end of performance efficiencies, 60 percent to over 70 percent, at near zero emissions. It features the capability of power generation systems to have fuel flexibility while generating a variety of energy products along with low-cost electricity. Due to the inherent fuel flexibility of gasification and coal-based combustion systems, they may be synergistically integrated into industrial processes (e.g., refineries, paper mills, food processing plants), delivering even greater economic and environmental benefit by converting process waste to electricity, steam, and chemical products as needed. The resulting fleet of large, high-efficiency power systems included in Vision 21 would perform well below the New Source Performance Standards (NSPS) for SO_2, NO_x, and particulates emissions, with the most advanced systems achieving near zero emissions of regulated pollutants.

DOE and its predecessor agencies played a significant role in development of nuclear fission power in the United States. The most recent example is the Advanced Light Water Reactor program that resulted in the design certification of new evolutionary and passive light water reactor technology. However, in light of the uncertainties facing nuclear power, the President's Committee of Advisors on Science and Technology (PCAST) and the Directors of seven National Laboratories recommended that DOE reestablish a strong nuclear energy R&D portfolio. Although there were no nuclear fission programs in FY 1998, in FY 1999, Congress funded the Department's proposed Nuclear Energy Research Initiative (NERI). NERI will sponsor innovative scientific research and technology development to address the longer-term issues facing the future use of nuclear energy, namely proliferation, waste, and economics.

The Department's nuclear fusion program is conducted by the Office of Science. The Fusion Energy Sciences program conducts basic research in plasma science and alternative confinement concepts to understand the physics of plasma (the fourth state of matter), identify and explore innovative and cost-effective development paths to fusion energy, and explore the science and technology of energy producing plasmas, the next frontier in fusion research.

Advanced Coal Gasification and Combustion Systems

Budget: FY98-$61.3M, FY99-$68.5M, FY00-$60.9M

The coal gasification and combustion program is part of the Vision 21 program plan described above. Its overall goal is to make available, by 2010, coal-fueled power technology: (1) with a net electricity system efficiency of at least 60 percent (new plants are currently about 35 percent); (2) that reduces emissions to less than 1/10 of New Source Performance Standards and CO_2 emissions 45 percent below conventional plants; and (3) achieves a cost of electricity below that of conventional new pulverized coal power plants. There are 3 technologies addressing this area.

Advanced Coal Combustion - LEBS/HIPPS

Budget: FY98-$21.0M, FY99-$21.5M, FY00-$10.0M

Description, Objectives, and Performers. This program is re-engineering today's pulverized coal boiler to incorporate advanced combustion and innovative flue gas cleaning into the original design, rather than adding them after the plant is built. The low emissions boiler system (LEBS) has been underway since 1992 and builds on earlier research in the areas of emission control, materials, and combustion. The program will be completed in FY 2001 with operation of a small proof-of-concept plant. The program objective is, by the year 2001, to make available technology: (1) with a net plant system efficiency of at least 42 percent; (2) that reduces emissions to 1/6 of the Clean Air Act's New Source Performance Standards (NSPS) for SO_2 and NO_x and 1/3 the NSPS for particulates; and (3) that achieves a capital cost of less than $1,000 per kilowatt and a cost of electricity 10 percent lower than a conventional pulverized coal power plant. The program is a cost-shared partnership with industry, supported by university and National Laboratory research.

Also as part of advanced pulverized coal combustion, a program to develop an indirect fired cycle having (1) a net plant system efficiency of at least 47 percent; (2) emissions 1/10 of the Clean Air Act's NSPS for SO_2, NO_x, and particulates; and (3) a capital cost 20 percent lower than that of a conventional pulverized coal power plant. In addition to inherently high system efficiency, indirectly fired cycles have other advantages that include no requirements for an oxygen plant or hot gas cleanup, and fuel flexibility, since the products of coal combustion do not contact the gas turbine. This high performance power system (HIPPS) program is also a cost-shared partnership with industry supported by university and National Laboratory research. The engineering development and testing associated with this program ends in 2001, with designs for large commercial plants, prototype plants, and repowering for existing coal-fired plants. The next phase, if undertaken, would be the operation of a prototype HIPPS by 2006.

R&D Challenges. To achieve the more aggressive performance levels, there must be advances in the areas of combustion, heat transfer, and materials. These advances are needed in order to develop the high temperature air furnace, the coal pyrolyzer, and the char burner required in the indirect fired cycle.

R&D Activities. Two different concepts for an indirectly fired cycle are being pursued, but both require R&D necessary for technology and systems development to support the design and operation of the major subsystems, particularly, a high temperature air furnace. Designs for these subsystems will be verified in test facilities. Equipment to be developed includes radiant and convective air heaters, coal burners, integrated slag removal and slag handling components, and char combustors. Research in high-temperature ash deposition, materials, and CO_2/O_2 recycle combustion is required in order for this effort to meet its objectives.

Accomplishments. Successes include the development of new combustion technology (so-called U-fired combustors) capable of reducing NO_x emissions below 0.2 lbs per million Btu

at very low cost. NO_x levels approaching natural gas firing are achieved with the addition of a copper oxide cleanup unit. The U-fired combustors produce a granular slag by-product that is preferable to flyash. A HIPPS 2000°F radiant air heater has been tested successfully.

Pressurized Fluidized Bed (PFB) Combustion

Budget: FY98-$17.9M, FY99-$14.6M, FY00-$12.2M

Description, Objectives, and Performers. The PFB program is developing an advanced combustion system capable of utilizing a wide variety of coals (including very low quality coals) to generate electricity cleanly and efficiently. The highly effective mixing of coal particles in the boiler allows combustion temperatures to be kept below the point where most nitrogen pollutants form. Elevated pressures produce a high-pressure gas stream that can drive a gas turbine, and steam generated by the boiler powers a steam turbine. The program has progressed from its basic research or idea stage to the commercial demonstration stage today. A large commercial scale PFB plant is now being designed under the Clean Coal Technology Demonstration Program. This first generation plant will have efficiencies in the 40 percent range and will lay the engineering foundation upon which further technology advances now in the R&D pipeline will be made to achieve the program's 2010 goals. The program objective is, by the year 2010, to make available technology: (1) with a net electricity system efficiency of at least 50 percent; (2) that reduces emissions to 1/10 of the New Source Performance Standards for SO_2, NO_x, and particulates; and (3) that achieves a capital cost of less than $1000 per kilowatt and a busbar cost of electricity that is 10-20 percent below that produced by a new conventional pulverized coal power plant.

The PFB program is a 20-60 percent cost shared partnership with industry, supported by university and National Laboratory research.

R&D Challenges. The key R&D challenge for PFBC is a reliable, available, maintainable, and affordable hot gas cleanup system. Hot gas cleanup systems for advanced high efficiency PFBC power systems remove virtually all particulate matter that would otherwise enter the gas turbine. These filter systems operate under high temperature conditions (e.g., 1400°F to 1700°F). Advanced high efficiency PFBC power systems of the future will include supercritical power conversion systems (PCS) steam conditions, fuel cells, and higher temperature gas turbines. These PFBC systems will necessitate that gas streams be free from impurities (e.g., sulfur, alkalies, and particulates) in order to provide for long term, reliable, trouble free operation.

R&D Activities. The thrust of the research is in hot gas particulate filtration, critical to advanced PFB systems, and improvements in subsystems and their interfaces to enhance system efficiency and reduce cost and pollutant emissions necessary for market entry.

Accomplishments. The program has already succeeded in developing and commercially deploying very clean, but lower efficiency (36 percent) atmospheric fluidized bed systems globally—over $8 billion in sales have been reported.

Integrated Gasification Combined Cycle (IGCC)

Budget: FY98-$22.3M, FY99-$32.4M, FY00-$38.7M

Description, Objectives, and Performers. In the IGCC program, a coal gasifier (which generates a synthetic gas by means of "partial combustion" of coal) is used instead of a traditional combustor and is coupled with an advanced gas turbine. This combination of technologies gives the advantage of adding steam power generation to gas power generation along with new coal gasification processes and breakthrough gas cleanup technologies. IGCC is unique in that it is highly flexible for all coals, liquids, and waste or other opportunity fuels; it can produce high value co-products; and its electricity is predominantly extracted from the more efficient gas turbine portion of the combined cycle. IGCC is the most efficient and cleanest of the available technologies for coal-based power generation. The objective of the program is, by the year 2010, to make available technology: (1) with a net electricity system efficiency up to 55 percent; (2) that reduces emissions to less than 1/10 of the NSPS for SO_2, NO_x, and particulates; and that (3) achieves a capital cost of less than $1,000 per kilowatt with a cost of electricity 80-90 percent of that produced by a new conventional pulverized coal power plant.

The DOE IGCC program is a 20-60 percent cost-shared partnership with industry, supported by university and National Laboratory research.

R&D Challenges. The key R&D challenge for IGCC is to reduce capital and operating costs while simultaneously lowering risk, increasing plant efficiency, and further reducing emissions. To accomplish these goals, the IGCC program has diversified its activities to include a range of technology options to meet existing and future market requirements for electricity and other high-value products. These activities are also consistent with the goals and objectives of the Vision 21 Energy-Plex.

DOE is investing in the development of novel air separation technologies that have potential for significantly reducing capital cost while simultaneously improving efficiency.

To employ advanced technologies such as fuel cells, to convert synthesis gas to other products, and to meet the environmental goals of Vision 21, the gas exiting the gasifier must be cleaned of all impurities such as sulfur, mineral matter, and other toxic materials. The development of reliable, affordable, and high efficiency gas cleanup technologies is, therefore, another major technical challenge for IGCC. First-generation hot gas cleanup technologies have been developed and are being demonstrated under the Clean Coal Technology Demonstration Program. Although suitable for power generation, these technologies must be extended to meet the stringent gas quality requirements for fuel cell and co-production applications. Novel approaches for achieving this, while simultaneously reducing cost and improving efficiency, are also being explored.

To meet the goals of Vision 21 for high efficiency and reduced emissions of greenhouse gases, low-cost technologies for hydrogen and CO_2 separation from the synthesis gas stream

are required. Advanced technologies using membranes are being investigated to accomplish the desired separation, as well as novel chemical approaches to separating CO_2 the gas.

R&D Activities. Currently, the focus of the program is centered around four primary activities: (1) Advanced Gasification, that includes accelerating development of the transport-bed gasifier and associated control devices, investigating cofiring of coal with other low-cost feedstocks, improvements in refractory design, and high temperature instrumentation; (2) Gas Stream Clean-Up that enables the production of ultra-clean syngas for fuel cell and co-production applications, novel gas clean-up technologies that minimize consumables and waste streams, and more sorbent development work to meet the need of more stringent applications; (3) Gas Separations that are aimed at enabling the development of new air separation technologies for producing low cost oxygen and enriched air, novel hydrogen separation technologies capable of operating at high temperatures and pressures in the presence of chemicals and particulate contaminants, and technologies for mitigating, separating and utilizing CO_2 emissions; and (4) Products/By-Products Utilization that is looking into aspects of improving slag/ash quality and direct sulfur recovery processes.

Accomplishments. The program has progressed from the basic research or idea stage 20 years ago to the early stages of commercial introduction. Three first-generation (42 percent efficient) commercial demonstration plants are now operating under the DOE's Clean Coal Technology Demonstration Program. In this 20-year time period, which is a typical lead time for developing new power systems, the program has been highly successful in developing the critical components of IGCC systems (e.g., gasifiers, gas stream clean-up subsystems, coal-fuel compatible turbines, and others), some of which have already been commercialized (e.g., the Texaco gasifier).

Advanced Gas Turbine Systems

Budget: FY98-$45.0M, FY99-$44.5M, FY00-$41.8M

Description, Objectives, and Performers. A gas turbine is a major component used in the generation of electricity. Advanced turbines are initially being developed using natural gas as the fuel, but will later be designed for use with other fuels derived from coal, biomass, etc. In the turbine, the high-temperature, high-pressure gases rushing out of the combustor push against the turbine blades, causing them to rotate. The turbine is connected by a shaft to a generator that turns to produce electricity. Much of the remaining heat supplied by the gas can be converted to useful energy in a steam bottoming cycle (i.e., a second lower temperature power generator).

The Department's Advanced Turbine Systems (ATS) program is developing ultra-high efficiency gas turbines for utilities, independent power producers, and industrial markets. The objective is to break the 60 percent barrier in net thermal efficiency for gas turbine systems and reduce SO_x emissions to zero and NO_x emissions to 9 parts per million or less, while achieving operating costs 10-20 percent lower than conventional power systems. The potential domestic and global markets for advanced turbines are large. At least half of all new power generating capacity to be added between now and 2010 is likely to use gas

turbines. EIA forecasts over 200 gigawatts of new gas capacity additions in the United States between now and 2015. If ATS were to capture half of this market, it would result in 0.43 quads less fuel use and 94,000 tons less NO_x in 2015 compared to using current systems that operate at an electric efficiency of 50 percent and generate about 10 to 24 parts-per-million of NO_x (without external controls). Because of their high efficiency, advanced turbines will emit less CO_2.

This program is an innovative partnership between DOE, State governments, gas turbine manufacturers, universities, natural gas companies, National Laboratories, and electric power producers for developing lower cost, higher efficiency gas turbines that have better environmental performance than existing machines, to meet current and projected power generation needs. A university consortia works directly with industry to resolve key technical problems encountered in the program. Current industry cost sharing is up to 70 percent.

Supporting research and development is performed as part of the ATS Program. This technology base effort includes the Advanced Gas Turbine Systems Research (AGTSR) managed by the South Carolina Energy Research and Development Center (SCERDC), Federal Energy Technology Center (FETC) research, Department of Energy Combustion Systems Cooperative Research and Development Agreements, research on advanced alloys, thermal barrier coatings, and catalytic combustion, and small business and innovative research.

The AGTSR, a national industry-university R&D consortium, is currently in its sixth year of operation. AGTSR is dedicated to supporting the advancement of land-based gas turbines for future power generation systems which include both the ATS and post-ATS technology programs. The major goals of AGTSR are to promote multi-disciplinary engineering education to realize gas turbine challenges for the 21st century and industry-oriented collaborative R&D with U.S. universities. There are 95 universities which qualify to participate in the consortium and 9 industrial review board members. Over the past 5 years, AGTSR has supported 51 research subcontracts at performing member universities. Ten new projects were selected in 1997. These selections include 3 projects in combustion, 4 in aerodynamics and heat transfer, and 3 in materials.

In advanced materials development, research to develop advanced alloys for ATS hot gas path components has continued. Advanced single crystal alloy developments are enabling the scale up of technologies used to produce high-temperature blades and vanes for the aircraft engines. Recent accomplishments have reduced levels of sulfur and defects in large production castings of these components. Future emphasis is being placed on the cost-effective manufacturing of these components. Projects have recently been initiated to develop advanced casting and fabrication methods to increase the yield rates to reduce the production costs of these components. Successful commercialization of these new processes is critical to achieving the cost of electricity goals of the ATS Program. Currently, the teams of Howmet Corporation-General Electric Company-Solar Turbines Incorporated and General Electric Company-PCC Airfoils Inc. are participating in the new casting projects under the advanced alloys program.

R&D Challenges. Technological advances in the turbine components and systems, such as cooling system design, materials development, and thermal barrier coatings, will permit higher gas turbine combustor firing temperatures that are necessary to reach program efficiency goals. Other design advances are needed to reach NO_x emissions goals and carbon monoxide and unburned hydrocarbon emissions of less than 20 parts-per-million without post-combustion cleanup.

R&D Activities. R&D activities focus on materials science advances, integral thermodynamic changes, base technology research, systems design, development, and integration. Solicitation and awards were made for "Advanced Turbine Airfoil Manufacturing Technology" to develop advanced manufacturing methods in order to increase the yields of turbine blades from low sulfur content, single crystal materials.

Accomplishments. Many technological advances have been achieved since 1992, when the ATS program was initiated. Howmet Corporation developed a single crystal material with a sulfur content significantly below 1 ppm in a non-production size heat and in production size heats (5,000 pounds) with a sulfur content around 0.5 ppm. They were able to produce utility size blades with acceptable grain defects. PCC has produced products with the grain defects contained only in the tips and platforms, has identified and partially eliminated core break locations, and has produced a single crystal of material with a sulfur content of 0.3 ppm using a melt desulfurization process. As a result, U.S. turbine manufacturers will be ready to supply the first ATS machines early in the next century (with expected further improvements afterwards including the incorporation of aeroderivative designs).

Under the industry-university consortium, significant accomplishments were made in the areas of heat transfer, combustion, materials and aerodynamics, providing many design methods, models, and concepts for the gas turbine industry. Faculty principal investigators completed sabbaticals at gas turbine manufacturers and successful workshops were conducted in areas of specific need or emphasis. Numerical models were developed for lean premixed combustion, simplified chemistry, unsteady aerodynamics, and heat transfer for designing advanced gas turbines. Novel probes and control strategies were developed for improving lean premix combustion processes, and advanced coating and materials development processes were produced.

DOE's Federal Energy Technology Center completed tests on new combustor lean pre-mix configurations using liquid fuels, tests of a novel low-NO_x burner developed by Alzeta Corporation that showed very low emissions performance, and a series of tests for humid air turbine configurations. The humid air turbine tests verified that very low NO_x and CO emissions can be achieved with high steam loadings in the combustor.

Under the Small Business and Innovative Research Program, Precision Combustion Incorporated of New Haven CT was awarded the Tibbetts Award in recognition of their unique contributions as an "SBIR Model of Excellence" in developing and commercializing important environmental technologies.

Advanced Large-Scale Fuel Cell Power Systems

Budget: FY98-$40.2M, FY99-$44.2M, FY00-$37.6M

Description, Objectives, and Performers. Over the longer-term, quiet, virtually non-polluting fuel cells could become a new option for electric utilities. Unlike conventional power generation technologies, fuel cells work without combustion and the associated environmental side effects—atmospheric emissions of sulfur and nitrogen compounds. Instead, fuel cells act like continuously fueled batteries, to produce electricity using an electrochemical process. In a fuel cell power plant, natural gas or coal gas is first cleaned, then converted to a hydrogen-rich gas by a fuel processor or by an internal catalyst. This fuel is then fed along with air to a fuel cell power section to generate high quality electricity. Fuel cell power plants can be built by combining cells into stacks to obtain the needed voltage and power output in a wide range of sizes—from 200 kilowatt units suitable for powering commercial buildings, to 100 megawatt plants that can add baseload capacity to utility power plants.

The program objective is to make available, by 2003, fuel cells for electricity production with up to 60 percent efficiency and negligible emissions of regulated pollutants. This performance, coupled with the quietness, small size and modularity of the technology, make fuels cells an attractive option for meeting fast-growing demand in global markets.

R&D Challenges. The challenges for advanced, large-scale fuel cells are, in the near-term, reducing costs and extending cell life and reliability. Longer-term challenges are the solution of integration issues related to combining fuel cells with turbines and gasifiers for hybrid fuel cell/turbine systems and for Vision 21 applications.

R&D Activities. DOE is continuing its industry cost-sharing partnerships to develop advanced, next generation fuel cells, with support from the National Laboratories. Molten carbonate and solid oxide fuel cell technology is being tested at full-scale. Supporting research is focused on improved electrodes, electrolytes, interconnects, materials and seal, and thin film advanced cell processing techniques.

Studies are being conducted on various fuel cell/turbine combined cycle configurations, and investigations will focus on pressurization, the design of fuel cell gas passages to allow integration with turbines, high temperature seals, reliability, fuel gas cleanup, improved thermal cyclability, and high temperature material issues. Hybrid system studies will investigate system reliability and operability, control, dynamic response, matching of gas flow rates, system optimization, mode of operation, and cost and ease of installation.

Accomplishments. The DOE, in partnership with industry, has cost-shared (30-50 percent industry contribution) the development of fuel cells since the mid-1970s. The first generation fuel cell products, phosphoric acid fuel cells (PAFC), entered the commercial market in 1992. More than 160 PAFC power plants have been delivered to sites in the United States, Europe, and Asia. The current fleet has an impressive availability above 95 percent, and demonstrates

reliable, safe operation in a variety of climates, applications, and service scenarios. The electric efficiency of these natural gas fired plants is in the 40-45 percent range. Early versions of molten carbonate systems have been tested at the 250 kilowatt and at the megawatt size, while solid oxide fuel cells are being tested at the full-size 100 kilowatt unit module.

Carbon Sequestration

Budget: FY98-$1.5M, FY99-$5.9M, FY00-$9.1M

Description, Objectives, and Performers. Fossil fuel-fired power plants emit about one-third of the Nation's CO_2 emissions. Moreover, these plants account for 70 percent of U.S. electricity generation, and are projected to dominate generation for the foreseeable future. If dramatic reductions in CO_2 emissions are to occur, it appears necessary that technologies will be required to sequester (capture, store, or transform) at least a portion of these emissions of CO_2. Sequestration has the potential to offset a large portion of the 1.6 billion tons per year of U.S. carbon emissions attributable to human activities. It is estimated that achievement of program goals can lead to sequestration of about 200 million tons per year of carbon in 2015, increasing to nearly 3 billion tons per year in 2100. The program objective is to develop sequestration technologies which make it possible to offset all growth in CO_2 emissions in the United States after the year 2015, for $5-10 per ton of carbon reduced, without introducing new environmental damages.

Compared to most research in the Department, sequestration research is a relative newcomer. Nevertheless, sequestration techniques are already being implemented on a very limited scale in promoting enhanced oil recovery, and to dispose of CO_2 associated with natural gas production. In addition, a number of reforestation projects have been implemented. It should also be noted that CO_2 injection into unmineable coal seams has been used to promote methane production, and efforts are underway to reduce the cost of this technology to make it economically practical at more sites. Most sequestration research in the Department is at a fairly fundamental level, as evidenced by the recent solicitation and selection of projects to identify "novel concepts" to sequester greenhouse gases.

R&D Challenges. The challenge is to find sequestration approaches which are both low in cost and which do not introduce new environmental problems.

R&D Activities. The Office of Fossil Energy is examining approaches which capture and store (e.g., in depleted oil or gas reservoirs) emissions from advanced power cycles, technologies which enhance natural processes for removing CO_2 from the atmosphere, and novel concepts which transform CO_2 to a valuable resource or a benign material

Accomplishments. The Office of Fossil Energy (FE) conducted a competitive procurement to solicit proposals pertaining to novel concepts to sequester greenhouse gases. In April 1998, 12 potential breakthrough research projects were selected form the 60 proposals that were submitted. FE has, and will continue to sponsor several workshops to bring together the experts on sequestration to advance the most promising R&D pathways and to develop a

roadmap that will lead to sequestration becoming a viable commercial technology. FE and DOE's Office of Science have also developed a formal working group on carbon sequestration research. The group held workshops at the Massachusetts Institute of Technology in June 1998, and at FETC in July 1998. The workshops respectively focused on (1) identification of priority research needs by major DOE stakeholders from the coal, oil and gas, electric utility, and other industries, and (2) coordination of Federal agency and National Laboratory programs to address gaps in current research activities. Subsequent workshops on topics ranging from CO_2 utilization to storage in geological structures will be conducted over the next year.

Nuclear Fission Systems

Budget: FY98-$0.0M, FY99-$19.0M, FY00-$25.0M

Description, Objectives, and Performers. The Nuclear Energy Research Initiative (NERI) complements Nuclear Energy Plant Optimization by addressing our Nation's nuclear energy future. Despite nuclear energy's advantages, unless issues such as plant costs and spent fuel disposal are successfully addressed, the United States is unlikely to see new orders for nuclear power plants. NERI, started in FY 1999, funds investigator-initiated research and development at universities, National Laboratories, and industry to advance nuclear power technology, paving the way for expanded use of nuclear energy in the future.

Science and engineering research is needed to develop new, innovative, and advanced reactor designs in three distinct areas: proliferation resistant reactor technology, high efficiency reactor concepts, and low output reactor applications. The overall objective is to develop new reactor designs that offer improved economics, reduced waste generation, increased safety, and proliferation resistance. Research proposals are solicited from a broad range of researchers, including universities, National Laboratories, and industry. International collaboration will be encouraged in order to leverage Federal research funds, although no Federal funds will be used to directly support research outside of the United States.

R&D Challenges. The new reactor design challenge is to bring the capital cost of nuclear power in line with other electricity supply options while also reducing the amount of spent nuclear fuel produced per kilowatt-hour of electricity generation. Internationally, several developing countries expect to see rapidly growing electricity demand over the next few decades and are looking to nuclear power as an option for meeting those needs. In those markets, issues of plant safety and proliferation risk are also of concern. The challenge in those areas will be to develop reactor designs that require a minimum of maintenance, operator action, and refueling during the lifetime of the reactor.

R&D Activities. Activities planned under NERI would focus on scientific and/or engineering research to further reduce the potential for proliferation of nuclear fuel materials and increase the efficiency of nuclear energy systems. Research into new fuel types and fuel cycles that reduce plutonium buildup, produce less waste, and improve efficiency will be studied.

Innovative research could be conducted on reactor designs offering improved thermal-to-

electric efficiencies or specialized, new applications such as cogeneration process heat/electricity systems to compete in the global market. Research would include technologies, design concepts, and approaches that incorporate construction and operations simplicity and cost reduction features.

Finally, research and development of innovative, low power reactor designs employing passive safety systems, and long life cores for electricity generation or process heat use in developing countries could be conducted. The ultimate objective is to develop small reactor systems, primarily for export, that need no on-site refueling for the life of the reactor, employ high safety margins, automated operation, minimized waste production, and cost effectiveness.

Accomplishments. The NERI program is a new start in FY 1999, so that program has no accomplishments to date. The first group of R&D grants and contracts selected from solicited, peer-reviewed research proposals will be awarded in May 1999.

Nuclear Fusion Systems

Budget: FY98-$226.6M, FY99-$228.2M, FY00-$190.2M
(These funds are part of the Science Portfolio and are repeated here for information purposes only)

Description, Objectives, and Performers. Nuclear fusion has the potential of being one of the best long-term means to meet future needs for a safe, clean, environmentally benign, and abundant energy source. The process of nuclear fusion—evident in stars, including the sun—releases enormous amounts of energy. It occurs when the nuclei of lighter elements (such as hydrogen) are fused together at extremely high temperatures and pressures to form heavier elements (such as helium). The program objective is to advance plasma science, fusion science, and fusion technology to establish the knowledge base necessary for the future development of economically and environmentally attractive nuclear fusion energy systems.

The Department's fusion program performers include numerous National Laboratories, universities, and industrial firms. The allocations of funds for FY 1998 is 44 percent for National Laboratories, 28 percent for universities, and 22 percent for industrial firms, with the remaining 6 percent applied toward educational programs, Departmental program direction, and other activities. The Princeton Plasma Physics Laboratory, the Department's only laboratory dedicated to fusion research, is the largest of the performer institutions.

R&D Challenges. The primary scientific challenge facing fusion energy development is advancing the understanding of high power density plasmas. This understanding, which will guide the development of innovations and concept improvements, will result from an integrated program of experiments and advanced theory and computational capability. The development of theory based computational tools with predictive capability will be an increasingly important part of the development of future experimental systems which are

becoming more costly. Innovations and concept improvements will contribute to demonstrating the scientific and technical attractiveness of fusion power plants. Significant technical challenges also exist in the development of low-activation materials, which are required to enhance the environmental attractiveness of fusion energy.

R&D Activities. Research activities supporting the program are designed to advance plasma science in pursuit of national science and technology goals; develop fusion science, technology, and plasma confinement innovations as the central theme of the domestic program; and pursue fusion energy science and technology as a partner in the international effort.

While fusion power outputs can be sustained now for only a few seconds, successes with the Tokamak Fusion Test Reactor (TFTR), the Joint European Torus (JET) project, and other elements of the United States and worldwide fusion research effort have provided confidence in the ability to pursue a scientific and technological feasibility demonstration experiment. Toward this end, the United States is collaborating with Japan, the European Union, and the Russian Federation on the design of, and supporting R&D for, the International Thermonuclear Experimental Reactor (ITER). If constructed, ITER would produce 100s of megawatts of fusion power for possibly 100s of seconds and would test the plasma physics operating modes and technologies needed for steady-state operation and efficient extraction of fusion energy for electricity generation.

The fusion research technical infrastructure that is needed to sustain the science objectives supported by Congress will also provide the basis for expanding fusion energy development activities in the future, as either research results or energy needs dictate that the Department should do so.

Relative to innovation, the Department's fusion program has substantially increased its efforts toward proof-of-principle experimentation on promising new fusion concepts and toward advanced energy technologies. The National Spherical Torus Experiment (NSTX), which will become operational at the Princeton Plasma Physics Laboratory in 1999, is the first in a series of new proof-of-principle experiments, with others now being planned through a competitive selection process that will identify the most promising concepts. Also, technology initiatives begun in 1998 are now aimed at proving the feasibility of advanced concepts for handling the high levels of particle and heat fluxes that will be produced in the high performance plasmas needed to achieve an attractive fusion energy source.

At a constant level of funding, the program will focus on fusion's underlying scientific foundations. This will enable the United States to exert leadership in selected areas of expertise in the international effort to develop fusion energy. Although the United States will be unable to pursue an independent fusion energy development program, it will attempt to remain a credible partner in the international fusion program that remains aimed at long-term energy development. Because Europe and Japan have energy situations different from that of the United States, fusion energy R&D has a higher priority in those countries. Europe's

fusion program is about 2½ times the size of the U.S. program and Japan's fusion program is about 1½ times the size of the U.S. program.

Accomplishments. Substantial technical progress has been made in domestic and worldwide fusion programs. In 1996, the Tokamak Fusion Test Reactor (TFTR) at the Princeton Plasma Physics Laboratory, became the first fusion device in the world to produce 10 megawatts of fusion power. This power was produced in a plasma with a deuterium-tritium fuel mix that is expected to be used in fusion energy sources. More recently, the Joint European Torus in England has produced even greater levels of fusion power than the 10 megawatts produced in TFTR. Substantial progress also has been made in the last 3 years in understanding and controlling plasma conditions to improve the energy confinement capability of Tokamaks. By selectively heating the plasma and shaping the current, the thermal energy of the plasma is better contained which would lead to a smaller and more efficient advanced Tokamak power plant.

Distributed and Hybrid Energy Systems

Budget: FY98-$188.3M, FY99-$212.8M, FY00-$237.4M

Background

The U.S. electric industry is undergoing fundamental change due to restructuring and the addition of new electric generation power suppliers and products, as well as the changing nature of decision making. Grid-sited, large central power plants have long dominated electric utility technology decisions and today these plants remain the backbone of the power system. However, market factors—including ample supplies of cheap natural gas, constraints at the transmission and distribution level, environmental considerations, and technological advances—are causing alternative, modular technologies such as fuel cells, gas turbines, photovoltaics, wind turbines, solar, geothermal, and biomass systems gradually to augment and sometimes to replace conventional, large-scale generating technologies. In particular, gas turbine technology has a dominant role in both distributed energy and hybrid systems.

Renewable resources, such as hydroelectric, wind, solar, photovoltaics, geothermal, and biomass, are abundant. Hydropower provided about 10 percent of the electricity consumed in the United States in 1996, while the remaining renewable resources supplied 1.3 percent. The primary advantage of these renewable resources in power generation is they produce virtually no harmful emissions or solid wastes. Their primary disadvantages are the cost of producing power (with the exception of hydropower) compared to coal and natural gas, and the need to create the infrastructure required to deliver electricity to the market. Because hydropower already has a well developed market and infrastructure, the Department currently does not invest significantly in hydropower technologies. The Department focuses instead on improving the performance and lowering the costs of the technologies using other renewable resources.

Where these technologies are available locally, the cost of infrastructure development on the transmission and distribution system is reduced, and a reliable power supply system is made available at critical times in those locations. In a recent study, the Electric Power Research

Institute indicated that these small modular units, located primarily on the distribution system, would capture at least half of all new U.S. electric capacity needs between now and 2020. These distributed and hybrid power systems using renewable and fossil energy sources have many benefits such as improving environmental quality, short construction lead time, modular installation, and low capital expense, which all contribute to their growing popularity.

The portfolio of technologies represented by distributed and hybrid systems have numerous applications, for example, at customer sites, to provide both heat and power; on the distribution system, to provide high value electricity and deferral of costly line upgrades and replacement; off-grid in stand alone power applications; and for electricity supply to the bulk power market.

Linkage to CNES Goals and Objectives

The Department invests in distributed and hybrid energy systems to ensure the availability of a portfolio of advanced power technologies utilizing renewable and hybrid energy systems that will increase the flexibility, capacity and reliability of the U.S. power system. This end supports:

- CNES Goal II, Objective 2 - Ensure energy system reliability, flexibility, and emergency response capability.
- CNES Goal III, Objective 1 - Increase domestic energy production in an environmentally responsible manner.
- CNES Goal III, Objective 2 - Accelerate the development and market adoption of environmentally friendly technologies.
- CNES Goal IV, Objective 2 - Develop technologies that expand long-term energy options.
- CNES Goal V, Objective 1 - Promote development of open, competitive international energy markets, and facilitate the adoption of clean, safe , and efficient energy systems.

Program Description

The Department is developing a suite of distributed and hybrid power systems to significantly contribute toward the goal of providing reliable and affordable power generated in an environmentally benign manner. Technologies being developed include renewable energy (wind, photovoltaics, concentrating solar power, geothermal, and biomass), combined heat and power (cogeneration), smaller fuel cells, and small combustion turbines and reciprocating engines.

Combined Heat and Power Systems

Budget: FY98-$1.0M, FY99-$1.5M, FY00-$2.0M

Description, Objectives, and Performers. Combined heat and power, or cogeneration, involves capturing the waste heat and putting it to some useful purpose at the customer site.

The development of combined heat and power systems for generation systems has the potential for over 85 percent fuel utilization efficiency in industrial, commercial, and residential applications. With conventional power generation systems, up to two-thirds of the energy is lost as waste heat. The program objective is to eliminate the barriers of combined heat and power technologies to increase the overall power industry efficiency and reduce atmospheric emissions.

With utility restructuring and competition in the power generation market and new environmental regulations on the horizon, the market landscape for energy production and use is likely to change. Government and industry, in partnership, have the opportunity to address the technology challenges associated with optimizing heat and power systems for on-site usage, as well as addressing technical issues associated with infrastructure development for energy transport and storage.

A related new initiative is the Combined Heat and Power Challenge (CHP) that addresses major existing barriers to the implementation of combined heat and power systems, including:

- Environmental permitting that is complex, costly, time consuming and uncertain.
- Environmental regulations that do not recognize the overall energy efficiency of CHP or credit emissions avoided from displaced electricity generation.
- Utilities that charge (or threaten to charge) prohibitive exit and/or stranded asset fees for customers wanting to build CHP facilities, or charge unreasonable rates for use of the distribution grid, and/or prevent the use of alternative backup and supplemental power suppliers.
- Long and varied Federal tax depreciation schedules for CHP investments that differ depending on system ownership.

The CHP Challenge will assist plants that experience the above problems when implementing CHP systems through assessments of future combined heat and power facilities, State outreach, modeling, and technology verification. The program has provided several grants to California, Vermont, Indiana, and Washington to initiate case studies to implement advanced combined heat and power technologies. The program is also investigating the use of biomass and black liquor (produced in the paper-making process) for large-scale combined heat and power systems that are synergistic with industrial processes and district heating/cooling needs.

R&D Challenges. R&D challenges include prime mover (fuel cell, turbines, etc.) technology development, related low emissions, cost effective technology development, and long-term materials development.

R&D Activities. Some of the power generation technologies being developed by DOE and

industry such as gasification, combustion, and fuel cells are aimed at fuel flexibility and other modifications to accommodate a variety of energy needs. For example, combined heat and power is included as part of the Vision 21 Energy Plex development program currently underway in the Office of Fossil Energy.

Accomplishments. In FY 1999, the program will hold a national workshop and aid in the technology demonstration of a ceramic combustor liner.

Advanced Turbine Systems (Industrial and Microturbines)

Budget: FY98-$34.7M, FY99-$51.0M, FY00-$31.3M

Description, Objectives, and Performers. Advanced turbine systems, with their wide range of potential sizes, are particularly attractive for distributed generation applications. Competition and emerging technologies are causing the power generation industry to abandon its larger-is-more-efficient philosophy for a customer-based, tailored energy mindset. In the competitive environment, electric power suppliers will need to pay more attention to customers needs in order to retain them. The result will be a growing demand for custom power plants designed to most efficiently meet the end-use residential/commercial/industrial customer's specific needs. DOE's Advanced Turbine Systems (ATS) Program is focusing on this market through it objective to make available turbine systems for distributed applications, including: (1) industrial gas turbines that are 40 percent efficient with single digit emissions and provide a 10 percent reduction in the cost of electricity while maintaining the reliability, durability and availability of today's industrial turbines, and (2) advanced microturbines with 40 percent efficiency and emissions of less than 10 parts per million NO_x and CO_2 at an equivalent reliability and reduced cost compared to today's technology.

Partners in the Advanced Turbine Systems Program include over 150 suppliers, universities, and National Laboratories. The program is a joint effort between the Office of Fossil Energy and the Office of Energy Efficiency and Renewable Energy.

R&D Challenges. Meeting the goals for the industrial turbine part of the Department's Advanced Turbine Program (begun in 1994) will require advancements in engine and component design, including innovations in cooling, materials, and coatings. The environmental goals will require the use of new combustion techniques such as the use of ceramics and catalytic combustion.

Currently, distributed microturbines are approximately 23 percent efficient. Meeting program goals will require the development of advanced materials such as ceramics and coatings, combustion systems, and recuperation technologies. Advanced ceramics and coatings will enable engines such as microturbines to have low emission levels, have long life (>18,000 hours), be highly efficient targets, and be fuel flexible. Microturbines can be coupled with a fuel cell resulting in a system efficiency ranging from 70 to 80 percent.

R&D Activities. DOE work on small turbine systems includes industrial and microturbine R&D. The Advanced Turbine Program funds major work in ceramics. Because of their superior high temperature durability, the application of ceramics as structural materials for gas turbine hot section components will enable a significant increase in the turbine rotor inlet temperature of current all-metal industrial gas turbines, resulting in improved thermal efficiency, greater output power, and reduced emissions of NO_x and CO_2.

In the microturbine area, the program is working with the Electric Power Research Institute (EPRI), the Gas Research Institute (GRI), and Edison Technology Solutions to test the current state-of-the-art microturbines available, a ceramic recuperator development effort with DuPont Lanxide Composites Inc., Rensellaer Polytechnic Institute, and Teledyne Ryan Aeronautical and a hybrid turbine/fuel cell system. In FY 1999 and beyond, funding will continue the design and development of microturbines, advanced recuperators, and ceramic components.

Accomplishments. An early success of the program is the announcement by Solar Turbines, Inc. of the demonstration of the “Mercury 50" advanced turbine set for 1999. A second success is, with DOE support, Solar Turbine’s ceramic development effort to replace cooled metallic hot section parts (combustor liner, vanes, and nozzles) with uncooled ceramic parts. To date, a ceramic composite combustor liner and silicon nitride blades have been run for approximately 2000 hours in an industrial gas turbine at ARCO Western Energy in Bakersfield, CA. The goal of the effort is to run the ceramic components (blades, vanes, and nozzles) for 4000 hours.

Distributed Fuel Cell Power Systems

Budget: FY98-$6.4M, FY99-$0.0 M, FY00-$0.0M

Description, Objectives, and Performers. Fuel cell power systems do not rely on combustion, but rather produce electricity from power plants based on electrochemical power conversion of a carbon-rich fuel. These modular systems are among the most efficient and cleanest power plants being developed. They can be deployed in applications ranging from small distributed systems (several kilowatts) to utility scale (multi-megawatts). The program seeks to help bring this promising alternative to combustion-based fuel cycles to the marketplace, and to ultimately ensure that renewable energy serves as the source of hydrogen fuel. The objective is to (1) lower the cost and improve the performance of fuel cells to meet the competitive market challenges of less than $1000 per kilowatt, and (2) develop an integrated fuel cell/turbine hybrid system for small-scale applications that promise system efficiencies of over 70 percent and costs below $700 per kilowatt. The Department is partnering with industry (supported by university and National Laboratory research) on a cost-shared basis (currently at 30-50 percent industry funding) to develop fuel cell technology for the restructured energy market.

R&D Challenges. R&D challenges for the fuel cell program include improving key advances to enhance the fuel cells output performance (cell voltage degradation), enhance longevity (minimum 5 years operation), and develop lower cost materials and components.

R&D Activities. R&D supporting these efforts is aimed at extending cell life, improving reliability, and reducing costs. Activities include advanced manufacturing techniques; improved electrodes, electrolytes, interconnects, materials, and seals; and thin film advanced cell processing techniques.

Accomplishments. The DOE fuel cells program has run over the last 20 years from fundamental research to stack and full scale prototype systems that are modules for larger size applications. The first generation fuel cell products, phosphoric acid (PAFC) fuel cells, entered the commercial market in 1992. More than 160 PAFC power plants have been delivered to sites in the United States, Europe, and Asia. The current fleet has an impressive availability above 95 percent, and demonstrates reliable, safe operation in a variety of climates, applications, and service scenarios. Early versions of molten carbonate systems have been tested at the 250 kilowatt and in the megawatt-size range.

Wind Energy Systems

Budget: FY98-$32.1M, FY99-$33.2M, FY00-$45.6M

Description, Objectives, and Performers. Wind turbines convert the kinetic energy in the wind into electrical energy. Most turbines today employ two or three propeller-like blades mounted on a rotor connecting to an electric generator that typically is 500-1000 kilowatts in output. Larger sizes that have been tested are just now entering the commercial marketplace. Because they are modular, wind turbines can be sited either individually, grouped in small clusters, or in larger windfarms totaling 10 to 50 megawatts or larger. In 1997, 3.2 billion kilowatt-hours of electricity were produced by 16,000 wind turbines in the United States.

The program's near-term objective is to develop advanced wind turbine technologies capable of bringing the costs down to $0.025/per kilowatt-hour by 2002 compared to today's cost of $0.04-0.05 per kilowatt-hour. In the longer term, R&D will focus on turbine systems, component materials, electronic controls, and wind forecasting combined with hybrid systems to expand wind energy applications. The target is 10,000 MW of wind energy installed in the United States by 2010, by combining a vigorous technology development effort with activities to reduce barriers and to promote supportive energy policies.

The program conducts R&D with significant cost-sharing through industry partnerships and collaboratives. Partners working collaboratively with DOE include the wind and electric utility industries, National Laboratories (National Renewable Energy Laboratory [NREL], Sandia National Laboratory [Sandia]), and universities.

R&D Challenges. Wind has proven to be an extraordinarily complex energy resource. To be cost-effective, a wind turbine must have high aerodynamic efficiency and must be durable and reliable, while also having minimal weight and complexity. The challenge for the wind program, therefore, is to assist industry in bringing the cost of wind technology to a level where it can compete with traditional energy sources.

R&D Activities. The wind program has three R&D thrusts. The first, the Applied Research program, focuses on basic issues of wind characterization, aerodynamics, structural dynamics and fatigue, hybrid systems, and advanced components and controls. The second, Turbine Research, includes five distinct efforts to develop advanced deployable technology. These efforts include next generation technology development for both utility-scale and small systems and field verification tests at actual operating locations. The third thrust encompasses a number of activities that support the development of certification and standards, technical assistance for industry's international programs, and operation of the National Wind Technology Center at Rocky Flats, CO.

Accomplishments. The DOE wind program has been increasingly successful in improving the performance and decreasing the cost of wind systems and subsequently enhancing its commercial prospects. Today, in areas with ideal wind resources, electricity can be produced for less than $0.05 per kilowatt-hour compared to wind energy in 1980 at $0.35 per kilowatt-hour—a decrease of 85 percent in just 15 years. Recent partnerships with DOE have produced 3 commercially-offered wind turbines, with another 8 now under development.

Photovoltaic Systems

Budget: FY98-$64.7M, FY99-$72.2M, FY00-$93.3M

Description, Objectives, and Performers. Photovoltaic (PV) solar technology uses semiconductor-based cells to directly convert sunlight to electricity. The greater the intensity of the light, the more power that is generated. PV can be used to produce electricity on almost any scale, depending only on how many PV modules are connected together. The worldwide market for PV is growing rapidly, with the United States retaining the largest market share in 1997.

The objectives of the PV program are: (1) by 2000, reduce the price of commercial modules by 15 percent from current average costs of about $4.25 per watt and increase annual sales of commercial modules from 225 megawatts in 1996 to 500 megawatts; and (2) by 2004, increase the efficiency of both thin film and crystalline silicon PV cells, reduce the retail sales price of commercial modules by 40 percent, increase lifetimes to greater than 25 years, and increase annual U.S. industry sales to 1 gigawatt.

Partners working collaboratively with DOE include the PV and electric utility industries, National Laboratories (NREL, Sandia), and universities. Almost all work with industry is heavily cost-shared.

R&D Challenges. Even though the cost of PV is rapidly decreasing, it is currently too high for the bulk power market. R&D challenges to reduce costs include improving the fundamental understanding of materials and processes to provide a technology base for advanced PV options, optimizing cell and module materials and design, scaling up cells to product size, validating performance in outdoor and accelerated conditions, and improving manufacturing processes.

R&D Activities. The Photovoltaic R&D program is divided into three areas. The first, Fundamental Research, includes the measurement and characterization of cell materials and devices. Work is also performed to improve cell structure and materials processing for thin film technologies. As part of the second area, Advanced Materials and Devices, the Thin Film Partnership Program is a government/industry/university partnership to accelerate development of cost-effective thin-film technologies. The program also operates a core research effort in high efficiency III-V gallium arsenide (GaAs) materials and devices for concentrator and flat plate applications. Finally, under the third area, Collector Research and Systems Development, the Photovoltaic Manufacturing Technology Project (PVMaT) is improving manufacturing processes for thin-film technologies and assisting industry in the development of advanced techniques for producing higher performance and lower cost commercial products. The program is continuing R&D on advanced PV Building products, concepts, tools, and modeling procedures in support of industry efforts for technology development/deployment. The Million Solar Roofs Initiative will increase outreach activities to establish partnerships with communities, cities, builders, Federal and State agencies, corporations, and financial institutions across the Nation.

Accomplishments. The program has contributed to a 50 percent reduction in the cost of producing PV modules since 1991, resulting in the technology being used in grid-connected, distributed power, and off-grid, remote electric power. A recent success is the development, in partnership with industry, of a Photovoltaic roofing shingle that is now on the market and can replace conventional roofing shingles to generate clean electricity.

Concentrating Solar Power Technology

Budget: FY98-$16.3M, FY99-$17.0M, FY00-$18.9M

Description, Objectives, and Performers. Concentrating solar power (CSP) systems use sun-tracking mirrors to reflect and concentrate sunlight onto a receiver where it is converted to high-temperature thermal energy. The high-temperature heat is then used to drive a heat engine and electric generator.

The CSP program has recently reviewed its objectives to ensure that the program is focused on the needs of the evolving utility marketplace. By 2004, the program will, in collaboration with industry, help develop a reliable (4000 hours mean time between failures) distributed power system and a competitively priced dispatchable power system. that will enable full participation by CSP systems in domestic generation markets, prompted by the restructuring activities in various States.

The Program has cost sharing with industry of roughly 50 percent. R&D partners working collaboratively with DOE include the solar thermal and electric utility industries, National Laboratories (NREL, Sandia), and universities.

R&D Challenges. The program is addressing the challenges of harnessing an intermittent resource, i.e., sunlight, and cost-effectively converting that resource into electricity that has

high value to the utility supply system. One approach is to store thermal energy for later conversion into electricity as utility system demand dictates. A second approach is to produce electricity whenever sunlight is available, and to supply that electricity to the grid either in high-value peak periods or in applications where the price of alternative power supplies is high. Because thermal conversion efficiencies are greatest at higher temperatures, the program is seeking advanced materials and heat receivers that operate at higher temperatures.

R&D Activities. The CSP R&D program activities are categorized into four paths. The first path, Develop and Demonstrate High-Reliability Distributed Power Systems, focuses on reliability of dish/engine systems for emerging markets for distributed energy sources. The second path, Reduce Costs of Dispatchable Solar Power, is currently focused in two areas: advanced trough component R&D and the development of high-temperature CSP systems. Penetration of broad domestic and international markets will, however, require further significant technology advances addressed in path 3, Develop Advanced Components and Systems. A fourth path, Expand Strategic Alliances and Market Awareness, will keep technology efforts focused on the most critical needs of industry, ensure a technology capable of meeting market needs, and support domestic and international information flow and policy decisions favorable to renewable energy.

Accomplishments. The CSP program is concluding a decade-long program to develop a utility-scale dispatchable solar electricity system. The 10-MW Solar Two power tower concept, being demonstrated in Southern California, incorporates molten salt thermal storage to extend its operation into early evening hours at a more competitive level of cost.

Geothermal Systems

Budget: FY98-$5.1M, FY99-$6.0M, FY00-$7.0M

Description, Objectives, and Performers. Geothermal power plants use the natural heat in the earth's interior to drive a turbine generator and produce electricity. Currently, the installed commercial geothermal electric capacity in the United States exceeds 2,800 megawatts. Today, electricity is produced domestically only from hydrothermal resources (reservoirs of steam or hot water) in the western United States. In the future, hot dry rock resources, which are far more abundant, could contribute to clean power production.

The program objectives are: (1) by 2005, lower the cost of geothermal energy production to $0.035 per kilowatt-hour from typical geothermal resources, compared to current costs ranging between $0.05 and $0.08 per kilowatt-hour; and (2) by 2010, provide technology to facilitate increased geothermal power that will supply electric power to 7 million U.S. homes, and meet the needs of people in developing countries.

The DOE Geothermal Electric R&D program is implemented through a combination of contract research at National Laboratories (principally Idaho National Engineering and Environmental Laboratory, Sandia National Laboratory, and National Renewable Energy

Laboratory) and financial assistance to private companies whose proposals are selected by a competitive process of objective merit review.

R&D Challenges. Longer-term (beyond 2005) geothermal R&D challenges include improved methods for predicting reservoir performance and lifetime, innovative low-cost drilling technologies, improved conversion of energy from hot dry rock, and lowering equipment costs through materials science and process chemistry.

R&D Activities. The Geothermal Electric R&D Program focuses its efforts in three areas. Exploration and production technology work seeks new, more cost-effective ways to identify and exploit geothermal reservoirs. Support for drilling technology development includes drill bit development and advanced computerized well logging tools. Energy conversion technology focuses on advanced systems for controlling non-condensible fluids in geothermal fluids, and development of a small-scale demonstration plant at a remote location.

Accomplishments. The DOE Geothermal Electric R&D Program improved the flashed-steam cycle during the 1970s and 1980s by developing technology for managing solids, making possible exploitation of over 200 megawatts of the geothermal resources near the Salton Sea in California. More recently, it has developed technologies that have achieved 5 to 10 percent efficiency improvements of power plants operating with high non-condensible gas loading (at The Geysers, CA) and with reduced brine temperatures (at Mommoth, CA). The program was a key participant in the development of the polycrystalline diamond drill bits now used in about 40 percent of oil and gas drilling worldwide, and since then has demonstrated the use of slimhole drilling for geothermal exploration, reducing drilling exploration costs by 30 to 50 percent.

Biopower

Budget: FY98-$27.8M, FY99-$31.5M, FY00-$39.0M

Description, Objectives, and Performers. Biopower systems generate electric power from resources such as energy crops, agricultural residues, wood, and wood residues. These can be co-fired with coal, burned directly as a single fuel in new power plants, or converted through a gasification process to a high energy gas stream to be burned in an advanced, high efficiency gas turbine to produce electricity. Biopower systems can also be integrated in industrial processes such as paper and allied products.

Objectives of the program include: (1) develop advanced biomass conversion technology that, when combined with dedicated crop and tree feedstocks, will reduce the cost of electricity production by nearly 50 percent compared to current costs of $0.07-0.09 per kilowatt-hour for direct biomass-fired power plants now in the marketplace, (2) increase the viability of clean, efficient, biopower technologies for a variety of markets to achieve an additional 3,000 MW of new biomass power in the United States by 2004, and (3) develop integrated biomass/black liquor process streams for the manufacturing sector.

Biomass power research performers include industry partnerships and consortia, the National Laboratories (NREL, Oak Ridge National Laboratory [ORNL], Sandia), and other Federal agencies such as USDA. The program has significant cost-sharing with industry.

R&D Challenges. Short-term R&D challenges include finding ways to improve fuel feed systems, combustion characteristics, gas cleanup, effects on materials and component life and heat transfer performance, discharge handling, NO_x reduction potential, and ash chemistry. Regarding advanced gasification, near-term objectives focus on demonstrating the feasibility of various conversion technologies. Research challenges include demonstrating long-term operation of gas turbines on biogas, improving materials, developing sufficient energy crops for feedstocks, demonstrating advanced technologies, and integration into the forest products sector.

R&D Activities. The Biopower Program is pursuing the development and use of "dedicated" crops and trees which would be regrown to recapture the carbon dioxide emitted when the biomass is burned as a fuel in power plants, creating an energy cycle in which there is no net greenhouse gas emissions. Biomass gasification technologies are being developed through a program that examines advanced techniques for thermochemical conversion of biomass feedstocks and that demonstrate the use of gasifier technology in utility and industrial manufacturing settings. The development of biomass co-firing in existing coal power plants is being pursued in partnership with the utility industry.

Accomplishments. Program successes include the demonstration of the gasification process at the Vermont Biomass Indirect Gasification Project (8-12 megawatts). Three projects competitively awarded in 1996 to industry consortiums will validate integration of dedicated feedstocks with existing or new power plants. These are Niagara Mohawk/Salix Consortium Willow Cofiring Project—47-megawatts of biomass power in an existing coal plant, the Minnesota Valley Alfalfa Producers Gasification Project (MnVAP)—a new 75-megawatt alfalfa biomass-based power plant, and the Chariton Valley RC&D (Iowa) Switchgrass Cofiring Project—35-megawatts of biomass power cofired in an existing coal plant.

Reciprocating Engines

Budget: FY98-$0.3M, FY99-$0.4M, FY00-$0.4M

Description, Objectives, and Performers. Reciprocating engines are piston internal combustion engines (typically less than 20 megawatts) that are well known for their use in combined heat and power applications. Advantages of reciprocating engines are low capital cost, fuel flexibility, and easy maintenance and operation. These advantages will continue to make reciprocating engines the option of choice for onsite power production for the foreseeable future while more advanced technologies such as microturbines or fuel cells are under development. Primary markets include the chemicals, petroleum, natural gas, agriculture, metal refining and casting, and waste disposal industries. Reciprocating applications include cooling, power generation, backup power, compression, and transportation applications such as locomotive. The objective of this activity is to develop a

50 percent efficient natural gas fired reciprocating engine with emissions less than 5 parts per million NO_x (at 15 percent O_2).

R&D Challenges. Challenges include high emissions, low relative efficiency, ignition challenges, and the heavy use of lubricating oil.

R&D Activities. Begun in 1994, the Department's Advanced Reciprocating Gas Engine Technology Program is a key component to enhancing industrial power generation/cogeneration technologies through the development of ceramic technologies, advanced ignition systems, combustion development, sensors and controls, catalyst development, and oil reduction. Efforts include the development of a gas engine consortium with the Federal Energy Technology Center, Gas Research Institute, and Southwest Research Institute, and the testing of a ceramic engine valve.

Accomplishments. FY 1998 accomplishments will include the demonstration of a ceramic valve guide and the completion of the technology roadmap for reciprocating engines.

Technology Improvement of Operating Plants

Budget: FY98-$17.2M, FY99-$22.7M, FY00-$33.7M

Background

The existing fleet of operating plants include fossil, nuclear, and hydroelectric units, which make up over 98 percent of the power generated in the United States. The existing fossil fleet is aging, while the licenses for the fleet of operating nuclear plants will begin to expire in large numbers beginning in 2010. Environmental concerns created by hydroelectric plants, particularly with their impact on fish life, are increasing.

Despite expected energy efficiency measures, the projected growth in electricity demand coupled with expected plant retirements would require over 400,000 megawatts of new power capacity by 2020. It is critical, therefore, that the contribution of current fossil, nuclear, and hydroelectric powered plants be optimized. In order to do so, improved technology must be deployed in current power plants and a large percentage of existing nuclear power plants must achieve license renewal.

Linkage to CNES Goals and Objectives

The Department protects the Nation's investment in existing baseload power plants through the development of improved information management systems, sensors and controls, aging management, and regulatory compliance programs. This end supports:

- CNES Goal I, Objective 1 - Support competitive and efficient electric systems.

- CNES Goal V, Objective 1 - Promote development of open, competitive international energy markets, and facilitate the adoption of clean, safe, and efficient energy systems.

Program Description

DOE and industry are partners in the development of technologies to improve the operations of fossil energy plants, to provide for cost-effective compliance to new environmental regulations, to ensure acceptable levels of safety and reliability as these plants begin to age, and to improve efficiencies for their remaining life.

With respect to nuclear plants, the Department is conducting no R&D in FY 1998 or FY 1999, but has proposed for FY 2000 a new R&D initiative, the Nuclear Energy Plant Optimization (NEPO) program. The NEPO program will be 50-50 cost-shared with industry with a goal of ensuring that current nuclear plants can continue to deliver adequate and affordable energy supplies up to and beyond their initial 40-year license period. Technology improvements for both fossil and nuclear plants are targeted primarily in three areas: information management systems, aging effects in key components, and sensors and controls.

Regarding hydropower plants, the Department's work is focused on the development of improved hydropower turbines.

The continued operation of existing U.S. nuclear power plants avoids emission of over 620 million metric tones of carbon dioxide annually. Nuclear energy's continued role in electricity production is necessary so that our Nation can meet its global climate change commitment. In addition, the loss of nuclear power plants would not only have negative environmental impacts, but also threaten the reliability of the electric generation systems in several States.

Aging Effects in Key Components

Budget: FY98-$5.2M, FY99-$6.2M, FY00-$7.0M

Description, Objectives, and Performers. In coal-fired plants, technical issues related to plant aging include fouling, corrosion/erosion, fatigue, and creep life of components. The DOE and industry, with support from the National Laboratories and universities, are developing improved materials, developing fabrication techniques, and conducting research to gain a better understanding of the combustion science, corrosion, and transport mechanisms that impact the life of components. Although the research and development are aimed primarily at advanced coal power systems, these improvements would be applicable to components in existing plants and could be deployed at the time of scheduled maintenance and change out.

Degradation of materials in nuclear reactor plant structures and components caused by radiation, high temperatures, high pressure cyclic stresses, and a relatively corrosive environment costs utilities that operate light water reactors (LWRs) hundreds of millions of dollars each year. Not only does this degradation increase current operating costs significantly, but, if continued, material degradation could force the premature shutdown of

some plants before the end of their initial 40-year license term. Even for plants that can operate until the end of their current license period, material degradation issues will strongly affect license renewal decisions. Work in this area under the NEPO program will be conducted by a combination of universities, National Laboratories, and industry.

R&D Challenges. The challenges are to develop improved materials and detection devices to reduce costs associated with component aging in coal and nuclear power plants.

R&D Activities. Advanced austenitic alloys will be developed to address the issue of stable alloys in super heaters and reheaters of advanced coal combustion plants with 1300 ºF and 5000 psi steam conditions. Creep strengthening of promising alloys such as iron aluminites will be accomplished through oxide dispersion strengthening. A New generation of corrosion resistant high temperature alloys will be developed as hot components in advanced fossil energy combustion and conversions systems.

Research is planned in the NEPO program to understand, characterize, and manage service-induced degradation of steam generation tubes, reactor internals, primary system piping, electric cables, and safety-related structures. Technology development will be focused on timely detection, mitigation, and prevention of significant long-term effects of aging such as stress corrosion cracking, irradiation assisted stress corrosion cracking, reduction in fracture toughness due to neutron irradiation, thermal embrittlement of cast austenitic stainless steels, piping fatigue, and structure degradation. Research will involve laboratory tests, component inspections, and technology demonstrations.

Accomplishments. The development of the modified-9Chrome-molybdenum steel alloy by DOE and Oak Ridge National Laboratory over the last 20 years has been a resounding success for boiler tube applications in coal-fired power plants. The application of new alloys and ceramics or refractory materials can improve plant life and reduce the frequency of scheduled maintenance.

The NEPO program will be a new start in FY 2000, so the program has no accomplishments to date.

Nuclear Power Plants

Budget: FY98-$0.0M, FY99-$0.0M, FY00-$5.0M

Description, Objectives, and Performers. The United States is at a critical juncture with regard to the continued operation of its nuclear power plants. Faced with regulatory and economic uncertainties, some utilities already have closed nuclear facilities well before their license expiration dates. In the past 3 years, 6 reactors have closed. Licenses of U.S. nuclear power plants will begin to expire in large numbers in 2010, and licenses for 13 more plants will expire in 2014 alone. According to the Energy Information Administration's *Annual Energy Outlook 1999*, more than 80 percent of the nuclear power plants now operating in the United States will be retired in the first 2 decades of the 21st century if no action is taken.

The Nuclear Energy Plant Optimization (NEPO) program, part of the President's Climate Change Technology Initiative, is a new program proposed for the FY 2000 budget. The goal of NEPO is to cooperate with industry to develop advanced technologies that can help ensure that existing U.S. nuclear power plants continue to safely generate reliable and affordable electricity up to and beyond their initial 40-year license periods. Overall, NEPO aims to help increase the average capacity factor of existing nuclear power plants from 71 percent in 1997 to 85 percent by 2010.

R&D Challenges. NEPO will work with industry to develop and apply new technologies to improve plant economics, reliability, and availability. The program will work to resolve issues related to plant aging while maintaining a high level of safety.

The Department is well prepared to take on this challenge:

- NEPO will be guided by a chartered subcommittee of the Nuclear Energy Research Advisory Committee.
- The Department and the electric utility industry's Electric Power Research Institute have developed a Joint Strategic Research and Development Plan to prioritize and coordinate research and development needed over the next 7 to 10 years to sustain the operation of commercial nuclear power plants.
- The Department will continue to coordinate its program planning activities with the Nuclear Regulatory Commission to ensure that agency activities are not duplicated, but are complementary and performed in a cost-effective manner.

R&D Activities. Funds provided by the Department will be matched by industry in conducting peer-reviewed research and development to include: managing long-term effects of component aging, improving nuclear power plan capacity factors, and generation optimization through efficiency and productivity improvements. In FY 2000, NEPO will accomplish two major tasks that will contribute to improved nuclear power plant operating performance. The first is a laboratory benchmark of technology to reduce stress crack corrosion in nuclear plant components, and the second is demonstration of a prototypic method to non-destructively measure steam generator tube cracking. Both efforts are aimed to increase plant availability and capacity factors by reducing maintenance and outages.

Accomplishments. The NEPO program will be a new start in FY 2000, so the program has no accomplishments to date.

Regulatory Compliance

Budget: FY98-$11.2M, FY99-$13.3M, FY00-$14.7M

Description, Objectives, and Performers. Existing coal-fired power plants must comply with a number of existing EPA regulatory requirements. Additional requirements are being considered by the EPA, or have been proposed, but not promulgated. DOE research provides

three types of inputs into this process. First, DOE contributes to the science base of regulations by collecting data on emissions and environmental quality near power plants, and by drawing on its knowledge base of mitigation technologies to identify the likely cost and performance of pollution control technology. Second, DOE develops emission control technology for major categories of pollution, such as sulfur dioxide, nitrogen oxides, particulate matter, and toxic air pollutants. Finally, DOE evaluates pending regulations which can significantly impact the electric power sector, and offers recommendations to EPA during the OMB-refereed interagency review process. Current goals for continued research in this area include the development of sound scientific data on which environmental regulations can be based, and the development of lower cost emission control technology to address current and future regulatory mandates.

The Nation's nuclear power plants are aging and approaching the end of their licensed period of operation. Extension of these licenses is critical if this carbon-free source of electric power is to continue beyond 2020. In order to continue to realize the benefits from operation of the current fleet of nuclear power plants, a viable, demonstrated process for license renewal is required within the next few years. Unnecessary costs and uncertainties associated with license renewal need to be eliminated, and practical, economic solutions to generic technical issues have to be developed today and confirmed through longer term R&D activities. The Department, working with the National Laboratories, universities, the Electric Power Research Institute, participating utilities, and other industry organizations, will help resolve the generic issues associated with license renewal and demonstrate a viable license renewal process.

R&D Challenges. During the 2003-2010 period, make technologies available for existing coal power plants that will significantly lower the cost of meeting more stringent environmental regulations.

R&D Activities. DOE is continuing development of technologies to reduce NO_x emissions from fossil-fueled power plants, primarily to reduce the cost of known technologies. In addition, DOE is pursuing several technologies to reduce mercury emissions from power plants, and technologies which simultaneously reduce multiple pollutants including particulates ($PM_{2.5}$), mercury, and SO_2.

Research under the NEPO program will address the three primary needs that nuclear utilities have with respect to license renewal: (1) generic license renewal technical issues need to be satisfactorily resolved now so that the costs of license renewal will be known with more certainty; (2) the entire license renewal process has to be successfully demonstrated, removing the economic uncertainties associated with preparation, approval and operation under a renewed license for plant designs that are representative of current operating plants; and (3) the utilities need a license renewal process that is efficient and relies largely on existing programs so that the cost of a renewed license does not make license renewal uneconomic for smaller, single unit nuclear power plants.

Accomplishments. This effort has met with major successes. For example, due to DOE-

sponsored stack testing of power plants, it was no longer necessary to use inaccurate estimates of emissions of toxic air pollutants. The better quality data resulted in decisions that further pollution controls for most of these pollutants would not be productive or necessary, saving perhaps billions of dollars per year. Technologies for conventional air pollutants emitted from power plants, developed over the past 25 years through collaboration between DOE, EPA, industry, and academia, are in use both in the United States and internationally. Currently, about one-fourth of all U.S. coal-fired power plants have been equipped with control hardware for sulfur dioxide; nearly all units will have nitrogen oxide controls by December 1999. Research by DOE and the private sector has roughly halved the cost of meeting related environmental regulations. Continued research in this area is projected to have an additional payoff of about $7 billion per year, in reduced compliance costs, by 2010.

The NEPO program will be a new start in FY 2000, so the program has no accomplishments to date.

Hydropower Turbines

Budget: FY98-$0.7M, FY99-$3.3M, FY00-$7.0M

Description, Objectives, and Performers. Hydropower currently contributes a carbon-free 10 percent of the Nation's electricity. However, existing generation is declining, due to a combination of real and perceived environmental problems, regulatory complexity and pressures at the Federal and State level, and changes in economics as a result. Potential hydropower resources are often not being developed for similar reasons.

Current hydropower technology, while emission-free, can have undesirable environmental effects such as fish injury and mortality from passage through turbines, as well as detrimental changes in the quality and quantity of downstream water. The Department's hydropower R&D program is therefore focused on developing advanced hydropower turbine technology which will allow the Nation to maximize the use of its hydropower resources, while minimizing adverse environmental effects.

Program activity is principally applied R&D, managed by Federal personnel and performed by industry partners and National Laboratories. FY 1998 biological testing and analysis activities were performed entirely by National Laboratories, while the proof-of-concept testing initiated in 1999 will be conducted with an industry partner, and the detailed design and model/prototype construction and testing activities in the out-years will be conducted with competitively-selected industry and university partners. The program will continue to be supported with environmental and engineering research and analysis by National Laboratories.

R&D Challenges. The challenges are to demonstrate turbine technology capable of maintaining a dissolved oxygen level of 6 mg/liter by 2005 (ensuring compliance with Federal and State water quality standards), and technology capable of reducing turbine-induced fish mortality to 2 percent or less by 2006, compared to current levels of 30 percent

or greater.

R&D Activities. Experiments are currently under way to assess the effects of shear and turbulence on juvenile fish, with emphasis on juvenile salmonids and American shad. The fish will be exposed to levels of shear and turbulence that they might encounter during passage through a turbine and draft tube, and the biological effects will be quantified. The resulting data will be used to develop biological performance criteria for shear and turbulence for advanced hydropower turbine design.

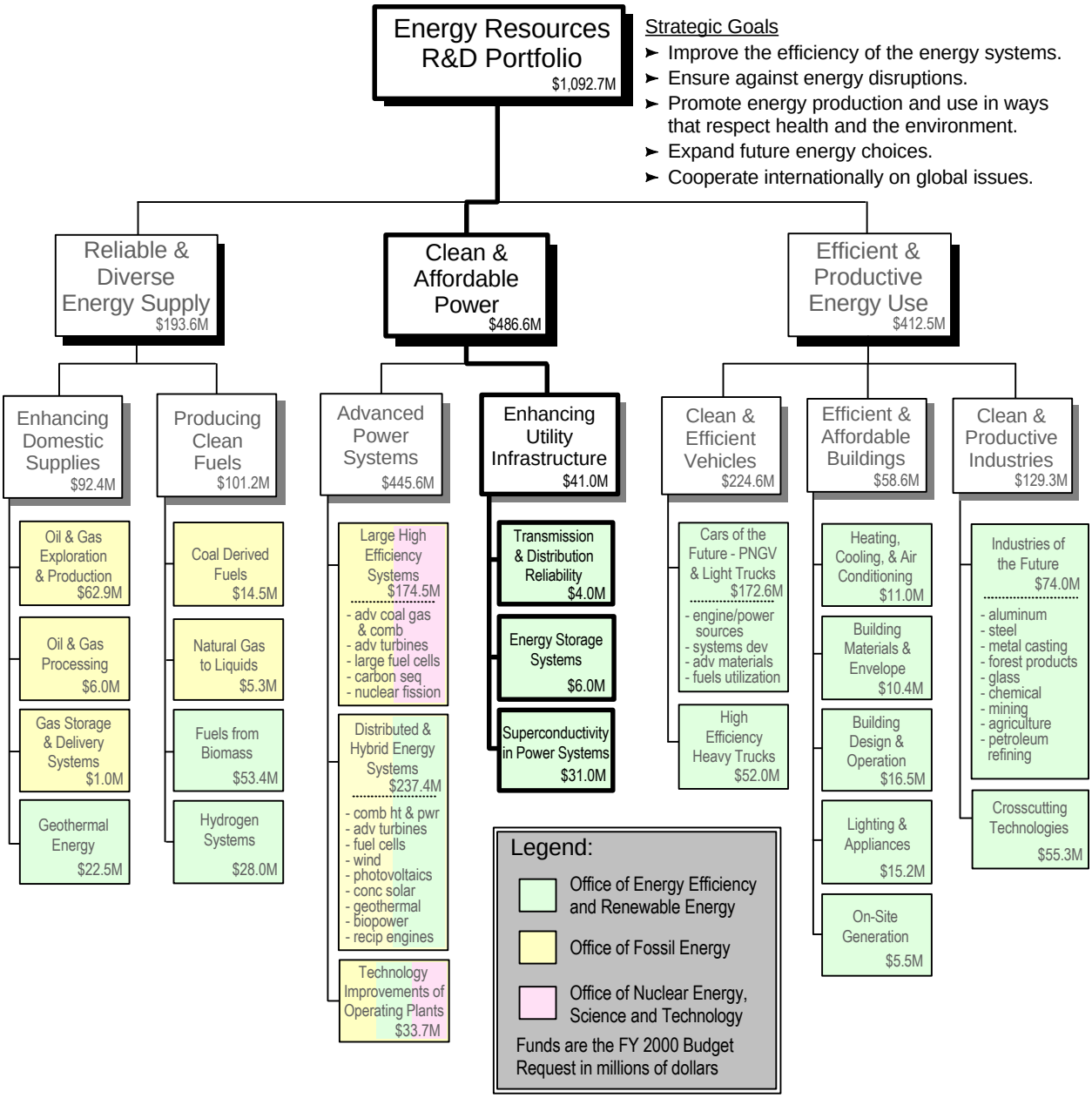
Proof-of-concept testing of a conceptual design completed in 1997 will be initiated in 1999 in order to verify predicted biological performance. Detailed design and model construction and testing activities will begin in 2000, followed by full-scale prototype testing at operating hydropower facilities.

Accomplishments. In 1995, the Department, in collaboration with industry and other Federal agencies, initiated research and development to provide a biological and engineering basis for advanced hydropower turbines. Conceptual designs completed in 1997 incorporate "fish-friendly" features which (among others) minimize the number of blade leading edges, minimize the gap between the blade and blade housing, and maximize the size of flow passages, with minimal penalty on turbine efficiency. The conceptual design phase also revealed gaps in the knowledge of fish response to physical stresses experienced in the turbine environment. Research is now underway to understand these stresses and effects and provide biological performance criteria for advanced turbine detailed design.

Summary Budget Table (000$)

Advanced Power Systems Research Areas	FY 1998 Appropriated	FY 1999 Appropriated	FY 2000 Request
Large High Efficiency Systems	**147,989**	**182,116**	**174,456**
Advanced Coal Gasification & Combustion Systems	61,256	68,526	60,873
- Advanced Coal Combustion	*21,039*	*21,500*	*10,010*
- Pressurized Fluidized Bed Combustion	*17,875*	*14,638*	*12,202*
- Integrated Gasification Combined Cycle	*22,342*	*32,388*	*38,661*
Advanced Gas Turbine Systems	45,000	44,500	41,808
Advanced Large-Scale Fuel Cell Power Systems	40,210	44,200	37,649
Carbon Sequestration	1,523	5,890	9,126
Nuclear Fission Systems	0	19,000	25,000
Distributed and Hybrid Systems	**188,344**	**212,750**	**237,409**
Combined Heat and Power Systems	1,000	1,500	2,000
Advanced Turbine Systems - Industrial and Micro	34,650	51,000	31,300
Distributed Fuel Cell Power Systems (EE)	6,400	0	0
Wind Energy Systems	32,128	33,200	45,600
Photovoltaic Systems	64,691	72,200	93,309
Concentrating Solar Power Technology	16,317	17,000	18,850
Geothermal Systems	5,119	6,000	7,000
Biopower Energy Systems	27,789	31,450	38,950
Reciprocating Engines	250	400	400
Technology Improvement of Operating Plants	**17,165**	**22,735**	**33,744**
Aging Effects in Key Components	5,225	6,225	7,000
Nuclear Power Plants	0	0	5,000
Regulatory Compliance	11,211	13,260	14,744
Hydropower Turbines	729	3,250	7,000
Total	**353,498**	**417,601**	**445,609**

Chapter 6
Enhancing Utility Infrastructure



Chapter 6

Enhancing Utility Infrastructure

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Overview

Definition of Focus Area

The electricity infrastructure not only delivers over $200 billion worth of electric service to U.S. customers every year, but also powers other critical national service infrastructures such as telecommunications, and water supply that are basic to the functioning of U.S. society. Electricity infrastructure consists principally of the transmission and distribution system, but also extends beyond the utility meter on the customer side, and into the power plant on the production side. Customer equipment such as large motors, power quality management, and load control technologies are included, as well as efficient mechanical equipment for generating electricity. As electric industry restructuring revolutionizes the way electric power is produced and consumed, the continued successful development of regional and interregional competitive markets depends upon the availability of a robust, efficient, reliable electricity infrastructure.

National Context and Drivers

The Nation's electricity infrastructure is being asked to operate in ways for which it was not designed at the same time that new demands for improved performance are being made on it.

- Competitive electric markets operate across far larger geographic areas than the traditional utility service territory. Regional or even national purchase contracts are possible, and national branding campaigns are already underway. Wide area competitive electric markets depend upon reliable transmission with capacity for large scale transfers across long distances.

- The North American Electric Reliability Council (NERC) in its Reliability Assessment (1998-2007) states: "Transmission systems are increasingly challenged to accommodate demands of evolving competitive electricity markets. Market driven changes in usage patterns, the number and complexity of transactions, and the need to deliver replacement power to capacity-deficient areas are causing new transmission limitations to appear in different and unexpected locations."

- Measures taken to limit transmission loading and preserve system reliability were a contributing factor leading to shortages of power on the Midwestern wholesale market during the summer of 1998, resulting in short-term prices in excess of $5.00/kWh.

- The cost of lost production and spoilage suffered by California industry alone for the August 10, 1996, western outage was in the range of $1-3 billion. A 20-minute outage at an integrated circuit fabrication plant can result in loss of a day's production worth $30 million. In our increasingly digital society, disturbances lasting less than a second can be almost as devastating as true outages. Business Week estimates the annual cost of momentary power disturbances to U.S. electric customers to be over $26 billion.

- According to the Energy Information Administration, network inefficiencies annually consume 3 quads of primary energy and produce 50 million metric tons of carbon equivalent in greenhouse gases. Adding in losses on the customer side of the utility meter in equipment such as motors and industrial transformers could double these figures.

- Construction and sometimes reconstruction of transmission facilities are routinely opposed by the public on a number of grounds, including environmental impacts, visual intrusion, property value effects, or concern over the health impacts of electromagnetic fields. Even relatively minor projects can consume years in the permitting process.

Linkage to CNES Goals and Objectives

The Enhanced electric infrastructure program directly supports the five CNES Goals:

- CNES Goal I, Objective 1 - Support competitive and efficient electric systems. *(by reducing network and end use losses with superconducting power equipment technologies)*

- CNES Goal II, Objective 2 - Ensure energy system reliability, flexibility, and emergency response capability. *(by developing active system controls, storage technologies, and advanced superconducting applications such as the superconducting fault current limiter)*

- CNES Goal III, Objective 2 - Accelerate the development and market adoption of environmentally friendly technologies. *(by development of control and storage technology that could help enable the integration of distributed and renewable resources)*

- CNES Goal IV, Objective 2 - Develop technologies that expand long-term energy options. *(by increasing system capacity, removing bottlenecks, and enabling distributed resource options)*

- CNES Goal V, Objective 1 - Promote development of open, competitive international energy markets, and facilitate the adoption of clean, safe, and efficient energy systems. *(by working with other countries through the International Energy Agency to promote communications and collaborations)*

The Enhanced Electric Infrastructure program has 3 objectives that support the strategic goals and will be achieved through partnerships with industry. The objectives are (1) provide technical and policy options to enable the operation of large scale, interregional, real time, competitive electricity markets while maintaining system reliability; (2) develop technologies that could reduce by one third the approximately 9 percent of electricity lost to network inefficiency and the associated greenhouse gases produced, by 2020, while system demand increases by 35 percent; and (3) provide network technology options that would allow the electric system to incorporate market-driven penetration by distributed resources, including renewable generation technologies, of up to 25 percent of system peak.

Uncertainties

Both technical and political uncertainties could affect the success of the electricity infrastructure program. Technical challenges (possible barriers to achieving either performance or cost goals) are described in the program planning documents and are summarized in the subsequent R&D challenges sections. Non-technical issues include uncertainty over the nature of incentives for construction of transmission in a competitive electric marketplace. Without assurance of investment recovery in the regulated transmission system, providers may limit involvement in new technologies. Also, with the reduced costs of electricity forecast to result from electric industry restructuring, high efficiency alone will not be sufficient to attract commercial interest to any technology. It is therefore the goal of all the technical components of the Enhancing Utility Infrastructure program to provide performance improvements that justify their cost independent of increased efficiency.

Investment Trends and Rationale

The FY 1998 DOE investment in the Enhancing Utility Infrastructure program was $43.3 million, an amount projected to decline to $40.0 million in FY 1999 and rise to $41.0 million in FY 2000. The changes in overall spending reflect the cessation of funding for the Electric and Magnetic Fields R&D program, and increased emphasis on power system and energy storage technologies.

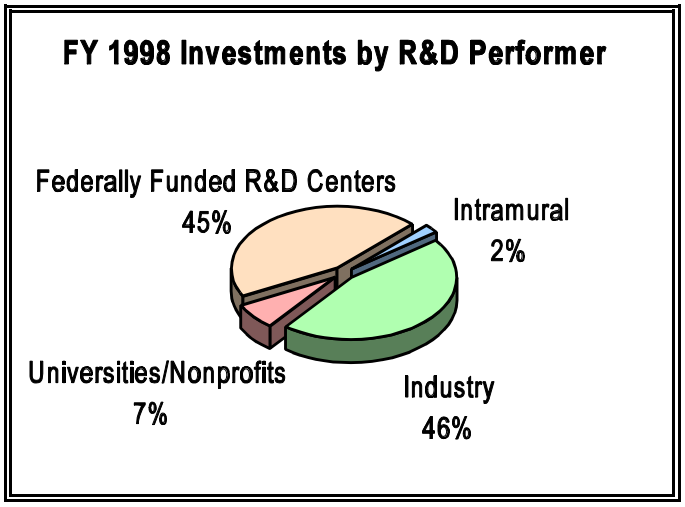
The Electric and Magnetic Fields R&D program studies the biological effects of electromagnetic fields produced by power lines. It was established as a 5-year program by the Energy Policy Act of 1992 and extended for 1 additional year (FY 1998) to permit completion by the National Institutes of Environmental Health Sciences (NIEHS) of a human health risk assessment report. No FY 1999 or FY 2000 funding has been requested. The FY 1998 funding level was $6.8 million.

The Energy Storage Systems program develops storage technologies that enhance power system capacity, power quality, and reliability. Funding for this effort will be augmented from $4.5 to $6.0 million in FY 1999 and FY 2000 to increase focus on advanced storage technologies such as flywheels and superconducting magnetic energy storage (SMES).

The Superconductivity in Power Systems program was charged in 1989 with fostering cooperative research and development with U.S. industry to capture the benefits of high-temperature superconductors for power applications. Six new cost-shared, multi-year partnerships designed to produce operating, pre-commercial power equipment using the best available long-length HTS wires will be underway in FY 1999. In addition, to help accelerate the development of wires based on 1996 National Laboratory discoveries, new cooperative research projects will also be initiated with industry. For these partnerships, funding increased in FY 1998 to the $31.6 million level, and funding will remain at a relatively constant level in FY 1999 and FY 2000 to enable continued progress at the laboratories and within the industry teams.

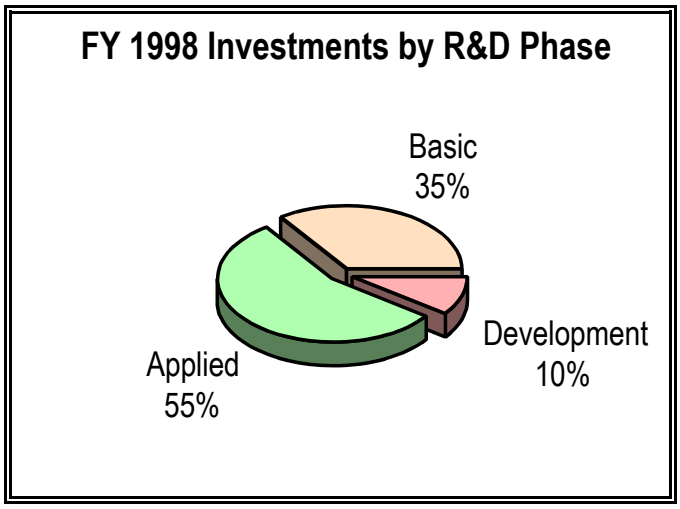
Finally, recognizing the need for a program element focused on the development of system technologies to enable competitive markets and maintain reliability in a restructured utility industry, a new initiative, the Transmission and Distribution Reliability program is proposed in FY 2000. This initiative, with initial funding of $4 million, will focus on development of technologies and policy options to enhance the reliability of the Nation's electric delivery system during the transition to competitive power markets.

The figure below indicates the division of FY 1998 funding between the principle performers of research tasks. Industrial firms account for 46 percent of the program's Federal funding, in line with the applied focus of the program and the desire to use partnerships with industry to hasten the development of necessary private manufacturing infrastructure for eventual commercialization. Pre-commercial pilot projects are selected by a competitive process which solicits cost-shared proposals from integrated teams including users, suppliers of materials and/or components, and systems integrators. This process minimizes public funding requirements, and determines the commitment of the marketplace to the technology. Such projects are cost shared with private sector funding at a level at least equivalent to the Federal share. After industry, the most significant performer is the complex of DOE National Laboratories, representing 45 percent of the Federal funding. The emphasis on National Laboratories reflects the need for sophisticated equipment, extensive facilities, concentrated expertise, and the sustained effort required. Though not counted as research performers, industry experts sitting on steering and oversight committees in all program areas provide important reality checks on the progress and future value of research activities.



The next figure shows the division of effort between basic, applied and development activities. In FY 1998, approximately 90 percent of research funding was devoted to basic or applied activities, reflecting the focus of major parts of the program on the long term development of technologies that enable fundamental shifts in concept for electric power equipment design. The relatively low level of development activities reflect the fact that the majority of the technologies under development have commercial horizons of 5 years or more. Development activities are

also heavily cost shared with the level of Federal funding rarely exceeding 30 percent of total project cost.



Federal Role

If the Nation is to continue to receive the highly reliable electric service it now enjoys, while simultaneously reaping the benefits of the competitive electric marketplace, increasing efficiency, and respecting environmental values, an adequate power delivery system is essential. The very existence of viable large scale markets for electricity depends on the ability to move power over long distances reliably with a minimum of restrictions. New technologies that increase the capability of existing systems while maintaining reliability, and that improve the public acceptability of new facilities are needed to maintain progress toward competitive markets in the electric industry.

At the same time that the need for new technology increases, the incentives for privately funded power delivery research in the restructured industry are being reduced. Delivery system research and development has traditionally been driven by the desire to take advantage of generation opportunities. Extra-high voltage transmission was developed in the 1930s to allow the exploitation of Western hydroelectric resources, for instance, and more recently, interconnection system management was perfected to permit generation reserve sharing. However, with the unbundling of the utility industry, generation and delivery system incentives have been separated. While profit opportunities in the competitive marketplace will likely spur generation innovation, the Secretary of Energy Advisory Board (SEAB) Task Force on Electric System Reliability notes that it is " concerned that reliability related R&D with long term focus may be underfunded by market forces." For instance:

- Independent System Operators (ISOs) have been established to take over from utilities the responsibility for reliable operation and planning of the transmission grid while providing equal access to all market players. ISOs have made great strides toward establishing operating arrangements that support competitive markets, but as a result of the transfer of

responsibilities, reliability research efforts funded directly by utilities have largely been terminated and not been replaced.

- Historically, the bulk of public interest R&D on system reliability was carried out by the Electric Power Research Institute (EPRI), a research association funded by the Nation's electric utilities. As a result of changes in the business climate of its members, EPRI's budget has declined by approximately 30 percent since 1994. More importantly, the majority of EPRI effort now focuses on near term, proprietary, commercially viable technology. Projects in longer term strategic research make up less than 15 percent of the total budget, and their public interest value is limited by the proprietary nature of the work.

- State agencies, such as California's Energy Commission (CEC) and the New York State Energy Research and Development Administration (NYSERDA), have funded electric delivery system research and may continue to do so. CEC, with the guidance of the California ISO, funds electric power system reliability research on topics of importance to California consumers. California supports State public benefit research funding through transition charges on electric power sales. Transition funding usually has a limited duration, a focus on immediate benefits as opposed to strategic research, and may not be available to ISO's that cover multiple States.

- Federal support of electric power delivery research is becoming an increasingly important factor. For instance, EPRI leverages its limited strategic research funding by partnering with Federal agencies, exemplified by the collaboration between EPRI and the Defense Advanced Research Projects Agency (DARPA) on advanced power electronics. Delivery system research performed by equipment vendors is also increasingly dependent on leveraging with EPRI or government funding. Agencies such as the Department of Defense (DOD) fund electric delivery system research, usually focused quite specifically on the particular agency's mission. DOD-funded work on utility system modeling, for instance, assesses the security of electric supply to military installations only.

DOE funding of electric infrastructure research is necessary to maintain support for activities that are in the national interest, and to sustain adequate levels of long term development necessary to provide the basis for future industry innovations until new market and/or regulatory structures are developed that provide the incentives for the private sector to assume this work. The realities of electric industry restructuring call for an increased DOE role in power delivery research with both near term goals to assure reliable systems during the transition to competitive markets, and long range goals to develop advanced, enabling technologies.

- Near Term(< 3 yrs.)
  Execution of the recommendations of the SEAB Task Force for evaluation of risk based analytical tools for reliability assessment, examination of alternatives to central station reactive power supply, and monitoring of private research on reliability technologies to assure that gaps do not develop.

- Mid-Term (3-7 yrs.)
  Development of system control technologies that enhance system stability and market performance, distributed resource integration strategies that enhance the flexibility of electric delivery, and transmission technologies for low cost mitigation of bottlenecks.

- Long Term (7-15 yrs.)
  Development of fundamental and enabling technologies for high capacity transmission.

Perhaps as important as defining what is appropriate for DOE infrastructure research is identifying what would not be included. For instance, the immense investment in existing electric delivery facilities means that the introduction of new technology will only slowly change the nature of electric infrastructure. As a consequence, maintenance of existing systems will have a significant effect on electric system reliability especially in the near- and mid-term. Maintenance, however, is the direct responsibility of transmission and distribution service providers and adequate regulatory incentives exist to ensure an appropriate focus on maintenance technology development. For this reason, maintenance technologies will not form a part of the DOE Enhancing Utility Infrastructure program.

Key Accomplishments

DOE began investigating synchronized measurements of power system quantities in 1991 through National Laboratory and university research performers. In 1995, the DOE co-sponsored Wide Area Measurement System (WAMS), an advanced satellite-synchronized monitoring system, entered field trials on the western U.S. power grid. During the western system outages of July and August, 1996, this prototype synchronized measurement system proved its worth by dramatically reducing the time needed to understand the causes and progression of the outages.

In recent years, a number of integrated, multi-benefit energy storage systems have been field tested in collaboration with private partners. For instance, a newly-developed R&D 100 Award winning mobile storage system, operating at a Georgia lithography plant, successfully corrected over 90 percent of the plant's power quality events in its first 6 months of operation. A 3.5 MW storage facility at a heavy metals recycling plant in California carries critical emission control loads in the event of a power outage to eliminate environmental noncompliance. A 1.4 MWh storage system recently installed in Alaska improves power quality in an isolated power system on an Indian reservation. The success of these state-of-the-art systems is helping to address power quality and reliability problems, enable increased use of renewable power generation, and increase the productivity and competitiveness of U.S. industry.

Superconductivity Partnership Initiative (SPI) partners hold world records for high temperature superconducting (HTS) equipment of all types, including fault current limiters, motors, transmission cables, and power transformers. Current-carrying capability of HTS wires has increased 10-fold since 1990, and wire-making costs have decreased substantially as companies gear up for larger orders. A record 6 license agreements have been signed over the last 24 months for industrial use of the innovative second-generation wire technology developed with

DOE support. In addition, 4 R&D 100 Awards have been received for Department-sponsored HTS technology.

Transmission and Distribution Reliability

Budget: FY98-$1.0M, FY99-$3.0M, FY00-$4.0M

Background

The existing electric power grid links nearly 3,500 U.S. utilities operating under the supervision of 150 control areas and 22 security coordinators in 3 functionally and physically independent regional interconnections. It has been characterized as an energy superhighway, though it actually bears more resemblance to the network of two-lane roads that existed before the interstate highway system was built. That system allowed travelers to go from town to town, but those who attempted long distance travel risked delays due to bottlenecks created by local traffic congestion and fragmented, piecemeal routing. Similarly, the electric network has bottlenecks that can become congested and restrict power transfers, while routing for long distance power sales is often fragmented by multiple jurisdictions.

The revolution in system operations resulting from competition has increased pressure to cut costs and to drive the power grids harder, to squeeze as much economic value out of them as possible. Some catastrophic outages in the western system during the summer of 1996 pointed out the fragility of the network in the face of high levels of interregional power transfers. At the same time, the presence of system bottlenecks and the fragmented, independent control structure has made it more difficult for competitive, reliable regional electricity markets and institutions to thrive, and have frustrated attempts to create a national commodity market in electricity.

A major new DOE/industry initiative, Transmission and Distribution Reliability, will address near- and mid-term objectives of the Electric Infrastructure program. It will support a National Laboratory/electric industry partnership to conduct electric system reliability research in the context of competitive markets. The program will collaborate with industrial and academic partners on initiating a research agenda to develop technologies that promote competitive markets, ensure system reliability (adequacy and security), increase network capacity for large scale, long distance power transfers, and promote integration of renewable generation, distributed resources, and storage. Technologies that can automatically control networks over large areas at high speed, and that coordinate operation of distributed resources, offer the potential for creating reliable, interregional markets. Improved high capacity transmission options, and efficient use of distributed resources can eliminate system bottlenecks at minimum cost. This projected five-year program will be reassessed each year to determine the need for Federal involvement depending on the nature and implementation needs of new regulations, and the impact of market forces.

Linkage to CNES Goals and Objectives

The research and development program in Transmission and Distribution Reliability would contribute to the following CNES goals and objectives:

- CNES Goal I, Objective 1 - Support competitive and efficient electric systems.
- CNES Goal II, Objective 2 - Ensure energy system reliability, flexibility, and emergency response capability.
- CNES Goal III, Objective 2 - Accelerate the development and market adoption of environmentally friendly technologies.
- CNES Goal IV, Objective 2 - Develop technologies that expand long-term energy options.

Program Description

The Transmission and Distribution Reliability program, in collaboration with the electric industry, proposes initiating a reliability research agenda that would consider technology development in three program areas: Real Time System Control, Power Electronics, and Distributed Resource Integration. Work in High Capacity Transmission Technologies is described below, but no funding is requested in FY 2000. Because the Transmission and Distribution Reliability program is a new initiative, proposed program areas are under review and are subject to change based on industry input on the appropriate content and priority of program elements. As a result, descriptions of program elements are of necessity more general than is the case for programs with a substantial portfolio of ongoing projects. In general, the program initiates definition, fundamental design, and simulation of technologies for monitoring and control concepts identified by the electric industry. These concepts would be supported by work in the broad technology areas outlined below.

Real Time System Control

Budget: FY98-$0.0M, FY99-$2.5M, FY00-$3.4M

Description, Objectives and Performers. Conventional power system control uses off-line models, planned generation dispatch, and anticipated load patterns to identify secure system configurations. With relatively few configurations to monitor, manual control suffices to maintain the system in the secure state. In a competitive marketplace, with a multiplicity of possible generation and load patterns in a constant state of flux, the number of possible system configurations and potential modeling scenarios could become unmanageably large. Agile competitive markets that permit large numbers of long distance power transactions suggest a transition from manual control and off-line modeling to automated, on-line strategies that manage the system in real time. The objective of the Real Time System Control program is to develop technologies leading to automated security assessment and control based upon real time system measurements. High speed communications and distributed intelligent controllers would adjust power electronic network management devices and actively suppress disturbances with only limited human supervision.

Since this program element seeks to introduce a completely new paradigm in system control, initial efforts are expected to rely heavily on university and National Laboratory performers. Work on wide area synchronized measurements, which can be used in existing systems to more accurately investigate disturbances, would be done in cost shared partnerships with electric industry operations partners.

R&D Challenges. Technical developments that are necessary for successful real time control include:

- Measurement systems that extract information that allow calculation of system states in real time.
- Cost effective communications that securely coordinate high speed data exchange under dynamic circumstances.
- Security assessment models that operate in a distributed environment at high speed using system measurement data.
- Autonomous reasoning agents that can carry out secure distributed decision making and issue appropriate control commands.

R&D Activities. Real Time System Control research addresses near- and mid-term research goals of the Electric Infrastructure program. Near term activities include those identified by the SEAB Task Force, while the development of measurement based, automated system controls supports mid-term objectives. The following R&D activity elements describe tools that might meet the challenges.

Wide area synchronized measurements: This program element would extend work on system measurements that proved so useful in the summer of 1996. The existing network of satellite-synchronized transient data recorders could provide measurements to be analyzed using advanced transient analysis methods, such as wavelet decomposition, and correlated with models of known events. This will both improve the value of existing models and identify signatures of disturbances that can be used to guide control actions.

On-line measurement-based security assessment models: This element examines modeling algorithms that operate in a distributed environment to both validate measurements and rapidly screen the hundreds of contingencies represented by the expanded geographic extent of interregional competitive markets.

Adaptive automated control: The advent of power electronics devices capable of actively managing system power flows at high speed creates the need for an automated control capable of coordinating the response of widely dispersed groups of such devices. This research examines development of autonomous reasoning agents that can monitor the state of the system in real time and issue control commands to suppress developing disturbances.

Development of risk assessment planning models for transmission networks: This program element seeks to carry out the SEAB Task Force near-term recommendation by pursuing development of transmission planning models that incorporate real-time control systems and power electronics, as well as extend the accuracy of modeling to larger portions of the grid. Because, in very large systems, conventional deterministic contingency analysis becomes inadequate, the mathematical basis for assessment of transmission capacity through systematic statistical evaluation of a large number of individually unlikely risks could be developed. In order to better define the behavior of very large systems nearing collapse, non-linear modeling methods might also be devised.

Accomplishments. In addition to the WAMS project discussed above, which proved its worth during the summer 1996 western system outages, important successes were achieved in initial steps toward automated system control. A neural network-based voltage controller was developed that could simultaneously optimize the voltage profile and minimize system losses using only a single system measurement point. A multi-path fiber optic communications network for distribution system use was developed that could automatically route messages through damaged and reconfigured networks. The system was licensed to a utility who is currently using it as part of a wide area distribution automation scheme.

Power Electronics

Budget: FY98-$0.0M, FY99-$0.0M, FY00-$0.4M

Description, Objectives and Performers. Inverter based power electronic equipment offers high speed dynamic response and has the ability to manage power quality independent of system conditions. High capacity power electronics can manage power flow on transmission systems, and, under real time control, actively suppress system disturbances.

The objective of the Power Electronics component of the program is to reduce by 50 percent the cost of high capacity power electronic inverters. Performers of the research would include National Laboratories to assess and develop converter designs, and with industrial partners, develop pilot scale systems. Fundamental research on materials would likely be performed by National Laboratories, universities, and other research organizations.

R&D Challenges. Barriers to achieving the desired 50 percent cost reduction goal are as follows:

- Need for high efficiency multi-level voltage source inverter topologies for cost effective application to high voltage operation.

- Need for low cost, controlled turnoff switching devices made from materials that offer higher standoff voltages and better thermal performance than silicon.

R&D Activities. Power Electronics program research activities support the mid-term integration of distributed resources as well as long-term goals for high capacity transmission technology and improved customer power quality options.

Development of high power, high efficiency, low cost inverter topologies: Currently available inverter designs suffer from a series of drawbacks resulting in high cost for high voltage, high power applications. These include the need for series connection of switches, low efficiency for part-load operation, and a requirement for bulky accessories such as filters or interphase transformers to control harmonic distortion. This research activity proposes partnerships between National Laboratories and industry to develop advanced multi-level inverter topologies that are simpler and more efficient than conventional equipment. Funding would be leveraged through cost share, with the bulk of Federal funding applied to improvements in modeling of inverter topologies and in testing of concepts.

Development of economical wide-bandgap semiconductor switching devices: Switching devices made of new semiconductor materials such as silicon carbide and thin-film diamond offer significant improvement in voltage withstand capability and thermal performance compared to conventional silicon-based devices. Anticipated research activity could focus on fabrication of silicon carbide and diamond films with sufficient purity dimensions to be used in development of doping and device fabrication strategies. A consortium of National Laboratories, manufacturers, and material suppliers could be formed to construct a prototype switching device using the new materials. Performance targets for the device might initially be 25kV and 2000 Amps.

Accomplishments. Bench scale prototypes of high efficiency multi-level inverters were developed in a National Laboratory in 1995. One of these designs is now being used in a commercial dynamic reactive power compensator to be marketed by an industrial partner. Important progress had also been made in developing an advanced process for fabricating high purity silicon carbide at rates up to 10 times that possible with conventional techniques.

Distributed Resource Integration

Budget: FY98-$0.0M, FY99-$0.5M, FY00-$0.2M

Description, Objectives and Performers. Distributed resources include a variety of energy production and storage devices, such as small turbines, building-integrated photovoltaics, fuel cells, and energy storage systems with capacities from 1 kW to 10 MW. Another distributed resource is direct control of customer load for system and local benefits. Deployment of such resources on distribution networks could both defer investment in distribution and/or transmission facilities and increase the reliability of power delivery by placing energy sources (either generation or storage) nearer to demand centers. By providing localized reactive power support, distributed resources could improve power quality. By supplementing conventional power delivery systems, distributed generation and storage could offer supply flexibility, including greater use of environmentally benign renewable energy.

The Program will support the integration of distributed resources into the larger power system. Proposed tasks could focus on resolution of control requirements, protection issues, and development of case studies to address barriers to implementation. Research will be performed initially through electric and natural gas industry partners. Eventually, competitively selected cost shared proposals by integrated teams of equipment suppliers,

distribution system owner/operators, and users would field test approaches. National Laboratory and/or university expertise would be utilized to develop the theoretical bases for modeling and control.

R&D Challenges. The principal barriers to large scale deployment of distributed resources are:

- Lack of modeling, monitoring and control methods for planning and operating systems composed of a large number of sources which must be dispatched in accordance with the economics of the larger marketplace, as well as with consideration for local system constraints.

- Lack of an economical approach to distribution system protection and reliability for distributed resources.

R&D Activities. Research activities under this program area will stretch the new paradigm even further, and require examination of technical, economic, institutional, safety, and other issues. More detailed guidance from stakeholders will be sought to completely define this program area. The following elements are proposed as initial areas for investigation in support of near- and mid-term goals. Distributed resources provide a significant alternative to central station reactive power support, and the evaluation of such options is a near-term recommendation of the SEAB Task Force. In the mid-term, distributed resources offer the potential for increased customer choice and improved reliability of the larger system.

Control and protection of distributed resources: This program element will develop high speed multi-variate constrained optimization strategies for dispatching and control of large numbers of distributed resources. It will also assess the availability of cost-effective communications strategies that can accurately and securely exchange data at high speed to economically control large numbers of dispersed resources. This project will also explore options for protective systems that can be retrofitted to existing distribution systems economically and reliably.

Feasibility case studies: A key recommendation of the SEAB Task Force was the evaluation of alternatives to central station reactive power support. Distributed resources offer the most important mechanism for supplying reactive support close to the load. Cooperative efforts with industry will develop case studies assessing the feasibility of distributed resources in specific electric and natural gas systems. Potential partners would include energy producers, distributors, and users such as commercial building owners as well as equipment manufacturers. Case studies would identify the operational characteristics, safety and reliability issues, control system requirements, economic benefits, and emissions performance, as well as supply of reactive power support by distributed generation or storage technologies in an application environment.

Electric and gas systems integration: Most distributed generation is expected to rely on natural gas, at least in the near term. Examples include microturbines and fuel cells, both of

which may be applied either as cogeneration in commercial buildings or as stand-alone electricity sources. Gas infrastructure and supply will therefore be as important as electric system issues in determining the success of the application. A series of regional studies will be conducted with industry to examine the interactions of the gas and electric delivery systems from the perspective of each as a component of an integrated energy system, with special emphasis on decreasing overall emissions and minimizing the cost of the delivered energy services to the customer.

Accomplishments. Two reports were prepared at the request of Congress that used case studies with actual utilities to determine the potential for integration of renewable resources into the electric power transmission and distribution system. The 1994 report assessed the cost and benefits of integrating wind and solar electric generation resources into the electric power distribution system. Wind resources were found to be cost effective for much of the Nation where good wind resources exist, but, for most of the Nation, economic benefits-to-cost ratios for solar applications were low due to their high capital cost. A 1995 report concludes that in general, about 50 megawatts of power from renewable energy sources can be integrated into most existing transmission systems to supply local loads without significant upgrades. However, large remote generation plants might require additional transmission lines that could be a significant part of the system cost of power from these sites.

High Capacity Transmission Technologies

Budget: FY98-$1.0M, FY99-$0.0M, FY00-$0.0M

Description, Objectives and Performers. The objective of the high capacity power transmission program is mid- and long-term development of technologies capable of moving two to six times more power over a given right of way than conventional transmission lines. Likely performers of the research agenda would be industrial partners engaged in the development of electric power equipment, supported by National Laboratories and universities. Eventually, competitively selected industrial teams would present cost-shared proposals for demonstration of promising approaches.

There is no funding for this work in FY 2000, and the option for Federal support beyond FY 2000 will be reassessed in later years.

R&D Challenges. Research challenges in the development of high capacity retrofit technologies include:

- Standard overhead transmission line conductor is a commodity product of proven performance. Alternatives must meet demanding mechanical requirements for decades, possess low resistance or be capable of operating at high temperatures, and be producible at a cost premium consistent with the value of their increased capability.

- Cost reduction of terminal equipment for integrating available line upgrade options into conventional three phase networks. Such options include conversion from three phase to six phase or to high voltage dc operation.

R&D Activities. *High capacity transmission conductors:* This research activity will evaluate, in concert with industry partners, the feasibility of various line conductor designs for high capacity operation, including development and testing of sample conductors.

Assessment transmission options: Options for low-cost line conversion could help alleviate system bottlenecks. Strategies for conversion of three- to six phase could be evaluated, as well as application of advanced inverters developed under the Power Electronics program.

Accomplishments. High phase order transmission systems use 6 or 12 phases over the transmission right-of-way instead of today's 3-phase systems, and can carry 2 and 4 times the power, respectively. In 1992, a 6-phase transmission line was energized as a tie line in a 3-phase system to analyze and demonstrate the performance of high phase order transmission on a utility electric grid. The 1997 final report on the demonstration documented the technical feasibility of high phase order transmission in terms of safety and system protection.

Energy Storage Systems

Budget: FY98-$3.8M, FY99-$4.5M, FY00-$6.0M

Background

Competitive electric market pricing structures will stimulate development of new strategies for controlling electricity use and cost. Sophistication of both high-tech and manufacturing industries makes power quality increasingly important to U.S. productivity. As transmission networks more frequently operate at their stability limits, network operators search for means to increase network capacity at minimum cost. Energy storage systems could effectively address all of these issues. In addition, energy storage increases the value of electricity generated by renewable resources by making it available at any time. Accordingly, the Energy Storage Systems (ESS) Program focuses on three technological thrust areas: reliability, renewables, and productivity.

The ESS Program addresses the multi-billion dollar national power quality problem by developing systems that enable electricity providers to correct instantaneously for power variations. Power quality systems can be installed at a customer site or at a utility substation near customers in need of guaranteed quality power. Larger versions can improve stability and selectively increase capacity of the transmission system.

Large electricity users and providers can achieve important productivity gains and increase competitiveness through distributed siting of storage systems. Often, a single storage system can

be used for multiple purposes and result in substantial cost savings and improved operational efficiency through avoidance of monthly peak demand charges, power quality-induced equipment failure, and peak period overload of utility equipment.

The President's Committee of Advisors on Science and Technology (PCAST) stated that "if intermittent renewable energy technologies are to make very large contributions to electricity supplies in the longer term. .... technologies are needed that would make it possible to store energy for many hours at attractive costs." The ESS Program works with renewable energy system suppliers to optimize storage systems integrated with Photovoltaics (PV) and wind generators.

Linkage to CNES Goals and Objectives

The Energy Storage Systems program supports the following CNES goals and objectives:

- CNES Goal III, Objective 2 - Accelerate the development and market adoption of environmentally friendly technologies.

- CNES Goal V, Objective 1 - Promote development of open, competitive international energy markets, and facilitate the adoption of clean, safe, and efficient energy systems. *(by working with other countries through the International Energy Agency to promote communications and collaborations)*

Focused on the three thrust areas of reliability, renewables and productivity, the ESS Program will continue to team with industry in highly-leveraged agreements to develop improved, integrated, cost-effective storage systems with multiple benefits for electricity providers and users at scales ranging from small remote installations to large industrial facilities.

Application of energy storage technologies will be driven by reduced costs and improved flexibility as the Program develops systems that meet the cost goal of $700 per kW and the energy density goal of 5 kWh per sq. ft. of system footprint while meeting customer needs in the rapidly changing electricity marketplace.

Program Description

Research and development in the ESS Program is organized around three objectives: (1) integration—supporting the near- and mid-term development of complete energy storage systems for diverse applications that make use of modularity, factory integration, and transportability for cost reduction; (2) components—supporting the design, research, and long-term development of batteries, superconducting magnetic energy storage systems (SMES), flywheels, and other advanced energy storage devices along with improved, multi-use power electronics, controls and communications components; and (3) analysis—improving the understanding of application requirements, assisting U.S. industry in identifying high-value energy storage sites through modeling and engineering assessment, and identifying national benefits of storage in a restructured utility industry.

Integration

Budget: FY98-$2.0M, FY99-$2.2M, FY00-$3.0M

Description, Objectives, and Performers. By viewing a storage system as a single product, rather than a custom designed project composed of parts procured from various sources, major savings in construction cost and improvements in performance can be achieved. Benefits include cost savings of 30 to 50 percent through reduction of custom engineering and on-site installation labor, as well as reduced start up times. Standardized components, designed to optimize system performance, offer the potential for further cost reduction and longer life. Integrated hybrid systems, consisting of a renewable generator (PV or wind), storage system, and a diesel generator or gas turbine, offer increased flexibility to meet energy supply needs. Development of multiple integrated systems in a coordinated effort allows the program to leverage private and public resources through coordination of parallel R&D activities.

R&D Challenges. Experience has proven that good integration leads to optimal performance at the lowest cost compared to off the shelf or one-of-a-kind engineered designs. The major obstacle to greater levels of integration is the cost associated with low production volumes. Without further support for high-cost, high-risk prototypes and demonstrations, it will be impossible to generate the wide-spread interest and support necessary to optimize designs at a low enough cost to reap reliability and productivity benefits.

R&D Activities. *Transportable systems:* A mobile version of the award winning PQ2000 factory integrated battery-based power quality system is being developed. Mobile PQ2000 is a 2-MW/15-second system developed in collaboration with Omnion Power Engineering Co. that is currently being tested by Virginia Electric Power Company and at 3 other sites over the next 2 years.

Advanced battery systems: The ESS Program continues to work on development of zinc-bromine battery systems, which have 4 times the energy density of lead acid batteries. The Advanced Battery Energy Storage System (ABESS) is a high-risk, 3-year, 50-50 cost-shared project with ZBB to develop a transportable, modular zinc/bromine battery storage system, scheduled to begin a multi-year test at a utility or customer site by 2000.

Renewable generation and storage: The ESS Program works with the photovoltaic and wind industries to improve the compatibility and reliability of hybrid renewable generation and storage (RGS) systems while lowering system cost and maintenance requirements. In 1998, three studies commenced that will define the present and future needs of users of RGS systems, determine their application requirements, and help guide development of integrated system components.

Accomplishments. The PQ2000 system developed by the ESS Program and its industrial partners earned an R&D 100 Award as the first installation of a complete integrated power quality protection system with master control by the electric utility. The system meets the power quality needs of one of Oglethorpe Power Corporation's industrial customers, a

lithography plant in Homerville, GA. During the first six months of operation, the system corrected over 90 percent of the plant's power quality events.

A factory integrated 1.4 MWh, multiple benefit storage system by was developed by ESS and an industrial partner. Installed on the Annette Island Reserve, in southeast Alaska, the system absorbs the large load spikes caused by the local lumber mill. By displacing the output of a 3.3 MW diesel engine formerly operated at light load to control power swings, it reduced diesel fuel use by 180,000 gallons and cost by $310,000 in the first 8 months of operation. It greatly improved power quality for the island residents, the 1,700-member Tsimpshean Native American Indian tribe.

A 3.5 MWh storage system co-developed by the ESS Program and GNB provides multiple benefits at a lead-acid battery recycling plant in Vernon, California. The system's primary benefit is its ability to carry critical loads during power outages, ensuring that pollution control equipment remains operational. Additional benefits include peak-shaving and uninterruptible power.

Components

Budget: FY98-$1.4M, FY99-$1.4M, FY00-$2.1M

Description, Objectives, and Performers. The ESS Program works with industry partners to carry out fundamental research on advanced storage elements and power conversion equipment components that cost less, have higher performance, are smaller, and are better integrated with the other parts of the system. A great deal of the evaluation of prototype energy storage components is conducted in-house at Sandia National Laboratories. The Program also draws on the expertise and resources of a diverse group of partners including representatives from industry and an industry research association, a utility trade association, two engineering and consulting firms, and several university groups.

R&D Challenges. Materials and processing limit the life, and hence, the cost effectiveness of advanced storage equipment. For example, work must be done to identify electrochemical failure mechanisms in valve regulated lead acid (VRLA) batteries and find ways to delay failure. Key issues include loss of cell seal integrity, loss of conductivity due to changes in separator mechanical characteristics, and sensitivity to temperature extremes. Similarly, successful commercialization of advanced zinc bromine batteries requires improvements in the microporous polyethylene separator, increases in the rate capability of the bromine electrode activation layer, and in the robustness of the electrochemical cell stack.

Research is also needed on SMES, flywheels and power conversion systems. SMES requires low cost materials and cryogenics. Flywheels need high strength composite rotor materials and improved bearings. Power conversion systems require development of advanced, high power, low cost semiconductor switches, hybrid power controller software, and advanced converters.

R&D Activities. *VRLA batteries:* Low-maintenance, spill-proof, and more compact than conventional batteries, VRLA batteries have been commercially available for more than ten years. The ESS Program, using the extensive field data now available, will build on past work with industrial partners by collaborating on a VRLA reliability improvement project with the International Lead Zinc Research Organization. Studies will be conducted to define opportunities in existing VRLA designs for further improvement under typical utility battery operating conditions and use modes. Similar projects are in the planning stages for SMES and flywheels.

Power conversion systems (PCS): The ESS Program is teaming with power electronics firms, universities, and energy research institutions to develop power controller electronics and software for use in several advanced storage applications such as remote backup systems. The ESS Program supports testing at the Arizona Public Service Solar Test and Research Center of a state-of-the-art PV/battery hybrid controller developed by Trace Technologies. Results from the characterization testing will be used to develop operation strategies for village hybrid systems. ESS is also participating with the International Lead Zinc Association in a cost shared effort to develop testing requirements for remote area power systems. This project will greatly improve the reliability of modular renewable energy systems not tied to electric grids.

Accomplishments. Recently, the ESS Program completed development of a prototype 33 kW, 3-hour prototype zinc/bromine battery that exhibits four times the energy density of current lead acid batteries. This highly successful prototype is the basis for the ESS Program's ongoing ABESS project that will result in the development and demonstration of a transportable 300-kW/2-hour integrated system designed to showcase the potential of zinc bromine technology for peak shaving and other customer-side applications.

In 1998, the ESS Program completed an assessment of system configurations, cost, and standards for PCS use in the utility industry with recommendations for future R&D activities. This report will form the basis of future R&D work on a single PCS topology to serve the needs of batteries, flywheels, SMES, and renewable generation sources.

Analysis

Budget: FY98-$0.5M, FY99-$0.9M, FY00-$0.9M

Description, Objectives, and Performers. Projects conducted within the analysis program area are designed to improve the understanding of application requirements and assist industry in identifying high-value energy storage sites using models and engineering assessment tools. This work often forms the basis for R&D projects undertaken by the ESS Program and/or its partners.

R&D Challenges. Currently, the greatest source of uncertainty in the development of energy storage and other distributed resources is the future of the electricity industry. The emergence of a competitive marketplace for electricity will bring about many technological changes in the way electricity is generated, delivered and sold. A restructured electricity

marketplace is expected to lead to many opportunities for increased efficiency, resource utilization, flexibility and reliability through energy storage as utilities begin to tap the potential benefits of distributed resources. Understanding how the dynamics of this new marketplace will drive end user needs and quantifying the many potential benefits of energy storage are the major challenges confronting the energy storage community.

R&D Activities. *Hybrid system handbook:* In order for a hybrid system to demonstrate optimal performance at the lowest cost, components must be integrated in a configuration that meets the specific application requirements of that particular system. Requirements for a village system, for instance, are quite different than for a telecommunications application. In order to address this problem, the ESS Program is developing a handbook on energy storage for renewable applications. The handbook will provide technical guidelines to members of the renewable generation and storage communities for improved integration of energy storage with renewables. The completed handbook will include the results of a technology characterization testing existing renewable/storage hybrid systems.

Energy storage in a restructured environment: As electric industry restructuring proceeds, it will become increasingly important that electricity providers and related service companies understand the role energy storage can play in maintaining the reliability of the electricity infrastructure. The ESS Program will conduct a quantitative analysis of the impact of energy storage on reliability. This study will help determine the direction of development of integrated energy storage systems for reliability applications.

Non-grid applications: The need for distributed energy storage technology is particularly acute in remote areas not connected to utility grids. Congress highlighted this need in 1998 by requesting that DOE develop and demonstrate cost competitive, modular renewable energy technologies to "focus near-term research on the development of reliable systems for remote applications in occasionally hostile climates." The ESS Program is currently working with the International Lead and Zinc Research Organization on a feasibility study of hybrid photovoltaic/storage systems for use in remote villages in Peru. Results from this study will be used to assist in conducting a series of demonstration projects showcasing this technology.

Accomplishments. Recent progress in the development of both superconducting magnetic energy storage (SMES) and flywheel energy storage has made these technologies increasingly viable energy storage options in the United States. In order to further development of these advanced storage technologies, the ESS Program completed an analytical study that identifies areas of analysis and R&D necessary to advance SMES and flywheel technologies. Included in the study is a modeling tool that links cost and performance of SMES and flywheels over time and an updated definition of application requirements and potential markets.

A recent survey by Arizona State University supported by ESS and the Photovoltaic Program quantified sales of photovoltaic batteries domestically and world-wide in 1995, identifying market weaknesses and information needs. The information contained in the report has helped to improve the information exchange between the various industry groups involved in the development and manufacturing of PV/storage hybrid systems.

Superconductivity in Power Systems

Budget: FY98-$31.6M, FY99-$32.5M, FY00-$31.0M

Background

High temperature superconductivity (HTS) or the ability of some ceramic materials to become lossless carriers of electricity when cooled to the temperature of liquid nitrogen, was discovered in 1986. Materials that become superconducting at the much lower temperature of liquid helium are used in medical applications, but costs of refrigeration have made them unattractive for power equipment applications. HTS not only presents opportunities for constructing compact, high efficiency, high capacity power equipment but also opens possibilities for development of equipment, such as fault current limiters, that offer entirely new capabilities. HTS, in fact, has the potential to impact the production, delivery, and use of electricity as profoundly as fiber optics has impacted communications. Superconducting wires, with 100 times the current carrying capacity of copper wires, will result in transmission cables with five times the capacity of conventional cables. HTS motors, generators, and transformers will have half the energy losses and be half the size and weight of conventional systems. Superconductivity in Power Systems constitutes the principal long-term development effort for the Enhancing Utility Infrastructure program.

HTS offers many national benefits. HTS cables offer an alternative to new rights of way for overhead lines which are difficult to obtain, without the oil spill exposure that limits interest in conventional oil filled cables. Retrofitting HTS cable into existing ducts could increase transmission capacity of rights of way by up to five times with no environmental risks.

HTS motors and generators pack nearly three times the power into the same space as conventional machines and coordinate well with power electronic inverters to provide a double benefit of controllability as well as increased power density.

HTS fault current limiters ameliorate concern for added short-circuit current caused by system growth. Limiting fault currents to lower levels also enhances system stability, reliability, and safety, and improves power quality. The ability to efficiently control currents also offers new operating possibilities for power flow control.

HTS transformers offer utilities oil-free, fire-proof performance and the absence of a thermal aging mechanism, as well as high efficiency. HTS transformers can also be operated for long periods at up to double their rated capacity without loss of life, a capability not available in conventional units. Finally, the HTS transformer will likely have low-impedance, making it easier for utilities to maintain output voltage levels over a wide range of power levels, and they will incorporate fault current-limiting winding concepts to provide additional benefits. HTS transformers truly represent the first major hardware innovation in this mature industry since the development of oriented core steel.

HTS bearings for flywheel systems could be attractive to tomorrow’s utilities and large industrial

customers seeking diurnal storage efficiencies approaching 90 percent.

HTS magnetic separator technology is important both for the chemical industry and for hazardous waste processing.

The annual world market for HTS power technologies is estimated to be at least $30 billion by 2020. DOE leads the world in superconductor technology development and with the SPI projects described below, DOE and U.S. industry are partnered to move a step closer to being the world leader in sales.

Linkage to CNES Goals and Objectives

The Superconductivity in Power Systems program supports the following CNES goal and objective:

- CNES Goal IV, Objective 2 - Develop technologies that expand long-term energy options.

In 1988, DOE mobilized the resources of U.S. industry, National Laboratories and universities to accomplish two major technological goals: (1) solve the difficult problem of manufacturing electrical wires from the family of brittle ceramic superconducting materials discovered in 1986, and (2) develop practical equipment designs for efficient, pre-commercial electric equipment such as motors, transmission cables, generators, transformers, and current limiters that use these wires.

To accomplish these program objectives, specific goals must be met for superconducting wire, as well as for pre-commercial prototypes of power equipment using the wires. The wire goal is to achieve an operating capacity of 1000 amperes per square millimeter of wire cross-sectional area at a cost of 1 cent per ampere-meter. Goals for equipment are specific to individual technologies, but are met through operational tests of prototypes that prove the technology is ready to provide the specified performance advantages. Generally, devices will have only half the energy losses of conventional alternatives. In addition, it is the goal of the Superconductivity Program that, by 2004, U.S. industry will begin supplying the international electric power sector with the first HTS transmission cables, transformers, motors, and current controllers.

Program goals are achieved through a national effort that partners Federal and State agencies, universities, National Laboratories, and private industry in cost shared, industry led consortia focused on producing marketable products. HTS equipment will achieve market penetration not only based on efficiency, but also on superior performance, small size, and environmental benefits when compared with conventional equipment.

Program Description

The Superconductivity Power Systems program marries the entrepreneurial drive of high-tech companies with the vast technological resources of DOE's National Laboratories to meet the complex research challenge of long-term development of HTS technology for electric power. The HTS program contains three program elements: The Superconductivity Partnership Initiative (SPI), The Second Generation Wire Initiative, and Strategic Research.

The Superconductivity Partnership Initiative (SPI)

Budget: FY98-$14.0M, FY99-$14.5M, FY00-$14.0M

Description, Objectives, and Performers. The SPI competitively solicits aggressive industry-led projects to design and operate pre-commercial HTS electric power equipment. SPI projects include transformers, motors, cables, current limiters, flywheel energy storage, generators, and magnetic separation systems. A unique SPI feature is that each project must be carried out by a vertically integrated team, typically including an electric utility, a system manufacturer and a superconducting wire supplier, and National Laboratories. This vertical integration has proven to be a powerful way to quickly develop mature end user systems while leveraging resources.

The SPI program promotes cost-shared development by manufacturers of equipment design technologies necessary to take commercial advantage of advances in HTS wire technology. By the end of the program, it is expected that SPI teams will have built and operated refined HTS versions of all of the major power equipment technologies that could represent a significant benefit for the electric utility infrastructure.

A total of 9 SPI projects either are or will soon be under way. Performance teams include 17 manufacturers, 6 utilities, 2 utility research associations, 5 National Laboratories, and a State research organization. Projects cover the entire program range including a 15kV current limiter, a 5000 Hp motor, 2 power transformers and 2 cables, as well as a magnetic separator and a flywheel energy storage system.

R&D Challenges. SPI teams must resolve a number of key technical challenges including:

- Conductor availability, performance, configuration, and cost.
- Electrical and thermal insulation performance and durability.
- Interface between the ambient environment (room temperature, atmospheric pressure) and the cryogenic temperature, high-pressure environment.
- Cooling system research, design, reliability, and performance.

R&D Activities. *Cable projects:* Activities are underway to determine the optimum configuration for wrapping the HTS tapes to assure the lowest possible alternating current (ac) losses. Such losses can add substantially to the heat load of the cryogenic system required to keep the cable cold. In addition, two candidate dielectric systems are being evaluated by different teams. One system, based on room temperature, extruded dielectric material, takes advantage of the large base of conventional cable experience, while another, based on a novel cryogenic temperature dielectric, offers potential for reduced ac losses.

The characterization and measurement of ac losses is complex for cables and the SPI cable teams are developing two alternative methods for these measurements. Either a transport or a calorimetric method is used and the teams have made good progress toward developing a detailed understanding of the ac loss phenomenon.

Low cost, reliable cryogenic systems to keep the cable cold are of crucial importance to the success of HTS cable technology and both teams are also evaluating options for increasing the cable length between cooling stations.

Terminations and splices are a special topic of research in the cable SPI projects. Most failures in today's conventional cables occur in either the terminations or the splices. Electrical, thermal, and mechanical stresses on materials must be balanced.

Transformer projects: Research activities in the transformer SPI projects include the development of appropriate conductor geometries, dielectrics, and the cooling system. Investigation of low-loss conductor and winding configurations are essential as ac losses, like thermal losses, must be carried away by the cryogenic refrigeration system. The core design and core cooling systems are active areas of research.

HTS motor project: The SPI motor team is focusing on innovative fluid transfer coupling technology for entry and exit of cryogen at the motor/refrigerator interface. They are also developing the wire and motor coil technology necessary for cost-effective, 3-Tesla operation at temperatures near 30°K. Another active area of research is the concept of cryocooling in a rotating reference frame. Sophisticated high power test beds have also been developed for full scale characterization of HTS motor performance.

Accomplishments. World record performances were achieved by SPI teams. The 200-horsepower motor exceeded the design goal by 50 percent during tests in 1997, and the world's first superconducting current limiter met its technical goals during testing at a utility substation in FY 1998. The next version will feature the world's largest HTS coil and operate long-term on a utility grid, a first for the SPI program. The world's largest HTS transformer commenced testing in FY 1998, and the world's longest HTS cable completed its tests successfully.

The Second Generation Wire Initiative

Budget: FY98-$8.0M, FY99-$8.0M, FY00-$8.0M

Description, Objectives, and Performers. The Second Generation Wire Initiative is exploiting 1996 research breakthroughs at Los Alamos and Oak Ridge National Laboratories that promise unprecedented current-carrying capacity in high-temperature superconducting wires. These breakthroughs, which made headlines worldwide, will allow long wire lengths to behave as a single crystal, thus eliminating internal barriers to current flow that may limit use of wires now being manufactured. The interest in second generation wires for energy applications is enormous. A total of nine high-performance project teams involving six national labs and nine industrial partners are at work to further develop the wire technology.

R&D Challenges. Moderate lengths (1 to 10 meters) of coated conductors are needed for use in coils and device prototypes during FY 1999-2000. The performance goals for such moderate length wires are: critical current (I_c)= 50 amps and engineering current density (J_e) =20,000 amps per sq. centimeter. R&D challenges include scale-up of promising short sample results to produce substrates, verification of superconductor film growth by a number of industrially scalable techniques, demonstration of adequate texture and epitaxy over length, and development of simpler, and more robust buffer layer systems.

R&D Activities. *Substrate development:* This project investigates two methods of making buffered, textured metallic substrates, ion-beam assisted deposition ("IBAD"), and rolling-assisted, biaxially-textured substrates ("RABiTS"), both developed by National Laboratories. An industrial partner is developing electron-beam evaporation for depositing the superconducting layer upon either of two substrates. Concerns are process conditions for buffer layer deposition, adequate texture in the rolled nickel metal foil, and thickness of the superconducting layer while maintaining acceptable levels of critical current density.

Buffer layer development: A team led by an industrial partner is developing a non-vacuum buffer layer technology for deformation textured metal substrates. Such a structure could offer cost and performance advantages over conventional vacuum deposition of these layers. The work includes measurement of buffer layer texture, deposition of buffers and superconductor, and electrical characterization.

Alternative superconductors: A team of National Laboratories and industrial partners have also been working together to scale up yttrium-based (YBCO) coated conductors. Tasks include nonmagnetic deformation textured substrate development, substrate preparation, buffer layer development, IBAD sample testing, investigation of strain tolerance, statistical analysis of defects, environmental stability, microstructural studies, and measurements of critical current and critical current density. Near-term goals are a critical current density of 1 MA/cm^2 at 77^oK on a nonmagnetic, deformation textured substrate 1 meter long. The team has the ultimate goal of demonstrating the commercial feasibility of the coated conductor technology.

Accomplishments. Initial FY 1998 scale-up goals were met for wire processing breakthroughs. The first 2-cm lengths of coated conductor were produced in FY 1998 using an *ex-situ* deposition process.

Strategic Research

Budget: FY98-$9.6M, FY99-$10.0M, FY00-$9.0M

Description, Objectives, and Performers. The Strategic Research R&D area focuses on developing underlying knowledge needed for the success of industry-led projects. The Second Generation Wire Initiative evolved from five years of strategic research that achieved world record performance in short wire samples. In addition, research and analysis will be conducted on issues associated with integration of superconducting systems into an increasingly competitive and restructured industry framework. Strategic Research performers include four DOE National Laboratories, two Department of Commerce labs, seven universities, and two industrial partners.

R&D Challenges. Strategic research challenges include development of powder-in-tube wire that meets cost and performance needs of pre-commercial prototype developers, novel processing to increase pinning and connectivity to raise field and temperature operating windows for the HTS wire. Coils must be fashioned from the first lengths of second-generation wire, and the properties of these coils must be measured to provide input to system developers. An understanding of HTS material phase assemblage is critical to developing cost-effective HTS wire processes.

R&D Activities. Strategic research activities include bismuth/oxide (BSCCO) wire development research by two teams. The research includes development of novel means to produce high critical current density HTS tapes, including the new "coated BSCCO" approach that already has demonstrated over 40,000 A/cm^2 in short samples. The group studies the effects of processing conditions on the critical current and microstructure of the resultant wires.

Efforts to scale up the short sample BSCCO results to long lengths are conducted under several CRADAs. This research enables U.S. industry to use the National Laboratories' special facilities and staff resources to solve key technical issues of filament uniformity, grain growth (bridging) between filaments, ac conductor losses, and others.

Research is also conducted by the laboratories and several universities to exploit the higher critical temperatures of the thallium and mercury compounds. National Laboratories and universities, for example, are working to deposit and characterize thallium HTS on RABiTS. Results of the order 0.5 MA/cm^2 have been obtained on short samples.

Phase diagram research enables the National Laboratories and industry to understand the physical and chemical properties of HTS compounds. This research is cost-shared with the Department of Commerce. In another cost-shared effort, the mechanical properties of the

new laboratory-developed coated conductors are being examined, with plans underway to measure the private industry materials, as well, starting with the BSCCO tapes.

Strategic research also includes the fabrication and testing of small research magnets using the BSCCO compound (now) and the coated conductors when lengths of material become available. The understanding of normal zone propagation and quench characteristics of the new coated conductor in coil form will be needed if these wires are to be useful in electrical devices.

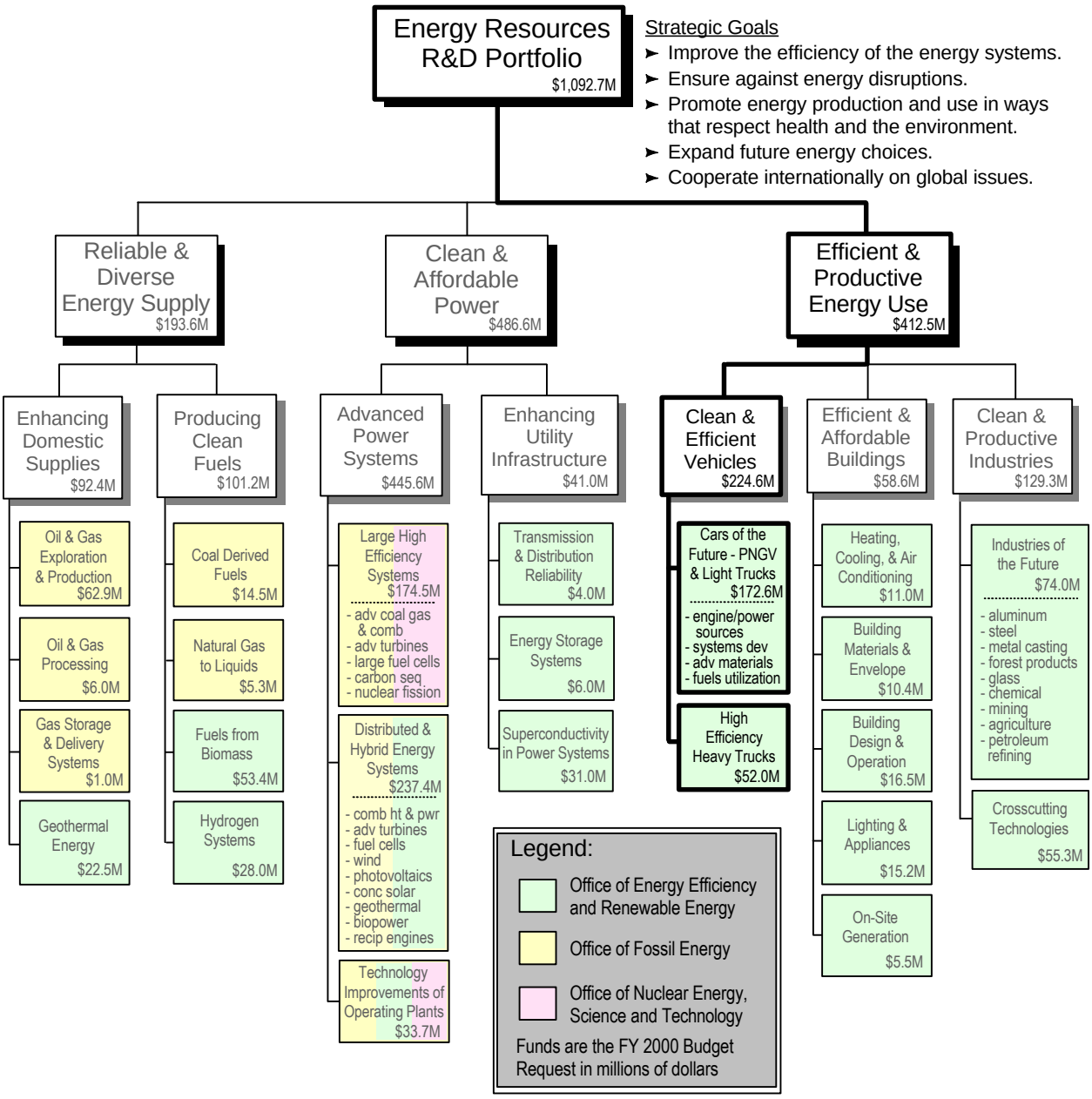
University research explores the physics of deposition of buffer layers and superconductor by electron beam evaporation, including the development of rate-monitoring apparatus, the nature of current flow through grain boundaries, and novel, high rate deposition of buffer layers.

Accomplishments. In FY 1998, the industry-led Wire Development Group achieved a record critical current density in BSCCO powder-in-tube wires of 71,500 A/cm^2. The average critical current in HTS wire made in FY 1998 for cables exceeds 100 amperes per tape in liquid nitrogen, a new record for commercially available wire.

Summary Budget Table (000$)

Enhancing Utility Infrastructure Research Areas	FY 1998 Appropriated	FY 1999 Appropriated	FY 2000 Request
Transmission and Distribution Reliability	**1,000**	**3,000**	**4,000**
Real Time System Control	0	2,500	3,400
Power Electronics	0	0	400
Distributed Resource Integration	0	500	200
High Capacity Transmission Technologies	1,000	0	0
Energy Storage Systems	**3,839**	**4,500**	**6,000**
Integration	1,950	2,200	3,000
Components	1,350	1,400	2,100
Analysis	539	900	900
Superconductivity in Power Systems	**31,579**	**32,500**	**31,000**
The Superconductivity Partnership Initiative	14,000	14,500	14,000
The Second Generation Wire Initiative	8,000	8,000	8,000
Strategic Research	9,579	10,000	9,000
Electric and Magnetic Fields R&D	**6,844**	**0**	**0**
Total	**43,262**	**40,000**	**41,000**

Chapter 7
Clean and Efficient Vehicles



Chapter 7
Clean and Efficient Vehicles

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Overview

Definition of Focus Area

Highway vehicles currently account for approximately 50 percent of daily domestic petroleum consumption (about 9.2 million barrels per day). Through significant efficiency increases in passenger cars and trucks, and development of cost-effective alternative fuels, the clean and efficient vehicles R&D portfolio seeks to reduce the growth of highway vehicle petroleum consumption.

National Context and Drivers

The U.S. transportation sector is dependent on petroleum for nearly 97 percent of its energy. In 1997, the transportation sector consumed 12.1 million barrels per day (MBPD) of petroleum products; highway vehicles account for 75 percent of transportation energy use with passenger vehicles alone using nearly 60 percent of the total. Without advanced, energy-efficient technologies, the Energy Information Administration projects that by 2020, the energy demand in the transportation sector will increase by 45 percent to 17.6 MBPD.

Transportation accounts for 65 percent of the U.S. annual petroleum consumption and uses 88 percent more petroleum than the United States produces. Currently, about half of the petroleum used in the United States is imported with U.S. dependence on imported petroleum growing. Annually, the cost of oil imports is one of the largest components of the U.S. balance of trade deficit. In 1997, oil imports were 34 percent of the merchandise trade deficit. The United States also remains vulnerable to future oil price shocks and manipulation by oil-producing countries, which, since 1972, has cost the U.S. economy $4 trillion.

The explosive popularity of low fuel-economy pickup trucks, vans, and sport utility vehicles used for personal transport, coupled with a growing economy, falling fuel prices, increasing numbers of drivers, and increasing miles traveled by each vehicle is pushing transportation fuel consumption higher. This situation will not change without a major advance in vehicle fuel efficiency. This could occur through regulatory or tax policies on vehicles or fuels and/or through technology improvements in the Nation's vehicles.

The Department of Energy's (DOE's) clean and efficient vehicles portfolio is the technological cornerstone for the Nation's initiative to significantly improve transportation energy efficiency.

Linkage to CNES Goals and Objectives

Technological developments from the clean and efficient vehicles R&D portfolio will contribute to meeting objectives contained within four of the five major CNES goals.

- CNES Goal I, Objective 2 - Significantly increase the energy efficiency in transportation, industrial, and buildings sectors by 2010.

- CNES Goal II, Objective 1 - Reduce the vulnerability of the U.S. economy to disruptions in oil supply.

- CNES Goal III, Objective 2 - Accelerate the development and market adoption of environmentally friendly technologies. *(pursuing research aimed at major improvements in vehicle efficiency, resulting in major reductions in greenhouse gas emissions, while meeting significantly improved emissions standards)*

- CNES Goal IV, Objective 2 - Develop technologies that expand long-term energy options. *(expanding long-term energy options such as hydrogen-based vehicle systems, enabling educational research opportunities, and building capabilities at educational institutions)*

By meeting OTT's goals and objectives, the Nation will reduce its dependence on oil and achieve energy savings as well as reduced carbon emissions. DOE, in the Quality Metrics Program Analysis, has estimated that by 2010, 1.8 quads of primary oil will be displaced, increasing to 3.7 quads by 2020. (For reference, 3.7 quads equals 638 million barrels of oil; highway vehicles currently use about 19 quads of energy annually). This will result in energy cost savings of nearly $10 billion in 2010 and over $20 billion by 2020; carbon reductions are estimated at 25 and 60 million metric tons in 2010 and 2020. (Motor gasoline use in the United States produces about 302 million metric tons of carbon per year).

Uncertainties

The technologies needed for the Cars of the Future and Heavy Trucks programs offer technical challenges identified in the technical roadmaps that provide the approach, milestones, and tasks needed to resolve the technical uncertainties. In addition to the uncertainties in technology development (the risk of being able to resolve technical barriers in a timely fashion), market and political uncertainties also exist. With low oil prices, fuel economy ranks low on the list of vehicle attributes that new car buyers desire. Consequently, one of the technical challenges is a result of market uncertainty—with an uncertain market for energy-efficient transportation technologies, efficiency needs to be produced with little to no incremental cost. In addition, there are some political uncertainties. For example, the regulatory process may establish extremely strict emissions standards that could preclude the adoption of some energy-efficient technologies.

Investment Trends and Rationale

Because 75 percent of transportation energy use is consumed by highway vehicles, virtually all of the DOE transportation technology R&D budget is directed at cars and trucks. And with 80 percent of highway vehicle energy use being passenger vehicles, the majority of the R&D budget is in the Cars of the Future (the major effort being the Partnership for a New Generation of Vehicles) and Light Trucks (which includes pickup trucks, vans, and sport utility vehicles). The area of heavy trucks accounts for the remainder of the DOE transportation R&D investment.

The Office of Transportation Technologies and its predecessor organizations have worked with the U.S. auto industry and engine manufacturers for over two decades to develop energy efficient technologies. Often the research was driven by Congressional mandates and various Administration priorities. Since the advent of the Partnership for a New Generation of Vehicles, DOE has worked even closer with the industry during the planning process to develop common technical roadmaps that would enhance the probability of commercial success. Technical roadmaps were developed first for the auto area and later for the heavy truck sector. Research and development plans were produced by OTT's Office of Advanced Automotive Technologies (OAAT) and the Office of Heavy Vehicle Technologies (OHVT). These plans underwent extensive external review. To assure the quality of the automotive R&D plan, the National Research Council (NRC) conducted an independent, comprehensive review of the OAAT plan last year, while the OHVT plans will be reviewed by the NRC this year.

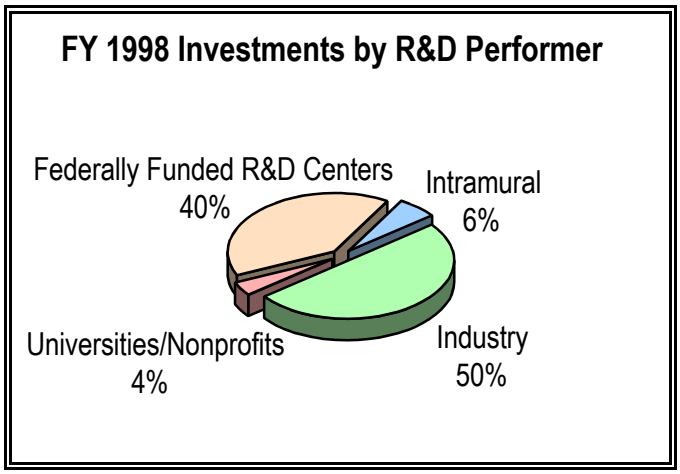
Major program thrusts are developed in cooperation with industry in order to maximize the likelihood of commercialization of the energy-efficient technologies. Consequently, budget changes tend to be characterized as "mid-course corrections" rather than radical adjustments. One area of increased emphasis is compression-ignition, direct-injection (CIDI) engines, commonly called diesel engines. CIDI engines have the highest thermal efficiency of any internal combustion engine and offer the greatest near-term potential for reducing transportation energy use and greenhouse gas emissions. The primary focus of DOE's R&D is reducing emissions of particulates and oxides of nitrogen, which are the major technical challenges for CIDI engines.

One way that risk can been reduced is to explore a broad range of technologies. For this reason, the Office of Transportation Technologies has a diverse research portfolio. Periodically, a technology selection process is used to evaluate research progress against established milestones and reduce the number of technologies to the most promising ones. The most recent example occurred with the Partnership for a New Generation of Vehicles at the end of 1997. Program diversity also occurs with respect to time horizons, research stage, and research performers.

By design, the OTT research programs have been long-term, i.e., typically ten years or longer. DOE transportation research in the 1980s on alcohol fuels has resulted now in commercially available flexible-fueled (gasoline or alcohol) vehicles. Current research into energy storage, fuel cells, and hybrid vehicle systems also has a long-term horizon, although industry will often "harvest" DOE-supported technologies before the technology development for an integrated vehicle system has been completed. Consequently, it is difficult to delineate with any precision whether the research fits within a near-, mid-, or long-term horizon for anticipated commercialization.

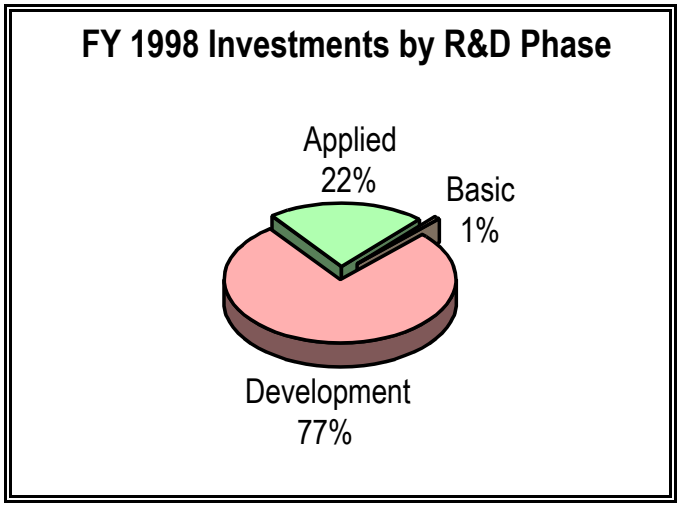
The portfolio consists of two main entities, Cars of the Future, which includes PNGV and light trucks, and High Efficiency Heavy Trucks. FY 1998 funding for Cars of the Future totaled 84 percent of the portfolio, with High Efficiency Heavy Trucks supporting the remaining 16 percent. As shown in the figure below, half of the research is performed by the private sector, either funded directly or through DOE laboratories. Approximately 40 percent of the research is

performed by the DOE laboratories themselves. A relatively minor amount of research is performed by other government agencies (6 percent) or universities (4 percent).



Research is often classified by stage—basic research, development, and applied research. Very little basic research is performed by the clean and efficient vehicles portfolio. Development is defined in the OMB Circular No. A-11 as, "...systematic application of knowledge toward the production of useful materials, devices, and system or methods, including design, development, and improvement of prototypes and new processes to meet specific requirements."

As the next figure shows, the bulk of the research dollars are devoted to development with the majority of the balance spent on applied research, and a minute portion on basic research.



Given the limitations of Federal resources, the clean and efficient vehicles portfolio is allocating its budget consistent with the opportunities for having the greatest impact on transportation energy use (cars, light trucks, and heavy trucks) and with the technical priorities established with DOE's cost-sharing partners.

Federal Role

The primary government R&D role is to support long-range, high-risk activities where breakthroughs offer large potential payoffs to the Nation, but are not reflected in current market pricing. This support includes funding, as well as access to unique R&D capabilities within the Federal laboratory system. With fuel prices at historic lows, the transportation sector has little or no incentive to undertake high risk research on its own to achieve breakthrough efficiency improvements. The DOE role is to conduct R&D, with cost-sharing industry partners, that would achieve the national goals of:

- Reducing the Nation's dependence on petroleum.
- Decreasing vehicle exhaust emissions, thereby improving urban air quality.
- Having a positive economic impact on the Nation's transportation sector, which accounts for one out every seven American jobs.

Key Accomplishments

The auto industry is already beginning to use many of the technologies developed in the Cars of the Future, Partnership for a New Generation of Vehicles (PNGV), and Light Truck Programs. This was dramatically demonstrated by the recent unveiling of several hybrid and other advanced vehicles at the 1998 North American International Auto Show, where concept vehicles showcasing DOE-supported technologies included the Chrysler ESX2, Ford P-2000, and the General Motors EV-1 platforms. OAAT-supported technologies that were integrated into these concept vehicles included advanced compression-ignition, direct-injection (CIDI) engines, parallel-hybrid vehicle configurations, a proton exchange membrane (PEM) fuel cell, a methanol reformer, and a nickel-metal hydride battery. While considerable R&D remains to make these technologies commercially viable, these public demonstrations clearly demonstrate the interests of the U.S. auto companies in bringing these DOE-supported technologies to market.

Cars of the Future, PNGV, and Light Trucks:

Budget: FY98-$139.1M, FY99-$150.4M, FY00-$172.6M

Background

The Partnership for a New Generation of Vehicles (PNGV) is a cooperative research and development (R&D) program between the Federal government and the United States Council for Automotive Research (USCAR) that was announced by President Clinton and the CEO's of Chrysler Corporation, Ford Motor Company, and General Motors Corporation (GM) on September 29, 1993. The three major domestic automakers are working with the Federal government, labor, suppliers, and universities, to develop efficient, low-emission vehicles for the 21st Century.

The PNGV has 3 goals:

- To develop manufacturing techniques to reduce the time and cost of automotive development.
- To improve fuel efficiency and emission performance of conventional vehicles.
- To develop a new family of vehicles with up to triple the fuel efficiency (i.e., 80 miles per gallon) of today's mid-size cars (i.e., Ford Taurus, Chrysler Concorde, and Chevrolet Lumina) while maintaining or improving safety, performance, emissions, and price.

The initiative represents a priority approach of the Administration to protecting the environment, improving the competitiveness of U.S. companies, and reducing the economic and geopolitical risks that result from this Nation's rising dependence on petroleum. Government is working with industry to develop the required technologies, and industry will make the choices necessary to meet America's transportation needs. Together, they will achieve important social and economic objectives for the Nation. Seven Federal agencies participate in the Partnership for a New Generation of Vehicles under the leadership of the Department of Commerce.

Currently the Administration is discussing expansion of the Partnership for a New Generation of Vehicles to include multi-purpose vehicles (Class 1 and 2 trucks which include pickups, vans, and sport utility vehicles). Sales of multi-purpose vehicles have increased dramatically in the past 13 years from approximately 3 million vehicles in 1983 to over 6.9 million in 1997 (from 25 percent to over 45 percent of the foreign and domestic sales in the United States). Consequently, the industry is shifting substantial manufacturing emphasis to light trucks.

Sales in the light truck segment are shifting towards the heavier Class 2 trucks, reducing the average fuel economy for this segment. As a result, the U.S. auto manufacturers are having difficulty meeting current light truck Corporate Average Fuel Efficiency (CAFÉ) standards. Both GM and Chrysler failed to meet the 20.6 mpg standard for the 1995 model year. GM's truck

fleet must exceed the CAFÉ standard of 20.7 over the next 3 years or face a prospective penalty for its 1995 shortfall.

Linkage to CNES Goals and Objectives

The R&D goals of DOE's programs in advanced vehicle technologies are to research, develop, and validate technologies that enable development of production prototypes of light-duty vehicles (automobiles, pickups, vans, and sport utility vehicles) which have (1) for automobiles, up to 3 times the fuel economy of comparable conventional vehicles; (2) for light trucks, 35 percent improvement in fuel efficiency (engine replacement only); (3) fuel flexibility; (4) emissions that at least comply with the most stringent statutory limits projected to be in the marketplace; and (5) other attributes, such as price, safety and performance, that render them competitive with conventional products.

This effort supports objectives contained in four of the five CNES goals:

- CNES Goal I, Objective 2 - Significantly increase the energy efficiency in transportation, industrial, and buildings sectors by 2010. *(developing more efficient transportation technologies)*

- CNES Goal II, Objective 1 - Reduce the vulnerability of the U.S. economy to disruptions in oil supply. *(helping reduce the consumption of petroleum)*

- CNES Goal III, Objective 2 - Accelerate the development and market adoption of environmentally friendly technologies. *(pursuing research aimed at major improvements in vehicle efficiency, while meeting significantly improved emissions standards)*

- CNES Goal IV, Objective 2 - Develop technologies that expand long-term energy options. *(expanding long-term energy options such as hydrogen-based vehicle systems, enabling educational research opportunities, and building capabilities at educational institutions)*

Program Description

Seven Federal agencies are collaborating with the U.S. auto companies in pre-competitive research to significantly improve automotive fuel economy. DOE's R&D program, which represents the majority of the Federal effort in PNGV, is conducted in partnership with the U.S. auto industry and the U.S. diesel engine industry. Research to overcome barriers to automotive technology development and utilization draws upon the unique capabilities of a dozen National Laboratories, combined with research facilities at universities, the major automakers and their suppliers. Coordination and prioritization of research portfolios is undertaken by technical teams comprised of representatives from industry, government, and National Laboratories. The technical areas include fuel cells, electrochemical energy storage, system analysis, manufacturing, four-stroke direct injection engines, materials and structures, electrical and electronics, and vehicle engineering.

Through consensus, each team develops a technical roadmap to overcome the barriers in its particular technology area. The teams review research progress and results, and recommend priorities for further research.

Research in the Cars of the Future, PNGV and Light Trucks Program Area can be grouped into four programs:

Engine/Power Sources

Budget: FY98-$68.3M, FY99-$96.1M, FY00-$123.2M

Advanced engine and power systems are critical to dramatic improvements in the fuel economy of automobiles and light trucks. Because the government does not manufacture vehicles, development of these technologies (which include advanced combustion engine R&D, fuel cells, high-power batteries, power electronics and electric machines, and electric vehicle batteries) will occur through a process that focuses on the research, development, and validation of hardware or prototypes to meet performance and cost goals. This collaborative process between the U.S. automakers, diesel engine manufacturers, and DOE follows technology roadmaps that have been developed, and are periodically updated, for each technology area.

Advanced Combustion Engine R&D

Budget: FY98-$14.8M, FY99-$34.2M, FY00-$46.8M

Description, Objectives, and Performers. The Advanced Combustion Engine R&D effort seeks to significantly improve the fuel efficiency of conventional piston engine technologies while cost-effectively meeting projected emissions regulations. The primary focus is on developing and validating compression-ignition, direct-injection (CIDI) engine technologies. In its 1997 technology selection, the PNGV identified direct injection engines as the most promising near-term energy conversion technology. Additional resources were requested in the FY 1999 and FY 2000 budgets to overcome the significant barriers that remain for this technology to meet anticipated emissions requirements. With the stringent emissions regulations proposed for particulates and nitrogen oxides, a secondary focus will be to enhance the performance of spark-ignition, direct-injection (SIDI) technology as a power system alternative to meeting the PNGV goals.

CIDI (diesel) engines have the highest thermal efficiency of any proven heat engine (brake thermal efficiency of 32-42 percent) and are excellent propulsion system candidates for both conventional drive systems and hybrid configurations. However, the use of CIDI engines in the automobile and light truck markets has been limited by shortcomings in performance, weight, size, noise, cost, and emissions. The greatest barrier to the future viability of CIDI engines for light-duty vehicles is the lack of effective, affordable emissions control technologies.

SIDI engines are being developed to support Goals 2 and 3 in the PNGV program. The status of current development and the potential of the SIDI engine suggest that it is a likely candidate for the incremental improvement of passenger car fuel economy (Goal 2), and a potential enabling technology for a three-times more fuel-efficient vehicle (Goal 3). The SIDI engine appears to be a viable alternative to the CIDI engine if, for a variety of reasons such as emissions, refueling, and service infrastructure, the latter is determined to be unable to achieve all the PNGV requirements.

R&D Challenges. Current NO_x emissions exceed the target (0.2 g/mile) by a factor of two and the proposed research target (0.05 g/mile) by a factor of eight. NO_x catalysts that operate with lean-burn engines are not available. Catalyst materials must be developed that operate in the presence of oxygen in the exhaust and that can perform over a wider temperature range. Other aftertreatment technologies are underdeveloped, costly, and do not have proven reliability and durability. Current particulate emissions exceed the research target (0.01 g/mile) by a factor of six. Particulate traps are costly (as much as 30 percent of the engine cost), energy-intensive (about 10 percent of fuel consumption), and have unproven reliability. Other aftertreatment devices (e.g., non-thermal plasma) are not adequately developed. In addition to the emissions problem, CIDI engines are about twice as expensive as conventional, port-injected, spark-ignition engines, principally because of the sophisticated fuel injection equipment. Higher operating temperatures and pressures also increase the cost of the engine structural components. Additional emissions controls (in-cylinder or aftertreatment) will simply add to the cost of the CIDI engine.

The key challenges for SIDI include reduction of NO_x, plus the reduction of unburned hydrocarbons (HC), and further reduction in particulates. The remaining challenge for SIDI is to improve the thermal efficiency (36-37 percent), which is better than the current port fuel injection engines (25-30 percent), but lower than CIDI engines.

R&D Activities. CIDI engine technology R&D focuses on in-cylinder and aftertreatment methods to reduce NO_x and particulate emissions as the primary barriers. NO_x reduction will target in-cylinder combustion control, catalysts, low-temperature plasma, and fuel modification and additives. Particulate reduction will target combustion control (such as variable air composition), traps, low-temperature plasma destructive technologies, and fuel and lubricant modifications. Research utilizes standard U.S. diesel fuel, low-sulfur California diesel fuel, and ultra-low sulfur European diesel fuel. Additional fuels that may have potential, such as dimethyl ether, are being evaluated. Design teams are focused on a 55 kW engine for hybrid applications in automobiles and a 150-200 kW engine for light trucks. The SIDI development effort is similar in approach, but smaller in scope.

Accomplishments. Program accomplishments include:

- In a joint DOE/industry hybrid propulsion program, two different CIDI engines were designed and developed. One engine was developed by Ford Motor Company and FEV Engine Technology, the other by Chrysler and Detroit Diesel Company.

- Initiated benchmark testing at the National Laboratories of state-of-the-art CIDI and SIDI engines.

- Completed initial performance specifications of critical enabling technologies, as well as cost goals, for the high efficiency diesel engine to replace the lower efficiency spark ignition gasoline engine for light truck applications (sport utility vehicles, vans, pickup trucks).

- Completed initial testing of first generation light truck engine systems. The efficiency improvement goal of 35 percent was met with one development team and exceeded by another, achieving 60 percent improvement. However, these tests did not meet the projections for 2004 emission standards.

Fuel Cells

Budget: FY98-$22.6M, FY99-$33.5M, FY00-$41.4M

Description, Objectives, and Performers. Fuel cells have emerged in the last decade as a potential replacement for the internal combustion engine in vehicles because they are clean, energy efficient (with a part-load system efficiency goal of over 50 percent and a full-load system efficiency goal target of 45 percent), and fuel flexible. Fuel cells offer the desirable attributes of low emissions, quiet and continuous operation, and modularity. Any hydrogen-rich material can serve as a potential fuel source for this rapidly developing technology. This includes fossil-derived fuels, such as natural gas, methanol, petroleum distillates, liquid propane, and gasified coal, or renewable fuels, such as ethanol or hydrogen (produced from renewable energy sources). The proton exchange membrane (PEM) fuel cell is the focus of current development efforts because it is capable of higher power density and faster start-up than other types of fuel cells.

R&D Challenges. Stack systems, fuel-flexible fuel processors, hydrogen storage, and power system integration are technical barriers for fuel cell development. Although fundamental scientific breakthroughs are not required to meet the program goals, substantial improvements are also needed in the areas of catalyst carbon monoxide (CO) tolerance and low-cost fabrication. Long-term durability and the efficiency of the integrated power system have not yet been demonstrated.

R&D Activities. Particular emphasis is placed on research to achieve high efficiency, quick start-up, long life, and low manufacturing costs. The R&D is focused towards development of low cost fuel cell components, fuel processor subsystem development, and integration of stacks, fuel processors, and balance of plant components. Methanol, ethanol, natural gas, and gasoline are being evaluated as fuels for on-board reforming. Industry teams led by Plug Power, International Fuel Cells, Allied Signal, and Energy Partners are completing development of 50 kW fuel flexible fuel cell systems under cost-shared contracts.

Accomplishments. Program accomplishments include:

- Conducted the world's first gasoline-fueled proton exchange membrane (PEM) fuel cell power demonstration with Epyx Corporation, Plug Power, and Los Alamos National Laboratory, integrating fuel-flexible fuel processing technology with carbon monoxide clean-up and fuel cell stacks to produce power from both ethanol and gasoline.

- Under a program with Ford Motor Company and International Fuel Cells, completed laboratory validation tests on hydrogen-fueled 50 kilowatt (commercial-scale) PEM fuel cell propulsion systems including testing under automotive drive cycle requirements.

- Under a program with General Motors Corporation and Ballard, completed testing of a 30 kW methanol fuel cell system that demonstrated extremely low emissions.

High-Power Batteries for Hybrid-Electric Vehicles

Budget: FY98-$8.6M, FY99-$12.8M, FY00-$15.0M

Description, Objectives, and Performers. A lightweight, compact, high-power energy storage device is one of the critical component technologies for a viable hybrid propulsion system. The primary functions of this device are to load-level the demand on the prime power source to maximize efficiency and minimize engine weight, volume, and cost; recapture the vehicle kinetic energy through regenerative braking; and capture the energy from the prime power source during braking and idle periods. In contrast to the high-energy requirement of electric vehicles, the energy storage device for hybrid vehicles must have high specific power (about ten times greater for hybrids than for electric vehicle batteries). Technologies that have the potential to meet the requirements for hybrid vehicles include: advanced high-power batteries, ultracapacitors, and flywheels. Currently only high-power batteries are considered sufficiently developed to have the potential to meet the schedule requirements of PNGV.

R&D Challenges. Batteries with power-to-energy ratios greater than 20kW/kWh and also have long cycle life, are needed. Electric and mechanical safety devices are needed to prevent overcharge or over-discharge. The candidate batteries all have operating temperature ranges that do not cover the entire operating temperature range required for automotive applications. Cost is too high by several factors, calendar life is unknown, and recyclability of the components is not known (the target is 80 percent recyclability at the vehicle level).

R&D Activities. Through a cooperative agreement between the United States Advanced Battery Consortium (USABC) and DOE, the USABC is focusing on the development of high-power batteries for PNGV. Two candidate battery chemistries have been identified as the most likely to succeed in meeting the requirements—nickel-metal hydride and lithium ion. The first of these offers relatively good power capability as a result of the good ionic conductivity of the aqueous potassium hydroxide electrolyte. The second offers excellent energy density that can be traded for higher power. Both chemistries are being investigated

under the USABC program, initially to establish the basic performance and life capabilities in small laboratory cells, and then to demonstrate the best of these technologies in full-size modules. Ultimately, full-capacity battery energy storage subsystems will be engineered for delivery and operation with technology-validation test-bed vehicles.

Four USABC subcontracts to establish baseline cell chemistries and electrode designs were completed in 1997 and two of the contractors were awarded follow-on subcontracts (one for lithium-ion cells and the other for nickel-metal hydride cells) to develop and demonstrate their high-power battery technologies at the nominal 50-V module level with electronic and thermal management. In addition, the USABC awarded two other subcontracts to further explore alternative lithium-ion technologies. Performance and cycle life testing of deliverable cells are being conducted by selected National Laboratories under a Cooperative Research and Development Agreement (CRADA) with USABC.

Accomplishments. Program accomplishments include:

- Fabricated 50-volt nickel metal hydride high power modules and initiated life cycle testing.
- Scaled up high power energy storage lithium-ion technology from one to 12 ampere-hour full-sized, cells required for integration into 50-volt modules.
- Developed abuse test requirements and protocols, and completed assessment of the high-power energy storage lithium-ion safety performance envelope.

Power Electronics and Electric Machines

Budget: FY98-$4.4M, FY99-$6.9M, FY00-$9.0M

Description, Objectives, and Performers. Power conditioning for motor controllers, chargers, and other interface electronics is a key enabling technology for hybrid electric vehicles. Development of electronic components and systems for vehicle applications has progressed from replacing mechanical systems to making features available that can only be realized through interactive controls and devices. Currently, the application of power electronics in conventional vehicles is aimed at integrated powertrain controls, integrated chassis system controls, multiplexing, and navigational and communications systems. In addition to these requirements for conventional vehicles, hybrid vehicle electric powertrains will require control devices with faster semiconductor chip operation, higher power density, and more power dissipation per device.

Electric machines in use today are typically driven by induction motors, which are inherently difficult to optimize for power and efficiency. Replacing them with permanent-magnet, switched-reluctance, or other advanced machines will result in lighter weight, more cost-effective systems with higher efficiency and power density needed for hybrid electric vehicles. Research and development is therefore needed to produce power electronics and

electric machines for automotive applications that are efficiently packaged, lightweight, low-cost, and reliable.

R&D Challenges. The primary barriers include: (1) Cost - materials, processing, and fabrication technologies for both power electronics and electric machinery are too expensive (by factors of 3 to 4) for automotive applications; (2) Volume - power electronics and electric machines are too large for automotive use; (3) Weight - electric machinery and power electronic controllers are too heavy and the extra component weight requires additional structural mass; and (4) Reliability and Durability - controllers have not been developed that meet 150,000 mile vehicle lifetime targets and existing electric machinery is not sufficiently rugged to operate in an automotive environment.

R&D Activities. For power electronics, OAAT is focused on developing technologies for automotive integrated power modules (AIPM) suitable for automotive applications. Baseline requirements for automotive controllers incorporating this power module architecture have been developed through close coordination with Chrysler, Ford, and General Motors. Additionally, OAAT is supporting development in the industry with the competitive award of 2 contracts at $10 million each to develop AIPM. OAAT work in this area is leveraged through an interagency agreement with the Office of Naval Research to jointly develop Power Electronic Building Blocks for use in automotive as well as military applications. The government-funded component development and testing is primarily being performed by DOE National Laboratories and U.S. Navy laboratories. In the electric machines area, OAAT is also supporting research to develop advanced technologies. Presently, industrial development is focused on induction motors, but weight, volume, efficiency, and cost goals are more likely to be met by switched-reluctance or permanent-magnet technologies if the existing technical barriers are resolved. OAAT plans for a similar solicitation effort to aid industry development of electric machinery for traction drives. A specification has been developed in a coordinated effort with Ford, GM, and Chrysler for traction drives. OAAT is also supporting laboratory R&D to improve materials useful in attaining the PNGV goals for power electronics and electric machinery.

Accomplishments. Program accomplishments include:

- Developed novel inverter topologies capable of meeting size, weight, reliability, and performance requirements for PNGV.

- Developed dc-dc converters with enhanced performance, size, and weight necessary in fuel-cell powered vehicles.

Electric Vehicle Batteries

Budget: FY98-$17.8M, FY99-$8.8M, FY00-$11.0M

Description, Objectives, and Performers. The California zero-emission vehicle requirements formulated in 1990, strengthened the interest of the auto industry in developing and introducing electric vehicles (EVs) into the automotive market. The key to market

success of EVs has always been battery technology. Vehicle range is limited by battery performance, and battery cost remains high. For the past eight years, DOE's EV battery research and development has been conducted under a cooperative agreement with the USABC. Currently, research is directed toward completing the nickel-metal hydride technology (that doubles the range of EVs) and the lithium-ion technology, as the most promising mid-term technologies, and toward the lithium polymer technology for the long term.

R&D Challenges. While the technical barriers are specific to the type of battery being developed for electric vehicle application, the general areas are similar, and include for the long-term lithium-polymer battery: power density (which needs to be improved from 250 to 450 W/l), specific power (targeted at 300 W/kg versus the current 200), energy density (which needs to reach 195 Wh/l compared to the present 110) and specific energy (from the current 75 Wh/kg to a goal of 135). Cost, safety, recycling/disposal, and manufacturability are also barriers.

R&D Activities. The development of advanced batteries involves battery developers and suppliers, small businesses, National Laboratories, and universities. These activities are coordinated by DOE through the EV Battery Exploratory Technology Research Program and by USABC through its Technical Advisory Committee. Key barriers (and attendant research) for lithium batteries are large cell safety, overcharge damage, electrolyte oxidation, and cathode limitations. The technical barriers requiring research for the development of the lithium polymer battery include material degradation, electrode and electrolyte performance, projected battery performance and cost, thermal and electrical management, safety, disposal, and manufacturability.

Accomplishments. Program accomplishments include:

- Initiated extensive laboratory testing of lithium-polymer electric vehicle batteries which will provide 3 to 4 times the range, and significantly greater performance and life, compared to conventional lead-acid batteries. These batteries will be commercially introduced by 2003.

- Nickel-metal hydride battery packs, provided by two separate developers, are currently powering electric vehicles in introductory market programs.

Systems Development

Budget: FY98-$45.6M, FY99-$24.8M, FY00-$23.9M

Description, Objectives, and Performers. Systems development provides the focus and guidance for the OAAT vehicle systems research and development activities. Work in this area provides development and validation of required propulsion subsystem technologies; validation of vehicle system component and subsystem technologies in the context of a vehicle operating environment; feedback to enhance predictive models; and validation at the vehicle level of the achievement of objectives.

In this context, the systems development objectives are:

- By 1998, develop and validate production-feasible propulsion subsystem technologies that will enable the achievement of 50 mpg in test-bed six-passenger sedans that meet EPA Tier 2 emissions requirements, and retain all the attributes of comparable competitive production vehicles.

- By 2004, develop and validate propulsion subsystem technologies and validate technologies that will enable the achievement of 80 mpg in test-bed six-passenger sedans that retain all the attributes of comparable competitive vehicles, including emissions controls.

- By 2011, develop and validate production-feasible vehicle subsystem technologies that will enable the achievement of 100 mpg in test-bed six-passenger sedans emphasizing non-petroleum-based fuels and zero emissions, and which retain all the attributes and features of competitive vehicles.

R&D Challenges. The technical barriers are defined for the engine/power sources, materials, and fuels programs. In the systems development program, the technologies produced in the other programs are brought together as a system, i.e., into a testbed vehicle or propulsion system in the laboratory.

R&D Activities. To overcome the technical barriers, technology requirements were first defined. Requirements were developed through coordination with industry and derived from a common vehicle systems perspective. A vehicle system computer modeling capability (ADVISOR) was developed in the first phase of the program. The propulsion subsystem performance models embedded within the vehicle system models are being validated and refined using data generated by the test and evaluation activities of both the Hybrid Program (50/50 cost-shared contracts with Chrysler, Ford, and General Motors) and the vehicles developed in the advanced vehicle competitions by a number of university engineering schools. Technology validation will occur within a total vehicle systems context. This activity can involve either actual testing and evaluation of technology-representative point designs in complete test-bed vehicles or simulation of the operation of such point designs using subsystem/component models embedded in a total automobile system model.

Accomplishments. Program accomplishments include:

- Completed the validation of the hybrid vehicle ADVISOR model against data from the four existing university-developed hybrid vehicles from the Advanced Vehicle Competition.

- Completed the Ford P 2000 rolling chassis, demonstrating the achievement of the target 2000 lbs curb weight with a conventional drivetrain. Preliminary tests show the fuel economy goal of 50 mpg will be exceeded by both the conventional and hybrid configurations.

- Concluded in 1998, the GM hybrid propulsion development program demonstrated the achievement of a Stirling-powered series hybrid configuration in a mid-size Chevrolet Lumina. Because of its series hybrid configuration, the vehicle also demonstrated a zero emissions capability for errands and short commutes. Compared to prior technologies, substantial improvements were achieved in developing affordable battery packs specifically designed for hybrid vehicles, and reducing the cost of the electric motor and the complexity of the motor's power electronics, as well as improving thermal control for the battery pack.

- A major success for the Chrysler hybrid propulsion development program in FY 1998 was the rapid design, development, and testing of the first generation parallel hybrid propulsion configuration. The program began in March 1996, and in just over 18 months succeeded in demonstrating a production based test-bed vehicle and an advanced lightweight concept vehicle, the ESX-2. The concept vehicle is an operational parallel hybrid system using an advanced three cylinder diesel engine. Both vehicles are paving the way for Chrysler's 2nd generation of hybrids that will address issues of manufacturing, cost, weight, accessory power requirements, emissions, durability, and reliability. Initial tests show the fuel economy and emissions targets will be exceeded.

- Launched the CARAT program which provides small businesses and universities an opportunity to solve critical technology barriers as part of the PNGV. Received 133 competitive proposals and have awarded 26 Phase 1 CARAT cooperative agreements.

- Initiated the GATE program with a solicitation for proposals. From the proposals, nine universities were selected to receive support in the development of multi-disciplinary graduate student automotive engineering programs that emphasize technologies critical to the development and production of cars of the future. Advanced technology areas include: fuel cells, advanced energy storage, lightweight and propulsion materials, direct injection engines, and hybrid electric drivetrain and control systems.

Advanced Materials

Budget: FY98-$20.9M, FY99-$22.7M, FY00-$17.0M

Description, Objectives, and Performers. The advanced materials research conducted by OAAT has two closely coordinated elements. The first is propulsion subsystem materials, which is focused on developing materials for propulsion components and subsystems to facilitate higher efficiencies, lower emissions, improved alternative fuel capabilities, and lower specific weight and volume, without compromising other factors such as cost, safety, and reliability. Research activities in this area are defined under the appropriate engine/power source. The other research element encompasses lightweight vehicle systems materials, where reduction of body and chassis weight is the focus of the research activities.

Both the propulsion subsystem materials work and the lightweight vehicle system materials research are closely coordinated with materials R&D for heavy vehicle technologies.

The major goals in the lightweight vehicle systems materials area are to develop and validate cost-effective lightweight material technologies that could significantly reduce vehicle weight without compromising vehicle cost, performance, safety, or recyclability. Research objectives include:

- A 25 percent reduction in the weight of the body and chassis by 2000.
- A 50 percent reduction in the weight of body and chassis components contributing to a 40 percent reduction in vehicle weight by 2004.
- A 60 percent reduction in the weight of body and chassis components, necessary to achieve 100 mpg fuel economy, by 2011.

R&D Challenges. Cost is the single greatest barrier to the use of lightweight materials in automotive applications. In terms of life-cycle cost, aluminum is about 50 percent (or less) as expensive as steel and polymer composites are 3 times (or less) as costly. Methods for high-volume production of automotive components from lightweight materials have not been adequately developed, and design data and test methodologies are inadequate. High-volume, high-yield joining technologies for lightweight and dissimilar materials do not exist. Technologies for cost-effective recycling and repair of advanced materials are lacking.

R&D Activities. The DOE research is focused on specific classes of materials using representative, nonproprietary components. As technical barriers are removed, the technologies are made available for industry to take in-house to perform proprietary, application-specific research. The technology development areas and individual projects have been identified through workshops, white papers, planning studies, and assessments. The lightweight materials of interest include aluminum, magnesium, titanium, and carbon-fiber and metal matrix composites.

Accomplishments. Program accomplishments include:

- Demonstrated a four-minute cycle time for glass-fiber preforms to enable high-volume production of glass-reinforced composite automotive components.
- Developed test methodologies for characterizing the Mode II response of adhesive bonding joints for automotive applications. Standardized test procedures and fracture-based guidelines were developed and have been transferred to industry.
- Demonstrated the technical feasibility of producing carbon fiber using microwave radiation with significantly reduced processing times and costs.

- Demonstrated new processing technology for the fabrication of pump components using particulate reinforced aluminum alloys, resulting in weight savings and improved performance.

- Developed non-heat treatable aluminum sheet with yield strength exceeding 35,000 psi.

- Developed a unique lightweight (0.5 g/cm^3), high conductivity (100 W/n•K) carbon foam that is being utilized for thermal management of electronics such as heat sinks and heat exchangers.

- Developed lightweight carbon composite bipolar plate materials in the laboratory that meet fuel cell requirements, and transferred a material recipe and manufacturing process to industry for scale-up.

Fuels Utilization

Budget: FY98-$4.3M, FY99-$6.8M, FY00-$8.5M

Description, Objectives, and Performers. DOE supports fuel R&D in two major areas: (1) alternative fuels for conventional engines, and (2) fuels for advanced engines in support of the PNGV program. Alternative (i.e., non-petroleum) fuels have the potential to displace significant amounts of petroleum, providing energy security benefits, and reduced emissions. Alternative fuels are at varying stages of development for use in vehicle engines, and the additional research needed to increase their viability for conventional vehicles varies accordingly. Research is also being conducted to address the potential of new fuels to ensure compliance with emissions regulations in high-efficiency advanced engines. Fuel composition changes may facilitate the effective use of aftertreatment/cleanup devices and enable advanced engines to minimize emissions while maximizing fuel economy objectives.

R&D Challenges. *Compressed Natural Gas (CNG):* The most critical barrier to retail consumer acceptance of the CNG vehicle is the high initial vehicle cost, due primarily to the high fuel tank cost. In addition, refueling infrastructure expansion is hindered due to the high cost of compressors and auxiliary equipment, resulting in CNG fueling stations that cost five times as much as gasoline stations. The third technical barrier is limited vehicle range (about half that of conventional vehicles) due to the mass and volume of the on-board gas storage tanks.

Ethanol: This renewable fuel has the potential to displace imported oil and reduce the transportation sector's contribution to criteria pollutants and greenhouse gases. The current ethanol R&D needed for long-term biomass production is described in the Producing Clean Fuels chapter of this document.

Dimethyl Ether (DME): Although not currently used as a transportation fuel, dimethyl ether is being considered because of its high cetane number and inherently low particulate emissions, which make it attractive for high-efficiency compression-ignition engines. The principal

technical barriers for DME exist because its supporting fuel systems (fuel storage, fuel delivery/injection) are in a very preliminary design stage; therefore the costs, reliability, durability, and safety are not known. Further, large-scale production, distribution, and refueling infrastructures do not exist.

R&D Activities. For CNG, several interrelated tasks will develop lower-cost, lighter-weight materials for the different types of CNG storage tanks and integrate these improvements into acceptable vehicle storage systems. The cost and reliability of fueling stations will be improved through compressor and auxiliary component technology development, with an emphasis on materials and design concept refinements. Vehicle range will also be addressed through improvements to achieve a high-efficiency engine. Research into the use of dimethyl ether will require development of fuel storage, fuel delivery, and fuel injection systems. Fuel infrastructure issues will also be evaluated.

In the future, the Fuels Utilization program for light duty vehicles and trucks will increase focus on development and evaluation of advanced petroleum based fuels to be used in direct injection engines and fuel cells. A major concern for these advanced engines is to be able to meet future emission requirements and efficiency goals. It will be necessary to work with energy and automotive companies to develop fuels that will meet these goals and that can be effectively introduced into the market. Testing of various fuels with advanced direct injection engines is underway. Future programs will evaluate the effect of oxygenates as an additive to diesel fuel to help with reducing particulate matter (PM) emissions, analysis of PM with regard to toxicity, and determining the impact that lubrication oil has on the formation of PM in the exhaust. Fuels for fuel cells will also be a major part of the program. Projects to identify major contaminants in advanced petroleum based fuels and their impact on fuel cell performance is underway. The tolerance level of these contaminants will be determined in future programs. In addition, testing of fuels in fuel processors to optimize the use of fuel constituents will be started.

Accomplishments. Program accomplishments include:

- Completed tests on 7 fuels (DMM, Fischer-Tropsch neat, Fischer-Tropsch 20, biodiesel, EPA-2D, CARB diesel, regular diesel) in an advanced direct injection, diesel engine, aimed at determining emission effects. Positive effects were observed on particulate emissions with up to 50 percent reduction gained from DMM blended with low-sulfur diesel.

- Demonstrated the Generation I integrated storage system (ISS), utilizing lower-cost, lighter-weight, Type II compressed natural gas tanks.

- The Ethanol Vehicle Challenge, involving 14 U.S. and Canadian engineering schools, demonstrated 30 percent better fuel economy than gasoline vehicles as well as comparable cold-starting (at 0°F) and driveability.

- Thirteen U.S. and Canadian engineering schools participated in the FutureCar Challenge (with vehicle goals similar to those in the PNGV program). The highest on-road efficiency was 75 mpg compared to 37 mpg with a control conventional vehicle.

High-Efficiency Heavy Trucks

Budget: FY98-$30.9M, FY99-$30.8M, FY00-$52.0M

Background

The health and continued growth of the U.S. economy are dependent on maintaining the energy security and profitability of the trucking industry, now and into the foreseeable future. Trucks are the mainstay for trade/commerce and economic growth. The gross domestic product (GDP), and hence, economic activity, is linked to freight transport. Total highway freight transportation expenditures (local and intercity trucks) were over $348 billion, accounting for 79 percent of the Nation's freight bill and approximately 4.8 percent of the GDP (1995). Meeting energy demand for movement of goods is, therefore, critical to the economy.

Linkage to CNES Goals and Objectives

The goals for heavy truck technology have been established according to truck class because of the vastly different use patterns across the weight classes.

(1) For class 7-8 trucks, the tractor trailer long-haul rigs, the goal is to develop by 2004, the technology for a fuel efficiency of 10 mpg (at 65 mph) meeting prevailing emission standards, using either diesel or a liquid alternative fuel.

(2) For class 3-6 trucks, predominantly urban delivery vehicles, the goal is to achieve double the fuel economy of today's vehicles, using conventional or natural gas fuels, in combination with a hybrid electric propulsion system.

(3) To support the alternative fuel requirements above, there are goals to develop alternative fuel engines with fuel flexibility and a thermal efficiency of 55 percent with liquid alternative fuels, as well as gaseous fuels.

This effort supports objectives contained in three of the five CNES goals:

- CNES Goal I, Objective 2 - Significantly increase the energy efficiency in transportation, industrial, and buildings sectors by 2010. *(developing more efficient transportation technologies)*

- CNES Goal II, Objective 1 - Reduce the vulnerability of the U.S. economy to disruptions in oil supply. *(helping reduce the consumption of petroleum)*

- CNES Goal III, Objective 2 - Accelerate the development and market adoption of environmentally friendly technologies. *(pursuing research aimed at major improvements in vehicle efficiency resulting in major reductions in greenhouse gases)*

Program Description

Research and development plans developed by OTT's Office of Heavy Vehicle Technologies (OHVT) were extensively reviewed by industry partners (truck manufacturers, diesel engine manufacturers, and their suppliers), fuel suppliers, other DOE organizations, other Federal agencies, National Laboratories, and other Federal research centers. The OHVT plans and programs were reviewed by an independent industry/government peer review panel and will undergo National Research Council review during 1999. Consequently, the research activities described in this portfolio are the result of rigorous planning processes and can be referenced in the OHVT Technology Roadmap and in the Multi-Year Program Plan. Research and development for the Office of Heavy Vehicle Technologies is carried out largely in cooperative programs between the DOE laboratories and industry, by universities, and by independent research institutions.

The High Efficiency Heavy Truck efforts can be grouped into four major categories:

Heat Engine R&D

Budget: FY98-$3.5M, FY99-$3.5M, FY00-$9.0M

Description, Objectives, and Performers. Heavy trucks rank closely behind passenger cars and light trucks in the Nation's annual fuel utilization. Their relatively high fuel consumption per vehicle provides an incentive to utilize more efficient technology as it becomes available, even in times of low fuel prices. Engine R&D for heavy vehicles focuses on advancements in fuel economy for petroleum savings and on emissions control technology to maintain compliance with increasingly stringent regulations. Mainstream R&D activities in engine technology are carried out in cooperative agreements with the major domestic engine manufacturers, with enabling technology R&D conducted in the National Laboratories. Targeted engine efficiency is 55 percent or higher, with the direct-injection diesel engine being the incumbent, and still most viable candidate, for highway truck applications. Engine efficiency improvement is a major contributor to overall goals of increasing class 7-8 truck fuel economy from nominally 7.5 mpg to over 10 mpg at 65 mph. Innovative and improved designs for higher cylinder pressures, improved exhaust heat utilization, and lower engine friction are key aspects of the technology roadmap. Emissions control R&D emphasizes a three-pronged approach: combustion systems, aftertreatment, and fuel formulation. Engine compatibility and optimization for non-petroleum diesel fuels is an additional objective to augment petroleum savings. These efforts are shared and coordinated with the fuels R&D projects in heavy vehicles.

R&D Challenges. Best current engines have efficiencies of nominally 46 percent. In order to achieve the fuel economy targets for heavy trucks, engine efficiency must be on the order of 55 percent or higher, requiring a 20 percent advancement. Improvements, focused on the

direct injection, "diesel-cycle" engine, are needed in a number of integrated technology areas including increased peak cylinder pressure, additional exhaust heat recovery through improved turbo systems, improved thermal management, less heat rejection, reduced parasitic friction loss, and improved combustion.

The greatest barrier for this high efficiency engine class is emission control, particularly NO_x and particulate matter (PM). Emissions reduction requires a systematic approach encompassing three areas of activity: (1) in-cylinder processes (combustion, air handling), (2) exhaust aftertreatment, and (3) fuels properties.

Success is dependent on advancements in basic engine design, in key subsystems such as turbocharging and fuel injection, and in supporting technologies like materials.

R&D Activities. Tasks are in progress to improve fuel injection systems, along with more fundamental research to improve the understanding of key parameters of the in-cylinder processes. New models of how NO_x and particulates form in engines have been developed. Research and development on exhaust aftertreatment includes particulate filters, NO_x catalysts, and plasma systems, plus improvement in the measurement and analysis tools needed to accurately determine what compounds the devices are reducing and what byproducts they may be producing.

Accomplishments. Program accomplishments include:

- A new type of particulate filter has been developed through the prototype stage.
- Small prototypes of NO_x catalysts have exceeded 50 percent reduction of NO_x and non-thermal plasmas devices have exceeded 70 percent reduction on a small scale.
- To date, engine efficiency of approximately 52 percent has been achieved in test engines, compared to 44 percent in production engines when the program began, and 46 percent today.
- The program has assisted manufacturers in reducing NO_x emissions by over 50 percent and PM by over 80 percent in production engines.
- New prototypes of diesel engines for sport utility vehicles have been built and are undergoing evaluation in test cells as well as in vehicles. Fuel economy improvements are expected to exceed 50 percent compared to gasoline engines.

Systems Development

Budget: FY98-$1.7M, FY99-$1.5M, FY00-$12.0M

Description, Objectives, and Performers. For class 7-8 highway trucks, systems R&D encompasses the reduction of aerodynamic drag and rolling resistance in heavy trucks, as well as reduction of parasitic losses related to auxiliaries and operating modes. In order to

achieve the truck fuel economy goals, for example, aerodynamic drag coefficients will need to be lowered from today's typical value of 0.60 to less than 0.50. The challenge is to make the cab and trailer modifications cost effective, while not hindering maintenance, reducing payload, nor violating regulations that govern the overall size of the unit. A detailed plan on aerodynamic drag has been developed with industry participation, and a similar activity is underway on rolling resistance. One part of the aero effort will be to advance the computational tools used for cab/trailer development. In particular the trailer has received much less attention in aerodynamic development. It will be the focus of near-term analysis using existing computational tools.

R&D Challenges. The trucking industry is reluctant to accept new technology unless it meets all State and Federal regulatory standards, standard trucking practices, and the return on the investment is realized within 2 years.

R&D Activities. DOE is fostering a proof-of-principle project to reduce truck idling that can save up to 3 billion gallons of fuel per year (reducing petroleum consumption by nearly 200,000 barrels per day). Several industry firms have agreed to make cab heater/cooler units available to truck operators who will record data on time in use and fuel consumed. The data will be disseminated in order to encourage the use of the devices. A substantial improvement in local air quality could also result.

For class 6 and lighter trucks (urban delivery trucks), the primary focus in systems R&D is on hybrid-electric technology. In a conventional vehicle powered by an internal combustion engine, the engine must deliver short bursts of high power for acceleration and also long duration steady-state power at lower levels for constant speed highway cruising. The variability in power requirement causes vehicle manufacturers to provide engines that are sized to meet the maximum power requirement. These "oversized" engines are less fuel efficient at low loads and idling and they produce higher emissions. Also, in conventional vehicles, mechanical friction braking is used to slow the vehicle when necessary, resulting in the conversion of kinetic energy into heat.

The use of a hybrid electric propulsion system allows the vehicle to have a smaller prime power source that can be optimized for efficient, clean operation while the hybrid system can still meet the high power requirements for acceleration. Also, regenerative braking can be easily incorporated into the hybrid system. Hybrid electric propulsion systems are ideally suited for use where the power demand is non-constant, such as in city driving where frequent starts and stops are required. The hybrid electric propulsion system is a natural replacement for the gasoline engine in medium duty urban delivery trucks. The attainment of a fully cost-effective technology is one of the hybrid's greatest challenges. Hybrid systems are being developed in the PNGV program for cars, and these systems should be applicable to light trucks.

Accomplishments. Program accomplishments include:

- A detailed R&D plan on heavy vehicle aerodynamic drag has been developed with industry. Efforts are started to improve computational tools for aerodynamic design of the tractor/trailer.

- A program has been started to compile data on the fuel savings from use of truck cab heaters/coolers to avoid truck idling. The presentation of the data is expected to promote the use of these fuel-saving devices.

Advanced Materials

Budget: FY98-$13.0M, FY99-$14.8M, FY00-$16.0M

The major program elements in heavy truck advanced materials are (1) propulsion system materials, (2) high strength weight reduction materials, and (3) the High Temperature Materials Laboratory.

Propulsion System Materials

Description, Objectives, and Performers. The purpose of the Heavy Vehicle Propulsion System Materials Program is to develop enabling materials technology to support fuel flexible low emission, high efficiency diesel engines for medium and heavy duty trucks.

The design of advanced components for high efficiency diesel engines has, in many cases, pushed the performance envelope for engine materials past the point of reliable operation. Higher mechanical and tribological stresses and higher temperatures of advanced designs limit the engine designer. Advanced materials allow the design of components that may operate reliably at higher stresses and temperatures, thus enabling more efficient engine designs. Advanced materials also offer the opportunity to improve emissions, noise, vibration, harshness (NVH), and performance of diesel engines for pickup trucks, vans, and sport utility vehicles.

R&D Challenges. Component cost and reliable cost-effective processes and manufacturing procedures for advanced materials present substantial barriers to their commercialization.

R&D Activities. New forms of materials, such as nanophase structures in both metals, ceramics, and alloys in the amorphous condition, are being investigated to determine if their unique properties such as high hardness, strength, corrosion resistance, and low coefficient of friction can stand up to the rigors of the new power plants.

Accomplishments. Program accomplishments include:

- Development and commercialization of scuff-resistant ceramic components for Cummins Engine Company fuel injectors that allow Cummins to meet EPA standards for particulate emissions.

- Successful development and testing of durable ceramic valves for a Detroit Diesel Corporation heavy duty engine.

High Strength Weight Reduction Materials

Description, Objectives, and Performers. The objective of the High Strength Weight Reduction Materials Program is to develop advanced materials and materials processing technologies leading to reductions in vehicle weight that enable heavy vehicles (trucks and buses) to be more energy efficient. The focus is on body and chassis components which are light weight while still meeting performance requirements in a cost effective way. Weight reductions will be achieved through the increased use of improved conventional materials and new, advanced materials and by developing low-cost, high volume manufacturing processes. When implemented, these materials technologies will reduce the weight of unloaded heavy duty tractor-trailer units by 20-30 percent, resulting in 10-18 percent reduction in fuel use and emissions. These goals are achieved through partnerships between government laboratories, industry, and universities.

R&D Challenges. High costs and component reliability and durability are major issues in the commercial truck market.

R&D Activities. Development of the technology to cast ultra-large aluminum components; application of metal compression forming to produce high integrity structural cast aluminum components; and the development of metal matrix composites are other avenues of attention for heavy vehicles.

Accomplishments. Program accomplishments include:

- Design of all major components of the Ultra-large Casting System including primary and holding furnaces, press, mold system, and caster cell was completed and fabrication of a major component is nearing completion. Installation and initial trials are scheduled for early FY 1999. Successful development will result in low-cost, high-volume production of single large components, thereby reducing the number of parts and corresponding assembly steps.

- Demonstrated a new casting process for aluminum alloys and metal matrix composites (MMC) which will enable the substitution of low cost cast components with significantly less weight than cast iron components while offering considerable cost savings over forged aluminum components.

High Temperature Materials Laboratory

Description, Objectives, and Performers. The High Temperature Materials Laboratory (HTML) is a national user facility, offering opportunities for American industries, universities, and other Federal agencies to perform in-depth characterization of advanced materials under the auspices of its User Program. Available are electron microscopy for microstructural and microchemical analysis, equipment for measurement of the

thermophysical and mechanical properties of materials to elevated temperatures, x-ray and neutron diffraction for structure and residual stress analysis, high speed grinding machines, and measurement of component shape, tolerances, surface finish, and friction and wear properties.

The User Program began in 1987, and has expanded over the intervening years from a few user projects per year to a current range of 80 to 110 project per year. In the eleven years between 1987 and 1998, a total of 819 projects were performed, with users from several hundred industries, colleges and universities, and other Federal agencies. The HTML focuses on materials for transportation, especially structural materials, with work being performed on engine and fuel system materials, chassis materials, and brake system materials. Cummins Engine Company, Detroit Diesel Corporation, and Caterpillar Inc. are frequent users. HTML also supports their suppliers, and especially catalyst materials developers and suppliers, since catalysts will play such an important role in the success of diesels in the future. Automobile manufacturers similarly work with HTML, especially Ford Motor Company. Projects involving non-transportation research are also undertaken at HTML, as long as they have a relationship to energy efficiency or renewable energy.

R&D Challenges. The HTML attempts to resolve materials issues at the atomic level. The primary barrier to that approach is the capability of the available equipment to provide adequate analysis.

R&D Activities. This year, HTML researchers and users spent considerable effort on characterization of catalyst materials, including use of transmission electron microscopy to evaluate several-atom clusters of Os species on substrates, and novel catalysts from Ford Motor Company. Much of the catalyst examination was performed via remote microscopy, wherein the user simply logs onto the HTML computer controlling the microscope and runs it from his/her home institution. This process is extremely cost-effective, avoiding the expenditure of both the user's travel time and money. Research was also directed at development of advanced materials for diesel engine fuel injection systems.

Accomplishments. Program accomplishments include:

- In an on-going HTML User project with Ford Research Laboratory, conducted via remote microscopy, Dr. C. K. Narula used the Hitachi HF-2000 transmission electron microscope to study experimental catalysts comprising Pt clusters on alumina, titania, and mixed Al-Ti oxide support materials.

- A basic catalyst research HTML user project has been initiated with Professor Bruce Gates and his students at the University of California at Davis. Professor Gates is preparing and studying catalysts comprising clusters of heavy atom species on a variety of substrates.

- Several Cooperative Research and Development Agreements (CRADAs) are now underway with major U.S. diesel engine manufacturers to apply the unique capabilities of the HTML to specific materials problems.

Fuels Utilization

Budget: FY98-$12.7M, FY99-$11.0M, FY00-$15.0M

Description, Objectives, and Performers. DOE has both near term and long range objectives and efforts in fuel utilization. For class 7-8 trucks, the most viable alternative substitute fuel in the near term is liquefied natural gas (LNG). Several LNG trucks are undergoing field trials, and have demonstrated NO_x and PM levels over 80 percent lower than similar vehicles operating on standard diesel fuel. A challenge remains to elevate the efficiency and power of the natural gas engines closer to that of the diesel engines they replace.

Natural gas engines, because of their demonstrated low PM and NO_x, are particularly attractive for urban delivery vehicles in class 3-6 trucks. These vehicles provide an excellent application for natural gas since most are operated as fleets with central refueling. Natural gas engines in class 3-6 need significant improvements in part-load efficiency since they normally operate with a lighter load factor than larger highway trucks. Urban delivery vehicles are prime targets for hybrid vehicle technology with the potential for up to 3 times today's fuel economy. Hybrid vehicles, for lowest emissions, will need a natural gas engine designed especially for the hybrid system.

R&D Challenges. Cost - the industry is reluctant to accept any new engine/fuel system which is not clearly cost attractive; Infrastructure - unavailability of an adequate number of fueling stations is a significant barrier to widespread use of alternative fuels; Operation, Maintenance and Reliability - the diesel engine is noted for its reliability and durability, and the industry is cautious about use of new fuels and engines due to concerns that reduced reliability will adversely impact operations.

R&D Activities. To meet this challenge, DOE, the Gas Research Institute, and the South Coast Air Quality Management District have jointly instituted projects with major engine manufacturers. The project teams will work to make incremental improvements to today's natural gas engines to help maintain a market for the technology. The teams will also develop stretch technology like direct injection natural gas engines to achieve efficiency goals of up to 55 percent.

The program strategy includes research and development of natural gas storage to complement these engines. One specific project focuses on the development of onboard high pressure fuel delivery systems for direct natural gas fuel injectors. Other projects include testing of conformable tanks, developing smart tank technologies, developing low pressure storage, studies on natural gas storage for heavy vehicle market penetration, and demonstrating the advantages of LNG/CNG refueling. Performance measures for this

activity are developing safe, reliable, cost efficient components for heavy vehicle fuels storage. Performance goals are as follows:

1. Use conformable tanks to achieve 40 percent more onboard storage than conventional compressed gas cylinders.

2. Reduce life cycle cost by 25 percent for natural gas storage for heavy vehicles.

3. Increase hold times, reliability and reduce boil-off for LNG storage.

4. Conserve 15 percent of the energy fuel value of natural gas by improving storage tank design, fuel delivery systems and fuel integration strategies.

The second major fuel thrust for heavy vehicles is alternate-feedstock liquid diesel fuels. Fuels with excellent qualities for high-efficiency compression ignition engines can be produced from biomass, natural gas, and in the long term, other vast resources such as coal and oil shale. These fuels have value in displacing petroleum consumption, and their typically low levels of sulfur and aromatic hydrocarbons, offer some inherent benefit for engine emissions. The low sulfur content may enable use of certain aftertreatment technologies (e.g. NO_x traps) for near-zero emissions. Oxygenated fuels such as biodiesel and dimethoxymethane are proven for lowering PM and are generally miscible with conventional diesel fuel. Even without optimizing an engine for the specific fuel, Fischer-Tropsch diesel fuel has been found to lower PM by over 30 percent. Most of these diesel-like fuels are also advantageous in being compatible with today's fuel distribution infrastructure.

Compression-ignition fuels can possess similar physical properties (density, viscosity) yet vary widely in chemical composition (aliphatic/aromatic ratio, oxygen content). Compression ignition engines also have particular design features depending on the manufacturer and application of the engine. Correlations relating fuel properties to engine efficiency and emissions are empirical and not very accurate, making the optimization of fuel and engine properties difficult. A two pronged approach has been initiated to remedy the situation and help fully exploit new fuels. First, research has been started to improve the fundamental understanding of the effects of fuel properties on emission formation. Optical access research engines and combustion vessels are being used to characterize how fuel properties affect spray and atomization, soot formation, and NO_x. For the present, we must continue to rely on test programs with experimental matrices of fuel parameters and engine designs. This program element is called the "Performance and Emissions Data Base for New Diesel Cycle Fuels," and was planned with participation of the engine manufacturers as well as fuel producers.

In addition to improving the utilization of conventional and alternative fuels in a diesel cycle engine, the program includes activities to improve the understanding of the effects of diesel engine emissions on air quality and human health. This will largely be accomplished by (1) participation and support for studies of diesel emissions and their health effects, (2) identification of major air quality problems affected by fuel-related sources, (3) examination

of emissions from heavy vehicles run on diesel, biodiesel, CNG, LPG, methanol, ethanol, and other fuels of interest, and (4) the study of the transport and fate of the pollutants and/or their precursors.

The Office of Transportation Technologies (OTT) is also collaborating with Fossil Energy and its Federal Energy Technology Center (FETC) to advance the development and deployment of cost competitive fossil-based replacement fuels. Four types of activities are being conducted under this collaboration: (1) production, characterization, and testing of Fischer-Tropsch diesel fuel and additives made from syngas for petroleum diesel blending; (2) small-scale, high-efficiency Liquified Natural Gas (LNG) production technology for remote site natural gas production and fleet LNG fuel production; (3) incorporation of renewable feed streams to refinery systems for carbon reduction; and (4) process economics to identify technical and market barriers for the deployment of replacement fuels additives. These activities are being coordinated by the OTT Fuels Crosscut Coordinating Team (FCCT).

Accomplishments. Program accomplishments include:

- Assisted industry in introducing and certifying alternative fuel heavy-duty engines in numerous applications. Includes natural gas engines for urban buses and alcohol-fueled engines for trucks and buses.

- Demonstrated LNG powered trucks with 80 percent less NO_x and PM than conventional diesel powered vehicles.

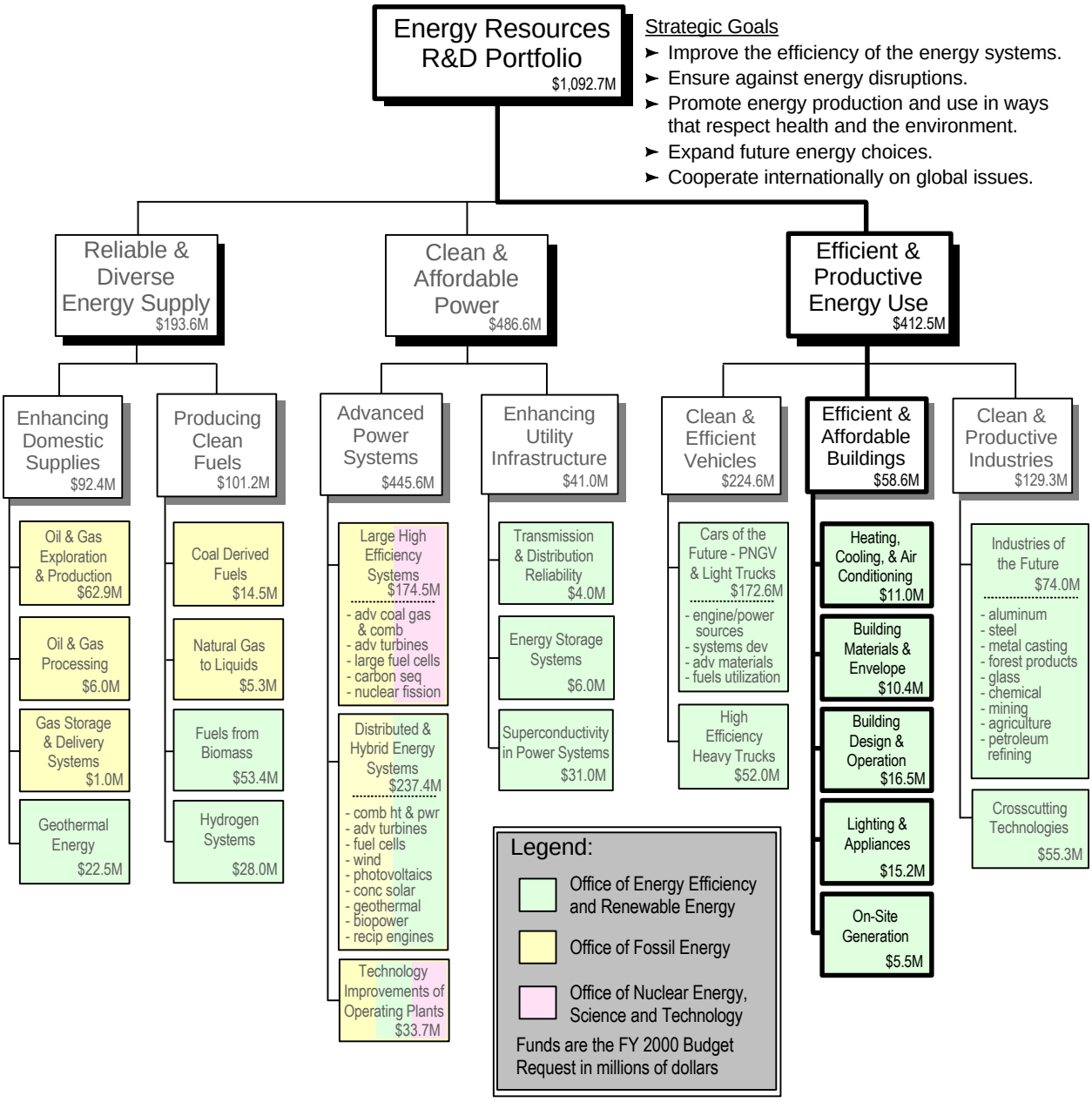
- Developed and demonstrated a multi-cylinder heavy duty diesel engine operational on M85 and diesel fuel interchangeably.

- Characterized the performance and emissions from diesel engines operating on advanced petroleum-like fuels such as biodiesel and Fischer-Tropsch diesel fuel.

Summary Budget Table (000$)

Clean and Efficient Vehicles Research Areas	FY 1998 Appropriated	FY 1999 Appropriated	FY 2000 Request
Cars of the Future - PNGV and Light Trucks	**139,066**	**150,356**	**172,580**
Engine/Power Sources	68,280	96,121	123,180
- Advanced Combustion Engine R&D	*14,818*	*34,175*	*46,800*
- Fuel Cells	*22,614*	*33,501*	*41,380*
- High-Power Batteries for Hybrid-Electric Vehicles	*8,620*	*12,750*	*15,000*
- Power Electronics and Electric Machines	*4,410*	*6,875*	*9,000*
- Electric Vehicle Batteries	*17,818*	*8,820*	*11,000*
Systems Development	45,582	24,815	23,900
Advanced Materials	20,855	22,655	17,000
Fuels Utilization	4,349	6,765	8,500
High Efficiency Heavy Trucks	**30,890**	**30,840**	**52,000**
Heat Engine R&D	3,500	3,500	9,000
Systems Development	1,700	1,500	12,000
Advanced Materials	13,015	14,820	16,000
Fuels Utilization	12,675	11,020	15,000
Total	**169,956**	**181,196**	**224,580**

Chapter 8
Efficient and Affordable Buildings



Chapter 8

Efficient and Affordable Buildings

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Overview

Definition of Focus Area

The focus of the efficient and affordable buildings R&D portfolio is on buildings in both the residential and commercial sectors. Residential construction includes single-family, multi-family, and "industrial" (manufactured) housing. Commercial construction includes buildings used for commercial business such as offices, restaurants, hospitals, schools, warehouses, etc. Research and development (R&D) in the buildings sector ranges from improvements to the building shell (i.e., walls, windows, foundations) to improving the equipment used for heating and cooling the space or for providing building services like lighting and appliances, to methods of integrating all of these through "whole building" design techniques.

National Context and Drivers

The United States consumed roughly 94 quadrillion Btus (quads) of primary energy in 1996. The Nation's 100 million households and 4.6 million commercial buildings consume 37 percent or 34.5 quads of this total. Buildings also use two-thirds of all electricity generated nationally. More than $230 billion is spent each year in the United States to provide heating, cooling, lighting and related energy services for buildings. Even if the energy intensity of buildings remains constant, as more buildings are constructed, energy consumption and associated economic and environmental costs will continue to escalate. Energy consumption in buildings is a major cause of acid rain, smog, and greenhouse gas emissions in the United States, representing 35 percent of carbon dioxide emissions, 47 percent of sulfur dioxide emissions, and 22 percent of nitrogen oxide emissions.

One of the primary challenges to achieving efficiency in the building sector is its fragmentation. To start with, the building construction industry encompasses literally thousands of different businesses and millions of individual decision makers. Developers, designers, builders, utilities, engineers, and occupants pursue objectives which often are at cross-purposes. Also, unlike the transportation sector that is dominated by a few major firms responsible for final assembly and product delivery, the building sector has hundreds of thousands of builders who assemble individual components into complete structures. Furthermore, vast variability exists within the constructed structures themselves, so that even a single community might contain hundreds of building styles and sizes. One result of all this diversity is that product integration is less than optimal and buildings are typically designed and constructed as complex amalgamations of individual technologies, each of which carries out its intended function largely independent of (or even in spite of) others, rather than as a tightly integrated system of interrelated components. Inefficiencies and lost energy opportunities are frequent consequences of this situation.

Unfortunately, the number of decision makers that must be influenced and the effort required to pursue a change in the current predicament is high. The buildings sector is a risk-averse industry that has been slow to adopt new technologies that are more efficient than conventional ones. Although not a focus of this paper, Federal efforts in the buildings sector therefore also place a fair emphasis on activities that are designed to encourage the deployment of new energy

efficiency technologies through education, training, and related efforts across the buildings community.

A third consequence of fragmentation is that the building industry spends relatively little on R&D. The industry is dominated by small firms that can ill afford research programs, and competition effectively prevents coordinated or integrated research. R&D expenditures for the buildings sector as a whole are an order of magnitude less than the national average. Given the importance of current energy consumption and projected growth in the buildings sector, maintaining and growing a vital research program for efficient buildings is critical to the success of the Department's overall strategic goal of increasing the efficiency and productivity of energy use.

Another significant element of the Department's R&D program is making homes more affordable for all Americans. Increased affordability is achieved by developing technologies and techniques which can either reduce the amount of energy used or improve the efficiency of its use in buildings at little or no net consumer cost. Such techniques are demonstrated, for example, by the Building America program which strives to increase a home's energy performance 50 percent over the Model Energy Code at little or no additional cost. The Building America program employs strategies such as improved design techniques that greatly reduce thermal leakage through the building envelope, or improved insulation and windows whose costs are offset by resulting reductions in the size of required space conditioning equipment. Other R&D efforts are focused on low-cost technology developments that offer sizable enough returns to justify their use within one or two years of implementation. One example is a thermal duct-sealing technology that can be used as part of the low-income Weatherization Program. This technology reduces leakage of thermal conditioning air by up to 30 percent and yet only costs a few hundred dollars to apply.

Linkage to CNES Goals and Objectives

The efficient and affordable buildings R&D portfolio directly supports CNES goal and objective:

- CNES Goal I, Objective 2 - Significantly increase energy efficiency in the transportation, industrial, and buildings sectors by 2010.

DOE's portfolio emphasizes areas where the opportunity for cost-effective energy reductions are greatest, such as heating and cooling, lighting, and systems integration. DOE estimates that successful realization of its R&D portfolio will reduce buildings energy use by 0.6 quads per year in the year 2010, and by 2 quads per year in 2020.

Uncertainties

The present R&D portfolio is a mixture of near and longer term research efforts. All R&D entails some measure of risk in that not all efforts are likely to come to fruition in terms of achieving the ultimate goal. Risk increases as endeavors become longer-term. Technical problems, both known and unknown, may arise that are insurmountable with current know-how

and are hence candidates for longer-term, investigative research. Spreading risk across such a portfolio increases the likelihood of technical success in at least some subset of the endeavors.

In the current context of the building marketplace, the ultimate goal is reducing energy consumption. However, even if technical capability is achieved, market barriers such as declining real energy prices or conservatism on the part of building designers or builders may still impede market penetration, hence reducing success in achieving this goal.

Finally, there must be sustained commitment with budgets sufficient to continue R&D at a minimum threshold to achieve any measure of success within a reasonable time frame. The minimum funding threshold for any given effort varies as to the program's technical goals, necessary time frame, number of related efforts elsewhere, number of participants, and other factors. Below that level, an R&D program essentially becomes a maintenance program where researchers can keep up with innovations being achieved elsewhere but are unable to achieve much success in their own endeavors. Uncertain or widely varying budgets from one year to the next have similar impacts as researchers and their invested experience move on to more consistent and reliably funded activities.

Investment Trends and Rationale

The current portfolio of investments is driven by both the energy use and market characteristics of the buildings sector. The Energy Information Administration (EIA) projects that the United States will add 28 million households and about 16 million square feet of commercial floor space between now and 2020. Once built, these homes and buildings will last 50 years or longer—considerably longer than most power plants. That is, the impacts of buildings design, construction, and equipment decisions cast very long shadows into the future. Fully 30 percent of commercial floor space and 40 percent of all housing currently in use were built prior to 1960. Therefore, the portfolio must not only address new buildings, but existing buildings through retrofit and renovation.

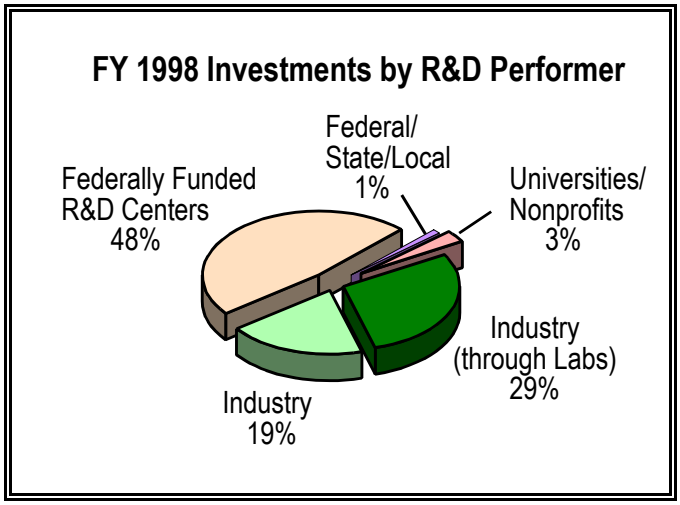
The potential savings impacts to the Nation's projected energy use in buildings are great—the Department projects that from 10 to 30 percent savings are cost-effective in existing buildings and from 30 to 70 percent in new construction. These savings will not only be realized in consumer's pocketbooks but also in reduced environmental impacts of energy production and use.

This paper presents an overview of the R&D portfolio for the buildings sector. R&D areas include (1) Heating, Ventilation, and Air Conditioning; (2) Building Materials and Envelope; (3) Building Design and Operation; (4) Lighting; (5) Appliances; and (6) On-Site Generation.

The first three areas target energy saving opportunities in heating, cooling, and ventilation, which account for 40 percent of building energy consumption on a primary basis. Areas 4 and 5 target the next largest areas of consumption. The final research area, On-site Generation, has the potential for addressing both electric and thermal needs of buildings.

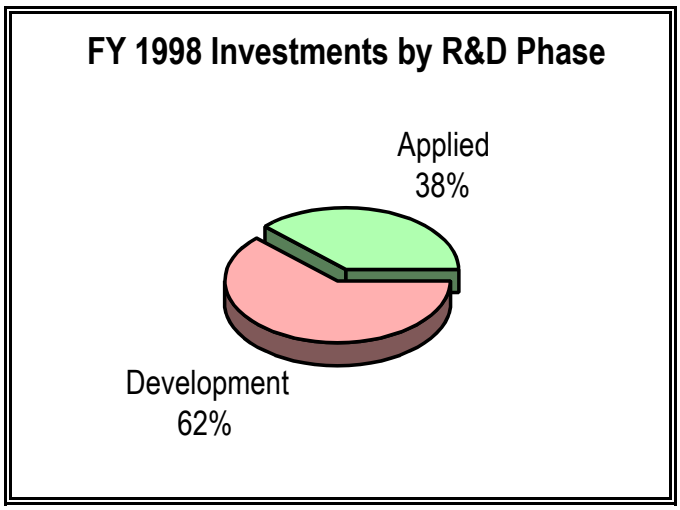
The buildings R&D portfolio is performed by two main entities, with monies spread roughly equally between them. About half (48 percent) of the research is performed by the private sector, either funded directly or through DOE laboratories. An equal amount of research is performed by the DOE laboratories themselves. Only a minor amount of the Department's research is performed by universities (3 percent) or other government agencies (about 1 percent).

Cost-sharing with the private sector varies greatly among research programs, but typically averages between 50 to 75 cents of private contribution for each dollar of public expenditure. Much of this cost-sharing takes place through Cooperative Research and Development Agreements (CRADA) and other types of cooperative research through the National Laboratories, as highlighted in the figure below.[1]



The next figure illustrates the funding divisions between stages of research—development versus applied R&D ("buildings" R&D is by definition does not include basic research). For these purposes, development is defined as enhancements to the performance or operation of a product or practice, with an emphasis on commercialization. An example might be the independent and objective testing or evaluation of a completed system under various operating regimes. Applied R&D examines broader research issues, such as materials compatibility or corrosion.

[1] The breakout of research, development, and demonstration (RD&D) by performer is based on the FY 1995 budget. However, the performer mix has not changed greatly since that time.



As the figure shows, the bulk of Departmental research dollars are devoted to development with the balance spent on applied research. This division is consistent with the primarily near- and mid-term focus of the current research portfolio.

Future Trends in Investment. The buildings R&D portfolio is undergoing a fundamental change. In the spring of 1997, it was recognized, with Congressional concurrence, that there was a need for broader industry input, increased competition and less fragmentation, and greater focus in the portfolio. The Office of Building Technology, State, and Community programs (BTS), which manages the bulk of the Efficient and Affordable Buildings research done by the Department, initiated a strategic planning process that is realigning the research in this sector.

In concert with the recently released Strategic Plan, BTS has initiated an effort to bring stronger focus and relevancy to the buildings R&D portfolio. The plan establishes a new way of doing business:

- Stronger and more effective partnerships with industry, including jointly developed government-industry technology roadmaps that incorporate consumer and end-user perspectives.
- A culture of competitively selected and peer reviewed projects.
- Establishment of BTS as the integrator of cost-effective, technology based, highly efficient energy consuming products and practices.
- An organization that is customer focused, highly productive and results driven.

In consultation with industry and other stakeholder organizations, BTS is developing technology roadmaps to define the future portfolio and to develop strategic alliances with industry. In 1998-1999, roadmaps are being developed for lighting; windows; heating, ventilation, and air

conditioning (HVAC) equipment; and commercial and residential buildings (buildings systems integration). Additional roadmaps will begin in 1999 and carry through 2000. The roadmaps will have an impact on the FY 2000 budget as they evolve.

Federal Role

Research by the Department in the buildings area fills four needs. First, the Department can provide the critical mass necessary to accelerate progress in an area in which the private sector does limited research. Second, in many cases, important research would not occur at all in the absence of the Department's efforts due to the fragmented nature of the buildings marketplace. Third, it provides industry with objective analysis on new technologies and techniques to reduce barriers to new technology adoption. Finally, buildings research can reduce the huge energy costs incurred by the Federal Government—the single largest consumer of energy in the United States.

Key Accomplishments

The Department has a history of supporting RD&D in the area of buildings efficiency technology that has paid off handsomely for the Nation. The net result of just 5 Federal investments made back in the 1970s-80s[2] have resulted in present value savings in the U.S. economy totaling nearly $33 billion through 1997, while simultaneously eliminating more than 60 million metric tons of cumulative carbon emissions. These case study results were reviewed in detail by the General Accounting Office and reflect their conservative accounting methods.

Heating, Cooling, and Air Conditioning

Budget: FY98-$14.7M, FY99-$15.4M, FY00-$11.0M

Background

The demand for HVAC in homes and commercial buildings consumes nearly 14 quads of primary energy per year—40 percent of the primary energy in buildings and 15 percent of U.S. primary energy totals—amounting to $90 billion annually. Buildings consume 4.1 quads of primary fuel to make electricity and 1.85 quads of electricity directly, 5.4 quads of natural gas, 1.2 quads of fuel oil, and 1.2 quads of other fuels (e.g., wood) for thermal comfort services. Space heating and cooling dominate, accounting for over one-third (37 percent) of total energy usage in buildings.

Linkage to CNES Goals and Objectives

[2] The five technologies include the Flame Head Retention Oil Burner, Advanced (Low-E) Glass, Electronic Fluorescent Ballasts, the Efficient Refrigerator Compressor, and the DOE-2 Building Design Software.

This program directly supports CNES goal and objective:

- CNES Goal I, Objective 2 - Significantly increase energy efficiency in the transportation, industrial, and buildings sectors by 2010. *(increase efficiency of space conditioning, ventilation, and thermal distribution equipment; reduce peak-load electricity demand; and enhance indoor air quality)*

Program Description

A variety of equipment provide space conditioning services, including heat pumps, furnaces and boilers, chillers, and others. Thermal distribution systems include fans, ducting, piping, heat exchangers, and controls and can also be the means of primary ventilation. More highly advanced systems incorporate computers, sophisticated building sensors, and complex control strategies.

The equipment used in a given building is determined by building size, function, geographic region, availability of fuel types, consumer preferences, and other factors. Opportunities for the most cost-effective energy savings and improved performance in a given application vary by technology. Therefore DOE has a number of technology development activities underway.

In 1998 the Department joined with the Air Conditioning and Refrigeration Institute (ARI) in developing a roadmap for HVAC research for the future. The ARI initiative, HVAC&R Research for the 21st Century (known as "21-CR") is a comprehensive, industry-generated research agenda. Its major elements include improved equipment efficiency and new refrigeration cycles development, building systems integration, and new working fluids. This effort will help define the next generation of research with implementation beginning in FY 2000.

Geothermal Heat Pumps

Budget: FY98-$6.4M, FY99-$6.5M, FY00-$0.0M

Description, Objectives, and Performers. The geothermal heat pump (GHP), also known as a ground-source heat pump (GSHP) works on the same principle as a conventional (air source) heat pump of transferring heat from a cooler temperature to a warmer temperature. But whereas conventional heat pumps transfer heat to and from outside air, GHPs transfer heat to and from the earth. While this technology typically has a low life-cycle cost and is more efficient than conventional HVAC technology, first costs are high. DOE funds geothermal heat pump research and development and technical assistance programs at the International Ground Source Heat Pump Association (IGSHPA), consisting of 24 utilities, and Oak Ridge National Laboratory (ORNL).

R&D Challenges. The objective of the DOE activity is to reduce the initial cost of the system. Research is needed to reduce the cost of installing the underground heat exchanger, the costliest portion of a GHP system. Reduction of costs in other system components also need attention. Goals include a 40 percent reduction in ground loop heat exchanger cost.

R&D Activities. Research is focused on developing methods to properly assess the thermal characteristics of the installation site to reduce the installation cost of the underground heat exchanger. There is also ongoing research on other system components and system integration, such as developing hybrid systems using small cooling towers, snow melt, and passive surface heat exchangers to reduce operating and capital costs.

Accomplishments. Among the DOE successes in this area were the use of improved simulation models to develop a "rule of thumb" for ground loop design that resulted in 40 to 50 percent shorter loops, and hence, lower first cost.

Absorption Technologies

Budget: FY98-$5.4M, FY99-$5.9M, FY00-$6.5M

Description, Objectives, and Performers. Absorption technologies are being pursued for both residential and commercial applications. The commercial research is focused on alternative working fluids and system enhancements to improve energy efficiency. The residential effort is centered around development of an absorption heat pump (AHP).

An AHP differs from an engine-driven heat pump in the way the refrigerant is compressed. An AHP absorbs the refrigerant vapor from the evaporator in a solution rather than using a mechanical compressor. The refrigerant is then separated from the solution by heating it with natural gas. A natural gas-fired absorption heat pump has the potential to have substantially lower (40 to 50 percent) operating costs compared to conventional heating and cooling systems and also offers an opportunity to serve cooling needs with natural gas. AHPs also have more uniform temperature distribution, can be operated at variable speeds, and provide significantly warmer air than that produced by electric heat pumps. An additional objective of the DOE effort is to help U.S. manufacturers recover a technical advantage in large commercial chiller applications by ultimately developing a gas absorption heat pump with a coefficient of performance of 1.8 in heating and 0.8 in cooling. The work is carried out through industry cost-shared programs with a major manufacturer and 3 small business establishments, 1 university and ORNL in close coordination with the Gas Research Institute (GRI) and major gas utilities. The program is 35 percent cost-shared.

R&D Challenges. The R&D challenge is the development of materials that will not corrode from the use of non-ozone depleting working fluids.

R&D Activities. Two different gas-fired absorption heat pump concepts are being researched. The Generator Absorber Heat Exchange ("GAX") is intended for markets where heating dominates energy use while the "Hi-Cool" unit is targeted towards cooling-dominated markets. In 1999, the first GAX prototype will be tested. This design uses a non-ozone depleting working fluid consisting of an ammonia/water mix. "Hi-Cool" research has advanced to initial stages of system development and is in the process of developing a prototype. Absorption chiller research continues with field testing of a lithium/bromide triple-effect chiller for cooling commercial buildings. Laboratory tests of this cycle have

demonstrated significant (30-40 percent) improvements in energy efficiency of chiller applications.

Accomplishments. A complete residential GAX heat pump assembly was put into full operation and laboratory-tested in 1998. Measured heating efficiency was found to be 100 percent better than the best existing gas-fired condensing furnace.

Desiccants

Budget: FY98-$2.4M, FY99-$2.5M, FY00-$4.5M

Description, Objectives, and Performers. Desiccant systems take advantage of thermodynamic relationships between air temperature and humidity. Desiccant materials have a higher affinity for water than does air and can therefore be employed to absorb moisture and lower air humidity. Once the air is dried, cooling it requires less energy than if it were still humid. Energy and cost savings (as well as precise humidity control and alleviation of moisture-related indoor air problems) are thereby possible with proper desiccant system design. Desiccant systems are complex and not fully understood. The objective is to develop and disseminate credible information on desiccant systems operation and design in order to ensure their use where economically advantageous from an energy efficiency perspective or to address problems of indoor air quality. The National Renewable Energy Laboratory (NREL) and ORNL assist 2 industry teams consisting of a major HVAC manufacturer and desiccant wheel manufacturers. This activity focuses on the continued development and integration of desiccant wheel and complete system testing of new designs and materials as they emerge from manufacturers. The program is 40 percent cost-shared.

R&D Challenges. The R&D challenges are to better understand the properties of solid desiccant materials and system operation, thereby developing the information needed to achieve optimal system design. With liquid desiccants, the challenge is to reengineer the absorber to increase the stability of the liquid/air interface and reduce the potential for droplet formation and carryover into indoor air.

R&D Activities. R&D activities include objective testing, analysis and feedback to industry on the design, performance, and durability of prototype solid desiccant wheels and humidity control systems. There is also ongoing field testing to integrate prototype desiccants into conventional HVAC systems. Research continues with industry on a cost-shared project to develop high efficiency liquid dehumidifiers.

Accomplishments. A highly successful testing and evaluation program of solid desiccant wheels with industry was achieved.

Furnaces and Boilers

Budget: FY98-$0.5M, FY99-$0.5M, FY00-$0.0M

Description, Objectives, and Performers. Oil furnaces and boilers provide heat and hot water in over 10 million buildings. Oil-heating is provided by heating air or through hydronics (water radiating heat through a piped system). An oil burner system delivers and disperses the fuel, and ignites and monitors the flame used to heat the air or water. The objective of the DOE effort is to reduce oil consumption through improved burner design. The program works with three equipment manufacturers and the New York State Energy Research and Development Agency (NYSERDA), and is cost-shared with about 60 percent of funds coming from industry. Future plans are to have the program become 100 percent funded by industry.

R&D Challenges. The challenge is to develop low-cost, low NO_x emission burner technologies.

R&D Activities. DOE research focuses on improvements to burner design and operation. DOE is testing a prototype low NO_x version of the fan atomized burner. Research is also underway on a second generation burner that will be lower cost and include self-tuning features to maintain efficiency.

Accomplishments. DOE funded earlier development of the flame retention head oil burner which now dominates the marketplace resulting in $5.0 billion in cumulative consumer cost savings.

Building Materials and Envelope

Budget: FY98-$7.2M, FY99-$10.7M, FY00-$10.4M

Background

The building envelope is the barrier between the interior and exterior environment. It consists of the walls, windows, roof, foundation, and doors. Energy demand for heating, ventilation, and air conditioning is determined by the thermal integrity of the building envelope, “air-tightness,” and by occupant behavior. There is much interaction between building envelope, lighting, and HVAC components. DOE conducts a diversified portfolio of research into components and systems.

Linkage to CNES Goals and Objectives

This program directly supports CNES goal and objective:

- CNES Goal I, Objective 2 - Significantly increase energy efficiency in the transportation, industrial, and buildings sectors by 2010. *(increase the thermal performance of the*

building envelope, increase indoor air quality, reduce the environmental impact of building construction, and increase occupant comfort)

Program Description

Component research includes advanced materials and insulations, high-performance windows, and innovative components such as self-drying roofs. DOE works with industry to develop systematic and objective evaluation methods for all envelope components. These range from thermal control windows ("superwindows") to dynamic wall systems, and from highly-reflective building surfaces designed to reduce cooling loads to energy efficient and durable commercial roofing systems. This research also provides the technical foundation for the industry consensus process for building standards and guidelines, such as those of American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) and the American Society for Testing of Materials (ASTM).

Windows and Glazings

Budget: FY98-$5.0M, FY99-$6.8M, FY00-$6.6M

Description, Objectives, and Performers. Windows are major determinants of heating needs, due to conductive losses, air infiltration, and solar gain; and to cooling needs, largely due to solar gain. As such, improving the thermal performance of window systems is an important element in reducing the energy required to provide consistent thermal comfort. The Department's goal is to conduct research and development on advanced window technologies and to develop design, rating, and information tools needed to optimize the use of these technologies. The program works with three manufacturers, two research institutes, an industry association, one university, and three National Laboratories in its research program. Roughly 80 percent of the funding goes to the National Laboratories.

R&D Challenges. Coating design, performance, and durability are technical barriers for electrochromic and other advanced window concepts. First costs for advanced window systems will also be barriers to market acceptance without substantial engineering improvements.

R&D Activities. Research on windows and glazing systems focuses on development of advanced materials, devices, and technologies as well as creating the analysis, simulation, and test procedures needed to accurately characterize performance. Electrochromic research continues on improving coating design and performance and durability of window that can be switched from clear to opaque to control cooling loads and manage daylight levels. This technology offers large energy savings potential, and the ability to shave peak electricity demand in the "Sunbelt," where much of the Nation's construction is occurring. DOE also provides testing of prototype high performance windows with superior thermal qualities using computer simulation, infrared, and thermal performance test facilities. Finally, DOE develops performance data, procedures, and tools that underlie the highly successful National Rating Fenestration Council windows rating system.

In 1998, the Department joined with industry partners in developing a vision and a roadmap for windows research for the future. This is the first portion of a broader building envelope roadmap. This effort will help define the next generation of research with implementation beginning in FY 2000.

Accomplishments. The low-emissivity (Low-E) window, which reduces the transfer of long-wave, infrared radiation was developed in the early 1980s. Currently, this technology accounts for 35 percent and 18 percent of residential and commercial window sales, with cumulative consumer savings of about $5 billion.

Walls, Roofs, and Foundations

Budget: FY98-$2.2M, FY99-$3.9M, FY00-$3.8M

Description, Objectives, and Performers. About 40 percent of the 34 quads of building energy use serves space conditioning and ventilation needs. The thermal performance of the building envelope is a major determinant of this energy use. The Department conducts research and development to significantly improve the thermal performance of walls, roofs, and foundations, and to investigate the effects of reflective surfaces and vegetation on building demand for cooling energy. In addition to the opportunity to lower energy use, other benefits include the increased durability of building envelope systems and materials and environmental improvements such as reduced construction waste, decreased use of ozone-depleting insulations, possible increased use of indigenous materials, and decreased summer temperatures (and air pollution) in urban areas through mitigation of the "urban heat island" effect. Major performers include ORNL, which hosts the Buildings Technology Center— a user facility that enables users (nearly 300 organizations) to share research costs with DOE. Lawrence Berkeley National Laboratory (LBNL) is the research organization for highly reflective surface research.

R&D Challenges. The lack of objective, widely available information on "whole-wall" and thermal reflective surface field performance, hinders market acceptance of novel, high performance technology. Uniform and comprehensive metrics are also needed to assess the environmental impacts of alternative insulation blowing agents. Durability of high performance roofing systems is another challenge.

R&D Activities. The Department's "Buildings Technology Center" tests, models, and rates whole wall systems for thermal resistance, thermal mass benefit, and air leakage. Simplified tools are maintained on the Internet that allow building professionals to design energy efficient and durable wall and roofing systems. Research is targeted towards the development of advanced manufacturing processes for "next generation" insulation alternatives such as aerogels, evacuated panels, and non-HCFC foams. Commercial roofing systems typically have an installed R-value of 10 and a service life of 15 years or 30 percent of the remainder of the building envelope. DOE is performing laboratory and full-scale field testing of advanced roofing systems that are significantly more durable and energy efficient. To reduce cooling loads, buildings can incorporate highly reflective surfaces and roofing materials but a key issue is establishing field performance levels. DOE is therefore working

to develop standardized protocols for measuring the energy performance of a variety of highly reflective roofing and pavement materials.

Accomplishments. Program accomplishments include the creation of a vacuum insulation panel that offers R-values an order of magnitude greater than that of standard insulation products.

Building Design and Operation[3]

Budget: FY98-$11.8M, FY99-$13.0M, FY00-$16.5M

Background

Buildings, although often "simple" in appearance, are in fact complex and dynamic systems made up of numerous components and subsystems. The interaction of these components and systems can have a profound impact on energy consumption, cost, and related pollution. Furthermore, because buildings differ greatly in size, shape, function, and intensity of use, these system interactions change from one building to the next.

The overall design and orientation of buildings have a substantial impact on energy consumption. The "pieces" of a building most relevant to an analysis of energy consumption are the building envelope (foundation, walls, windows, and roof); the heating, ventilating and air-conditioning subsystem; the lighting subsystem; the water heater and other appliances, including refrigerators, computers, and clothes washers and dryers; the energy controls associated with the HVAC and lighting subsystems; and the building occupants themselves. The energy requirements of a building or home depend not only on the *individual* performance of these components and subsystems but also on their *combined* performance when integrated into a unique building and how the building - as a system - is operated. There are large differences between building types in terms of systems design and operation considerations. For instance, in large office buildings, the interaction between lighting and other internal loads and HVAC is a very important design consideration, whereas this is not true in homes because lighting is a small energy user and is typically used in the evening hours when cooling loads are less.

An example may be useful for illustrating the importance of systems design approaches. In homes, the thermal integrity of the windows, walls, and roofs determines the heating and cooling loads the HVAC system must meet to keep occupants comfortable. A well-built home designed and oriented to take advantage of "passive" solar heating in heating climates, or incorporating "superwindow" technology that admits light but not heat in cooling climates, can meet its lowered thermal load with smaller and less costly heating and cooling systems, and perhaps without such systems altogether.

[3] This area includes research activities from "Building Integration" and "Design Tools and Strategies" budget categories.

Due to industry fragmentation, the Department has a key role as an integrator in optimizing the design, installation, and operation of energy related building components using a systems approach. Because a systems approach may be nonintuitive and not lend itself well to simple design guides and checklists, much of the effort focuses on development of interactive, user-friendly design tools for use by the buildings community.

Linkage to CNES Goals and Objectives

This program directly supports CNES goal and objective:

- CNES Goal I, Objective 2 - Significantly increase energy efficiency in the transportation, industrial, and buildings sectors by 2010. *(reduce energy consumption through energy-efficient design techniques, reduce construction waste, increase use of passive solar in building designs, and reduce operation and maintenance costs)*

Program Description

The Department's research activities center on both building design and construction, as well as operation and maintenance (O&M). During building design and construction, subsystem, and component choices are made and actual construction begins. During the O&M phase, the building is occupied and in use. DOE develops tools and protocols for building design and operation as well as providing the technical basis for the industry consensus process for standards and guidelines, such as those of ASHRAE and ASTM.

Commercial Buildings

Budget: FY98-$5.0M, FY99-$5.2M, FY00-$8.0M

Description, Objectives, and Performers. DOE's commercial building research focuses on integrating technologies and practices to optimize whole building energy performance both during renovation and new construction. The objective of the research is to lower energy use by 25 percent or more, relative to conventional approaches, while increasing occupant comfort and productivity. DOE funds joint research with an industry consortium on integrated buildings designs and systems that are adaptable to changes in building use. Partners include National Laboratories and a consortia of universities, industry, and government organizations.

R&D Challenges. The R&D challenges are developing commercial whole building approaches for both new and existing buildings that are simple to integrate and that integrate simply with other building systems. They must be economically and ecologically sustainable, be acceptable to their community, and must easily adapt to a rapidly changing workplace. Addressing these challenges will in part require design tools and techniques which are robust, user-friendly, and accurately portray interactions between system components. These tools and techniques must be adaptable and transferable across design, construction, and operation stages of the building life-cycle.

R&D Activities. The Department's research on commercial building design and operation focuses on two areas: design strategies and energy performance tools that enable architects to optimize building performance at the point of design; and advanced building controls and diagnostics to optimize building operation once the building is occupied. Both approaches actively encourage the use of a "systems engineering" approach to the design and operation of commercial buildings, and thus the benefits are large, and cost-effective. Current Department research activities include development of software that incorporates consideration of passive solar options into small commercial buildings designs; new performance simulation software to replace DOE-2 ("EnergyPlus"); and the Whole Building Diagnostician, a hardware/software system to monitor real-time building performance. These tools and new technologies are field tested with the building industry in the context of real building projects via DOE's Commercial Exemplary Buildings Project. Measured energy cost savings of from 42 percent to 63 percent have been cost effectively achieved with no compromise of functionality or comfort.

In 1998, the Department joined with industry partners in developing a vision and a roadmap for commercial buildings design and operation research for the future. This effort will help define the next generation of research with implementation beginning in FY 2000.

Accomplishments. A success in this area is "DOE-2," a widely used performance simulation tool that calculates energy use and cost from weather, building attributes, and other data. Approximately 15 percent of new commercial floorspace is designed with DOE-2 for cumulative energy savings to date of approximately $21.4 billion.

Residential Buildings

Budget: FY98-$6.8M, FY99-$7.8M, FY00-$8.5M

Description, Objectives, and Performers. DOE's residential systems research program focuses on accelerating the development of innovative residential energy systems by conducting full scale experiments on new residential buildings and manufactured homes. This industry consists of over 100,000 builders, and tens of thousands of component manufacturers. There is little integration or coordination of energy components in systems, and the industry is quite risk-averse in that it is very slow to adopt new technologies and embrace change. Through the Building America program, DOE facilitates integration of research and application in residential new construction. Experiments are conducted using an iterative design, test, redesign, retest sequence to ensure that technical barriers are fully identified and resolved during the research process.

The Building America program has established a unique arrangement with four consortia of private-sector firms in the residential building industry to carry out its research agenda. Each consortia is made up of a team of architects, engineers, builders, equipment manufacturers, material suppliers, community planners, mortgage lenders, and contractors, including more than 80 companies total. These four industry teams have committed $30 million over the next 3 years to implement full-scale systems engineering housing technology innovations. All projects are cost-shared between DOE and the Building America teams.

R&D Challenges. The challenges involve reducing the energy consumption of new residential buildings by 25 to 50 percent with little or no increase in construction costs. Achieving this will require development of building techniques that are quick and easy to implement, reliable, widely deployable, and inexpensive. One of the greatest barriers to implementation is overcoming worker reluctance to abandoning traditional building practices, thus new innovations must bear all of these qualities to be successful.

R&D Activities. DOE will test and evaluate alternative design and construction strategies. This includes analysis of alternative wall insulation designs on productivity in factory-built housing, air sealing strategies for modular housing, and development and testing of sheathing-integrated moisture and air barrier systems. Other activities include development of new low thermal loss duct designs, super-insulated ceiling systems, and AC control strategies for hot humid climates to maximize moisture removal during low load conditions. DOE develops and tests passive solar designs and phase-change materials. DOE develops computer simulation software and hardware to effectively monitor residential building energy performance. As part of this program, DOE has many partners including major builders, materials and equipment manufacturers, universities, research institutes, and industrialized home manufacturers. These partners contribute to research both through cost-sharing, research in-kind, or by sharing facilities.

Accomplishments. DOE worked with a manufacturer to design the first manufactured house to meet ENERGY STAR performance criteria and developed strategies to achieve 30-50 percent reductions in heating, cooling, and hot water energy use, the results of which, have been incorporated into new products by Carrier Corporation, USG Corporation, General Electric Company, Owens Corning, Tamarack Technologies, Inc., Ryan Homes, Pulte Homes, Beazer Homes, and others. To date, a total of 972 houses have been completed in Building America projects. Additional community-scale projects have been initiated in Denver, CO, Los Angeles, CA, Pittsburgh, PA, and Tucson, AZ.

Lighting and Appliances

Budget: FY98-$8.1M, FY99-$9.6M, FY00-$15.2M

Background

In 1996, lighting in U.S. residential and commercial buildings used about 4.8 quadrillion Btu of primary energy, or about 14 percent of all energy used in buildings, at a consumer cost of $34 billion. In commercial buildings, lighting service demand represents one-fourth of total energy demand. Conventional lighting technologies still predominate throughout the economy—incandescent and standard fluorescent lamps account for almost two-thirds of the energy used to light buildings in the United States. Significant room for efficiency improvement exists. As artificial lighting is exclusively an electric technology, any savings achieved at the point of end use is tripled at the utility generation plant, bringing with it concomitant carbon reductions and other associated benefits.

Appliance technology comprises major building energy-consuming equipment other than that for space-conditioning and lighting. Appliances provide a variety of energy services, including water heating, food preparation and storage, clothes washing and drying, dish washing, and other services ranging from entertainment to security. Many smaller appliances present a difficult target for improved energy efficiency because of their low individual energy use and low frequency of use. The best candidates for efficiency improvements are those that involve transport, compression, heating or cooling of fluids (e.g., refrigeration, water heating), or involve significant use of transformers or electric motors. In some cases, process substitution (e.g., microwave drying in place of thermal drying) may offer additional alternatives for energy savings.

Water heating is the third largest end use for buildings in terms of magnitude, consuming about 3.9 quadrillion Btu in 1996 (11.3 percent of total buildings energy use), at a consumer cost of $25.9 billion. Refrigeration/freezers are also large energy users, about 2.2 quadrillion Btu in 1996 (6.4 percent of total buildings energy use) at a cost of $16.3 billion.

Linkage to CNES Goals and Objectives

This program directly supports CNES goal and objective:

- CNES Goal I, Objective 2 - Significantly increase energy efficiency in the transportation, industrial, and buildings sectors by 2010. *(reduce the first-cost of energy efficient light sources, develop new and innovative light sources and delivery systems, integrate natural light into lighting systems, and measure and assess the impact of alternative lighting regimes on worker health, safety, and productivity; increase energy efficiency of major energy consuming appliances, integrate appliances to capture and reuse waste heat, and develop appliances which use renewable energy sources rather than fossil fuels)*

Program Description

Electric lighting improvements underway include new and more efficient light sources, fixtures, light distribution systems, and improved ways of utilizing lighting based on the effects of lighting on vision and workplace productivity. Improved daylighting systems allow daylight to be used in buildings to offset electric lighting needs while achieving improved heating, cooling, comfort, and health performance. In 1998, the Department joined with industry partners in developing a roadmap for lighting research for the future. This effort will help define the next generation of research with implementation beginning in FY 2000.

Improved technologies underway include heat pump water heaters, improved insulations for refrigerators, and "integrated" appliances where, for example, waste heat from one serves as a heat source for another.

Lighting

Budget: FY98-$2.4M, FY99-$3.1M, FY00-$4.5M

Description, Objectives, and Performers. Lighting is responsible for 15 percent of energy use in buildings. Lighting systems include sources, fixtures and distribution systems, and controls. Artificial light sources include incandescent, fluorescent and High Intensity Discharge lamps (the "bulb"), while fixtures, by use of reflectors and diffusers, distribute the light. Lighting distribution systems can also include more advanced concepts, such as fiber optics, for distributing light from natural or artificial sources. Controls include occupancy detectors for automatically turning off light fixtures, discrete digital timer controls, and centralized computer controls. Lighting quality is also an area of intense interest, affecting worker productivity, comfort, and even health and safety. DOE's program is intended to help cut the energy used by lighting in half over the next 15 years. The Lighting program partners with numerous manufacturers, utilities, universities, and users in carrying out its research agenda. The program is 75 percent funded by industry.

R&D Challenges. The R&D challenges include optimizing component performance, size, and manufacturing processes to achieve cost-effective substitutes for conventional technology.

R&D Activities. Research includes a cost-shared effort with industry to develop a low-cost compact fluorescent lamp (CFL). This involves optimizing the power supply circuit, electrodes, phosphors, and ballast for performance and low-cost manufacture. DOE is also researching a new light source, the low-power sulfur lamp, which involves scaling down current technology to develop a smaller bulb as well as a solid-state source for microwave production. Fixture research is focused on efficient light distribution from non-linear sources (such as fluorescent), by redesigning fixtures traditionally used for (incandescent) point sources. DOE is developing expert controls systems to manage and control lighting subsystems. In addition, DOE is researching distribution systems for natural and artificial high-intensity, light sources. Finally, DOE conducts experiments and field tests that include testing high intensity outdoor lamps of different spectrums to produce a better quality light that improves vision while allowing lamps to be operated with less energy.

Accomplishments. Research on energy-efficient electronic ballasts in the late 1970s resulted in a product that captured 31 percent of sales, with up to 30 percent reduced energy use and cumulative energy savings worth $3.7 billion over the life of the technology.

Refrigeration

Budget: FY98-$3.1M, FY99-$2.9M, FY00-$3.1M

Description, Objectives, and Performers. Refrigeration includes both residential refrigerators/freezers, and commercial refrigeration uses such as in supermarkets. It encompasses not only component efficiencies, but also replacements for ozone-depleting substances used as working fluids. The objectives of the DOE activity are to eliminate all use of ozone-depleting chemicals while simultaneously increasing the operating efficiency of

refrigeration equipment. BTS also works with four manufacturers and the National Institutes for Science and Technology in this research program. Cost-sharing in this area is essentially 1:1 in matching funds.

R&D Challenges. The R&D challenges are to reduce the costs and ensure compatibility of alternative working fluids and equipment designs so that they are economically competitive with conventional technology for widespread application.

R&D Activities. For new refrigerants, DOE is completing the successful seven-year, industry-led, jointly-funded program of materials compatibility and lubricants research. This program has paved the way for a new generation of chlorine-free refrigerants to replace refrigerants which deplete the ozone layer. DOE is completing laboratory development through a CRADA for a pre-production refrigerator/freezer using 50 percent less energy than current designs, and will be demonstrating supermarket refrigeration/HVAC energy savings in field tests of new systems with industry partners.

Accomplishments. A “fridge of the future” that uses half as much energy as today’s refrigerator-freezers and a fifth as much as 1972 models was designed and demonstrated at a DOE National Laboratory during 1997. This reduction in energy use (from 2 to 1 kWh per day) exceeds the decrease called for in a 1997 rule, which requires refrigerators sold in 2001 to use 30 percent less electricity than those on the market today.

Heat Pump Water Heater and Appliances

Budget: FY98-$0.0M, FY99-$0.0M, FY00-$2.1M

Description, Objectives, and Performers. Appliances and hot water account for nearly one-fourth of energy use in buildings. Of this, hot water accounts for about half. Current research is focused on the heat pump water heater (HPWH) which offers performance improvements 2-3 times that of conventional electric resistance water heating.

R&D Challenges. The challenge is to reduce the cost of equipment and installation through design improvements.

R&D Activities. Residential HPWH have the potential to cut electric water heating bills in half. Research is underway to develop and begin field testing of innovative heat pump water heater concepts that have much lower cost and are easier to install than conventional technology. DOE will be developing and testing “drop-in” HPWH designs in conjunction with major manufacturers. In FY 2000, the appliance research effort will focus on development of prototypes of high efficiency laundry equipment.

Accomplishments. Accomplishments include performance testing and evaluation of energy and water savings of H-Axis washing machines.

Solar Water Heating

Budget: FY98-$2.6M, FY99-$3.6M, FY00-$5.5M

Description, Objectives, and Performers. Solar heaters consist of a collection system that captures the sun's thermal energy, a distribution system, and a control system to regulate these functions. Some types of systems also include an energy storage system.

R&D Challenges. The challenges are to increase the durability and effectiveness of components while decreasing the component costs.

R&D Activities. Research efforts are focused on exploring the use of new materials (polymers) and components (heat pipes) to create the next generation system. The goal, by 2004, is to reduce system costs for solar water heating from $0.08/kWh to $0.04/kWh and for pre-heating of building ventilation air from $0.02/kWh to $0.005/kWh .

Accomplishments. Solar hot water systems research has resulted in a total reduction in cost from $0.20/kWh in 1980 to the current $0.08/kWh. A recent accomplishment is the development of a selective absorbing coating for solar collectors, *Black Crystal*, that has the potential to replace the industry standard material, black chrome. The transpired solar collector for pre-heating ventilation air won an R&D 100 Award and reduced costs to $0.02/kWh.

On-Site Generation

Budget: FY98-$1.0M, FY99-$1.8M, FY00-$5.5M

Background

Generating electric power at individual building sites versus at remotely-located central power plants offers a number of potential benefits to the Nation. First, on-site generation avoids many of the disadvantages associated with transmission and distribution—costly infrastructure and permitting, health and aesthetic externalities, and energy loss. Second, because distributed generation often takes place in close proximity to other thermal loads, such as space conditioning and water heating, the “waste” heat that is rejected from the generation process can be used by these other applications, i.e., cogeneration. This leads to very high system efficiencies, on the order of 80-90 percent (i.e., the electric and thermal output divided by the fuel input). These high efficiencies translate, in turn, into reduced emissions relative to conventional central station fossil generation.

Linkage to CNES Goals and Objectives

This program directly supports CNES goal and objective:

- CNES Goal I, Objective 2 - Significantly increase energy efficiency in the transportation, industrial, and buildings sectors by 2010. *(reduce overall energy consumption by eliminating line loss caused by electricity transmission, increase the use of natural gas as*

generation source for electricity, and increase opportunities for cogeneration of electricity and heat for building space conditioning)

Program Description

On-site power plants can range in size from a few watts to several hundred kilowatts. Potential "distributed" generation technologies include fuel cells, photovoltaics, micro turbines, and reciprocating, and rotary engines. The Department's buildings research in this area is currently focused on fuel cells.

Fuel Cells

Budget: FY98-$1.0M, FY99-$1.8M, FY00-$5.5M

Description, Objectives, and Performers. Fuel cells are similar to batteries in that they produce electricity through electrochemical reactions. A battery depletes itself or must be recharged, but a fuel cell produces power continuously when supplied with an appropriate fuel and oxidant. A fuel cell consists of positive and negative electrodes immersed in an electrolyte. A hydrogen-bearing fuel is supplied to the anode along with oxygen, usually derived from air, to the cathode. During operation, the fuel is oxidized and the resulting chemical reaction produces direct current electricity. Waste heat from the reaction is available for recovery for thermal applications, from water heating to space conditioning, and in applications where all available heat is recovered, fuel cell system efficiencies—cogeneration—can exceed 85 percent. The objective is to develop the components and systems necessary to bring fuel cells to building applications. The BTS program works with five manufacturers and Argonne National Laboratory in carrying out its research agenda, with a cost-share of 40 percent.

R&D Challenges. The research challenges are fuel cell cost, longevity of components, and compatibility with various sources of hydrogen.

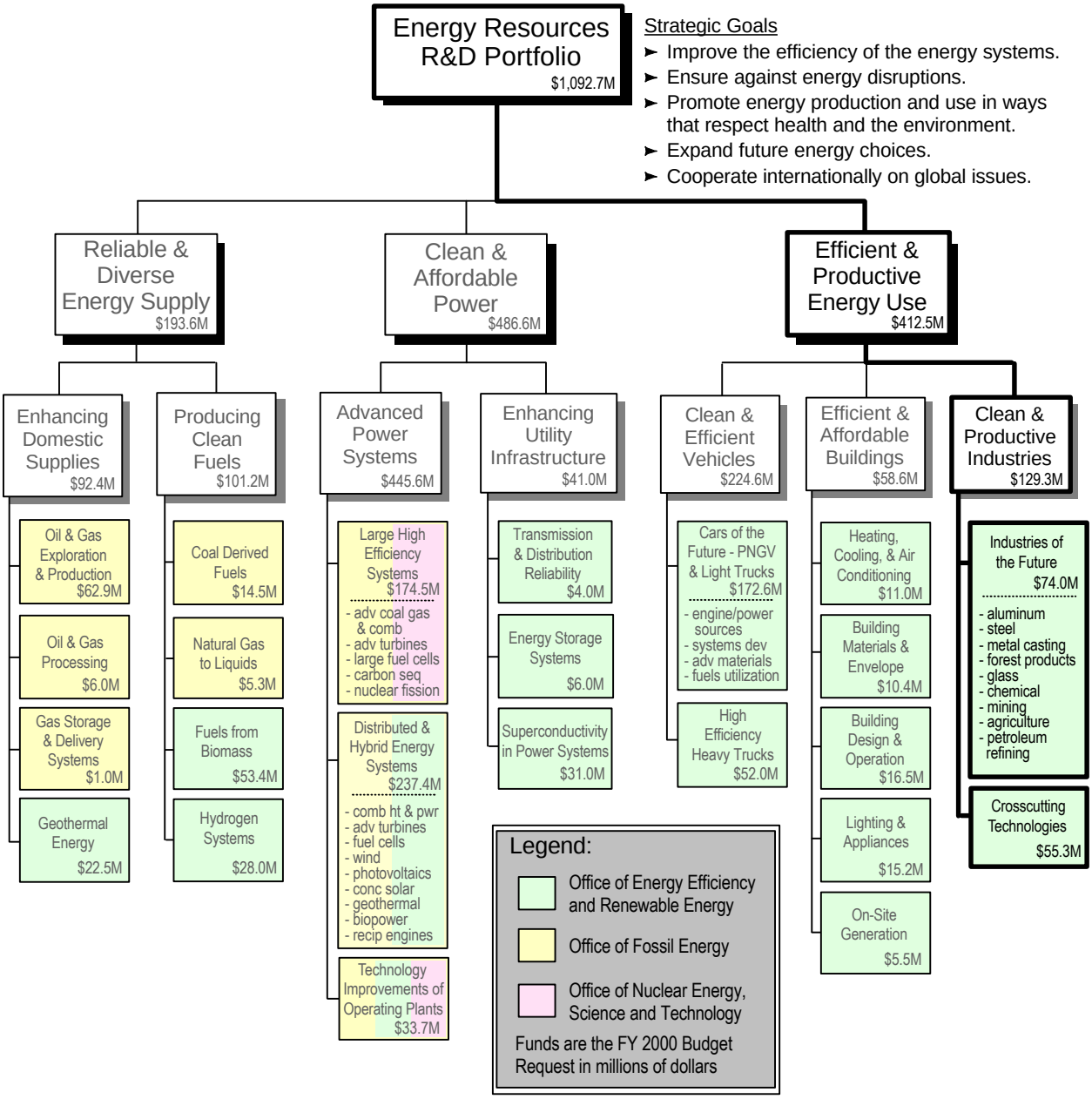
R&D Activities. The Department's research in buildings-applicable fuel cells, initiated in FY 1995, draws to the extent feasible on research in transportation and military applications, but focuses on the unique needs of buildings, that include lower noise levels, increased power densities, and durability in the 40,000 hour range (versus 3,000 for an automotive fuel cell). The Department's research is focusing on fabrication and testing of the prototype methane reformer and its incorporation into a Proton Exchange Membrane fuel cell. The Department's near-term R&D goal is to develop a first-generation prototype Proton Exchange Membrane fuel cell by FY 2002, and to demonstrate its performance in a commercial building.

Accomplishments. This is a new program so there are no accomplishment to date.

Summary Budget Table (000$)

Efficient and Affordable Buildings Research Areas	FY 1998 Appropriated	FY 1999 Appropriated	FY 2000 Request
Heating, Cooling, and Air Conditioning	**14,650**	**15,390**	**11,000**
Geothermal Heat Pumps	6,400	6,500	0
Absorption Technologies	5,400	5,910	6,500
Desiccants	2,350	2,480	4,500
Furnaces and Boilers	500	500	0
Building Materials and Envelope	**7,187**	**10,723**	**10,400**
Windows and Glazings	4,959	6,829	6,610
Walls, Roofs, and Foundations	2,228	3,894	3,790
Building Design and Operation	**11,811**	**12,970**	**16,500**
Commercial Buildings	5,000	5,200	8,000
Residential Buildings	6,811	7,770	8,500
Lighting and Appliances	**8,115**	**9,560**	**15,230**
Lighting	2,350	3,100	4,500
Refrigeration	3,140	2,860	3,130
Heat Pump Water Heater and Appliances	0	0	2,100
Solar Water Heating	2,625	3,600	5,500
On-site Generation	**1,000**	**1,750**	**5,500**
Fuel Cells	1,000	1,750	5,500
Total	**42,763**	**50,393**	**58,630**

Chapter 9
Clean and Productive Industries



Chapter 9

Clean and Productive Industries

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Overview

Definition of Focus Area

The clean and productive industries research and development portfolio focuses on generic pre-competitive research concentrating on cooperative projects with nine of the major process and extraction industries in the industrial sector. These industries, referred to as the Industries of the Future, include aluminum, steel, metal casting, forest products, glass, chemicals, mining, agriculture, and petroleum refining. In addition, the portfolio includes crosscutting research and development efforts on technology needs which have been identified in technology roadmaps across multiple industries, and which form technology bases from which more industry-specific developments can derive. The cross cutting activities also include technical information and outreach programs, demonstrations, training, and tool development which assist industry in evaluating and adopting these new energy efficient and pollution preventing technologies and techniques.

National Context and Drivers

Industry consumed almost 34 quads of primary energy in 1994—about 38 percent of all energy used in the United States The industrial sector contains extraction, and material processing and product manufacturing industries. Over 80 percent of the energy consumption in manufacturing (including feedstocks) occurs in only seven process industries: aluminum, steel, metal casting, forest products, glass, chemicals, and petroleum refining. Mining and agriculture are major energy users in the extraction industry. These nine industries are highly capital intensive, produce significant emissions and waste products with far larger energy and pollution abatement costs per unit sales, and typically invest far lower percentages of sales into research and development than the U.S. average. Overall energy intensity (energy per unit output) decreased from 1973 through 1986, but has since remained nearly level, while pollution abatement costs have continued to grow; due in significant part to energy consumption.

The major process industries are, and are becoming increasingly, highly capital intensive. Markets are continuing to become increasingly globally competitive. Many, such as steel, faced dire times in the 1960s and 1970s. They restructured and re-engineered themselves such that by the 1980s, they were world leaders. By the late 1990s, world financial markets, trade issues, increasing costs of environmental abatement and other costs, not necessarily shared by foreign competitors, and generally soft markets have again placed major strains on these industries. Reducing energy costs and reducing waste and reducing or eliminating environmental emissions upstream (closely related to energy use), are increasingly being recognized as controllable costs that can lead to increased productivity and profitability, increased product quality, and increased global competitiveness.

Linkage to CNES Goals and Objectives

The program is in direct support of CNES goal and objective:

- CNES Goal I, Objective 2 - Significantly increase energy efficiency in the transportation, industrial, and buildings sectors by 2010.

A reasonably ambitious goal for industry for the year 2010 is a 25 percent reduction in energy consumption per unit of output. The strategy to support the achievement of this goal, in addition to focusing resources on the most energy and waste intensive industries, is to partner with and across industries, and align industry and government resources to areas of greatest need.

Uncertainties

In addition to the normal uncertainties in the R&D process, timing uncertainties are in some industries of particular importance. Many large plants and large equipment modules were installed in the rapid economic growth period after WW II through the 1960s. These will be reaching their useful life by the end of the next decade. Hence, a window exists where the new technologies, if developed in time, may be adopted rapidly during the expected new or retrofit installations; if that window is missed, adoption will be slower in the face of recently installed high capital investment facilities. In addition, several of the major process industries are operating at very low or negative profit margins due in large part to low global prices associated with the current Asian and Eastern European economic situations. The restructuring of the utility industry, climate change, and emission requirements also have the potential for significant impacts, but the magnitude, and even the direction, are subject to the details of actual implementation; many of the details are also associated with State and local policies.

Investment Trends and Rationale

The program focuses its resources principally on the nine industries referenced above and referred to as the Industries of the Future (IOF). It supports collaborative research, development, and demonstration efforts to accelerate the development and adoption of energy efficient technologies and the incorporation of best practices in industry.

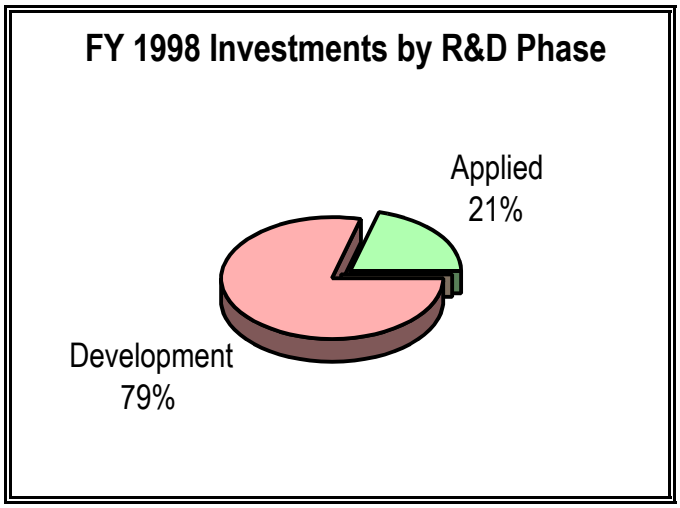
The IOF process includes:

- *Facilitate industry visions and technology roadmaps.* Industry leaders outline a future *vision* of their industry that is defined by explicit market, business, and technology goals. A *technology roadmap* is developed to articulate specific technology strategies and create a comprehensive R&D agenda. DOE's Office of Industrial Technologies (OIT) assists industry during this process and acts as a neutral party that can bring together competitors, suppliers, customers, and other key stakeholders.

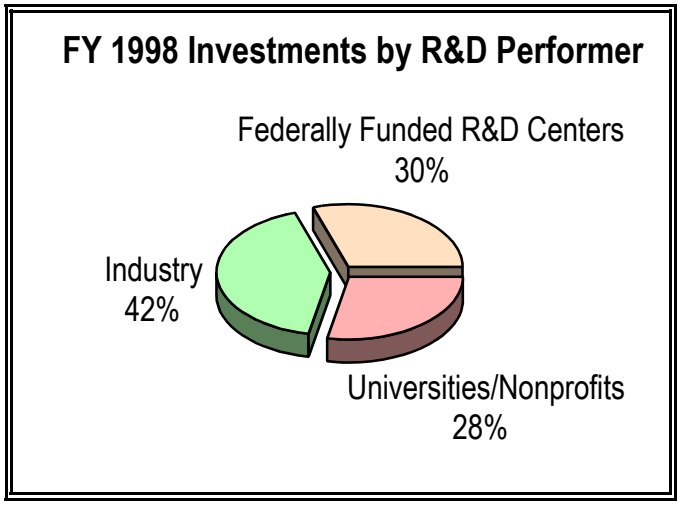
- *Cooperatively fund strategic projects.* Once industry has developed its technology roadmap, OIT selectively cost-shares technology projects contained within the roadmap that are consistent with the Department's strategic goals and the government role.

Essentially all research projects and research performers are selected through a competitive solicitation, with direct industry involvement in the process with universities, DOE laboratories,

and private sector companies performing the research. A significant number of efforts involve a mix of performers including industry-laboratory-university teams or combinations thereof. These mixes vary from industry to industry and the process is flexible to be responsive to the diverse nature of the different industries. The ratio of investments by R&D performer are shown in the figure below, however it should be noted that at the present time the estimates are based on the funding of the initial and primary recipient and do not reflect the sometimes significant percentage of funds flowing to subcontractors or collaborators which may be a different category of performer.



The strategy also includes providing an integrated set of activities ranging from the applied research phase through technology development to activities to accelerate the continued development and/or adoption of energy efficient technologies such as demonstrations of advanced technologies and best practices tools and training on both industry-wide and plant floor levels. An estimate of the ratio of investments by phase of research and development is shown in the figure below. Research is conducted principally at the industry-wide, pre-competitive stage,



with results available to all industry participants, rather than individual members of the IOF industries. Typically, the industry partnership is spearheaded by one (or occasionally more) industry trade association and/or professional society. Participation and consensus by the majority of the industry members is involved and individual companies provide staff for technical roadmapping teams, peer and program reviews, and other support. Projects and programs are cost shared, generally with IOF industry collaboratives to average at least 50 percent over the program's life.

Major program trends over the FY 1997 to FY 2000 time period include:

- The program initially focused on seven major process industries, temporarily decreased to six when one industry was unable to reach a consensus. That industry has since reached a level of consensus and in addition, mining and agriculture (in particular the bioproducts area of agriculture) have been added to the Industries of the Future portfolio. This represents a balancing of available resources and the major energy consuming industries; further expansion is not anticipated at current resource levels in order to maintain that balance. In addition, the development of IOF programs at the State level is being initiated providing closer relationships between State and Federal programs and promising more efficient development and adoption of technologies by local industries.

- The needs for advanced sensors and controls and advanced combustion technologies have been identified as a high priority need in many industry roadmaps, hence a focus and new applied research efforts in those areas have been initiated to help provide the technology base from which industry-specific sensors and controls and combustion components can be developed. In addition, the prior research portfolios for each industry have, by FY 1998, been revamped to match industry developed technology roadmaps. Most recently, the Chemical program has been reoriented and a catalysis program developed to support it. All FY 1998 catalysis research projects are new, replacing other prior efforts which were completed or terminated.

- Increasing integration of the totality of products and services provided by the industrial RD&D programs has been undertaken and is expected to be fully implemented in FY 1999. In this integration, industrial customers are made aware and encouraged to adopt technologies developed in other programs. For example, while the Aluminum program is developing, in collaboration with the aluminum industry, advanced aluminum processing technologies, more efficient technologies, tools, or techniques arising from other programs, such as in electric motor systems, steam, and compressed air, are being presented to the industrial customers along with a more overall system view of energy use and needs. Increasing collaborations with State energy technology institutes, and State energy and economic development and similar agencies, are also envisioned as an approach to assist the adoption of new technologies at the State and local level as well as to further the identification of State and local level needs into the national roadmapping process.

Federal Role

The energy consumption by industrial processes is intimately tied to emissions and environmental impacts as well as to productivity and economic competitiveness. In turn, this has major implications for the overall environment and the economy, affecting U.S. jobs and global competitiveness. This is particularly so in the major process and extraction industries, where global competition is not always based on completely free markets and where profitability as a function of sales is, in many cases, relatively low. In turn, this necessarily leads to relatively low private sector investments in R&D (as a function of sales) by these segments of industry as compared to industry as a whole.

The levels of risk involved in the adoption of major new technologies in these industries is also relatively high. Most process plants operate continuously at very high throughputs; down-times and retrofits or repairs associated with some new technology could be financially critical. These processes are also very highly capital intensive and involve plants with generally very long, even half-century, lifetimes. Competition for capital and the nature of the downside risks further hinder adoption of many new technologies. Less capital intensive advances such as process parameter changes or advanced sensing and controls and simulation capability suffer from relatively limited capability to maintain intellectual property.

Collectively these factors lead to individual companies being unable, or rationally unwilling, to invest in many areas of advanced R&D. Hence there is a need for a Federal role in helping to support, primarily, generic, pre-competitive R&D which can benefit the industry as a whole, from which individual companies can then further develop in a competitive environment, and which would be unlikely to occur without such Federal involvement. Further, it leads to the need for testing, verification, demonstration, and information dissemination to provide the levels of information needed for critical investment decisions for the rapid adoption of advanced technologies.

The program acts initially as a facilitator, assisting industry in coming together in order to collectively identify issues and develop an industry-wide vision of their long-term future. The program further facilitates and assists in the development of an industry technology roadmap which identifies and prioritizes the research and development needed to achieve that vision. The program then, in collaboration with the private sector, collaborates and cost-shares the generic pre-competitive research and development activities which meet industry priority needs and the Department's key missions. This role also involves bringing to bear the unique expertise and facilities of the National Laboratories to attack key technological and scientific problems.

Key Accomplishments

The industries participating in OIT's program are at some stage in developing a vision of where they want to be in 2020, and a roadmap for developing technologies in order to reach their goals. Some of the industries have embarked on R&D following their roadmaps, and have reported successful results from that R&D. The accomplishments of the nine current Industries of the Future include the following:

Aluminum Industry: The vision and roadmap documents are completed. The Inert Anode roadmap is also completed. Cathode research has achieved an 8 percent energy savings with a new cathode technology tested in a pre-bake cell, with no decrease in aluminum production.

Steel Industry: The vision and roadmap documents are completed. Several research projects were highlighted at Burns Harbor Showcase, 1998, including "Nickel-Aluminide Materials for Rolls in Steel Reheat Furnaces," whose use will save 6 trillion Btus/yr across the industry, and reduce production costs and waste. Direct Ironmaking technology is close to commercialization and will reduce energy use 25 percent in production of molten pig iron.

Metal Casting: The vision and roadmap documents were completed. The Lost Foam Consortium led to advances for reducing defects and producing higher-quality lost foam castings. By 2010, use of the technology will save 4.6 trillion Btus of energy and prevent 0.45 million tons of waste.

Forest Products: The vision was produced and "research pathways" have been defined. New cleaning technology allowing the use of lower grades of recycled paper by papermakers will permit 50 percent recycling of all paper used, reducing energy used for recycling by 0.l quads/year and lowering CO_2 emissions by 0.6 million tons annually.

Glass: The vision and roadmap were produced. Oxy-fuel firing for glass melting furnaces is in commercial use in 20 percent of glass furnaces, reducing a manufacturer's fuel use by 48 percent, NO_x emissions by 70 percent, and particulates by 60 percent, and increasing productivity by 25 percent. Advanced optical sortation removes over 90 percent of ceramics from glass cullet and sorts glass by color, saving 1 million Btus annually, and leading to 100 percent recycling of consumer glass.

Chemicals: There is a vision document, but the complexity of the industry requires several roadmaps, three to date. A membrane recovery system for volatile organic compounds (VOC) won an award from American Institute of Chemical Engineers. A novel process for producing nontoxic lactate ester solvents also received a national award, which has the potential for replacing 80 percent of the 3.8 million tons of halogenated toxic solvents used annually in the United States.

Mining: A vision document has been finished and roadmaps are in preparation. A compact was signed between DOE and the National Mining Association in May 1998.

Agriculture: A vision document was published focusing on plant-based renewable resources as a long-range goal. A compact was signed by representatives of the U.S. agricultural, forestry, and chemical industries, DOE, and the United States Department of Agriculture (USDA).

Petroleum Refining: A vision document is expected in FY 1999, and future collaboration with DOE is expected based on direct and indirect energy-efficiency technologies.

In the Cross-Cutting Technologies area:

Advanced Materials: Engineered ceramics are being tested and developed for high-temperature applications, e.g., continuous fiber ceramic composites (CFCC) hot gas filters will be tested in a chemical plant in FY 2000; and advanced industrial materials are focusing on advanced intermetallic alloys, with a new class of metal matrix composites expected by FY 2000.

Combustion Technologies: A vision and roadmap document were developed; oscillating combustion technology for reducing energy use in steel reheat furnaces is being tested at Bethlehem Steel's Burns Harbor, Indiana, mill. Research is also planned for improved controls and sensors, and increased systems integration**.**

Sensors and Controls: A need for improved sensors and controls has been identified in most of the technology roadmaps produced to date. There is a program goal to have, by 2009, significant advancements in the underlying science and technology of intelligent control systems.

Technical Assistance: This is a program to bring the full range of OIT's technical assistance and technologies to thousands of plant sites, in an integrated package that is easy for industrial partners to access. A recent highly successful showcase at Bethlehem Steel's Burns Harbor, Indiana, plant demonstrated a large number of advanced energy efficient technologies to representatives across the steel and other industries. Sub-divisions of this strategy include the Motor Challenge Program, that has already increased the use of advanced energy-efficient motors at the 3M Corporation; Steam Challenge, as part of the Motor Challenge, to provide technical assistance on steam and compressed air systems; and the Industrial Assessment Center Program, that has pinpointed and analyzed opportunities in over 7,000 small manufacturing sites for saving energy, reducing pollution, and increasing productivity.

Financial Assistance: This program contains two subdivisions: Inventions and Innovation, that, for example, provided funding to a corporation to develop a technology for the automated production of mold or die blocks (the LOM process), and the National Industrial Competitiveness through Energy, Environment, and Economics program (NICE^3), that, as another example, helped a company develop a new plating technology that reduces energy and eliminates wastes.

Industries of the Future:

Budget: FY98-$53.1M, FY99-$57.5M, FY00-$74.0M

Background

The nine Industries of the Future have developed (or are in the process of completing) technology roadmaps addressing their industry vision and their major priority technological needs. Competitively selected projects and performers are underway to perform research, develop, test, and accelerate the adoption of new energy efficient technologies.

Linkage to CNES Goals and Objectives

The program is in direct support of CNES goal and objective:

- CNES Goal I, Objective 2 - Significantly increase energy efficiency in the transportation, industrial, and buildings sectors by 2010.

A reasonably ambitious goal for industry for the year 2010 is a 25 percent reduction in energy consumption per unit of output. The strategy to support the achievement of this goal, in addition to focusing resources on the most energy and waste intensive industries, is to partner with and across industries, and align industry and government resources to areas of greatest need.

Program Description

Research and development programs, along with testing, demonstration, and evaluation, are undertaken on a broad array of technologies, identified by each industry in their Industries of the Future technology roadmaps as priority and which also meet the Department's missions and goals. Individual projects range across the spectrum from small focused research tasks and activities of relatively short duration to multi-year, major technology development projects and across the gamut of individual technical disciplines and multi-disciplinary research. The nature and balance of the portfolios of activities vary based on the characteristics and needs of each industry and are described below.

Aluminum

Budget: FY98-$7.3M, FY99-$8.1M, FY00-$11.2M

Description, Objectives, and Performers. Nearly ½ quad of energy is used in making primary aluminum and about 150 trillion BTU are used in secondary aluminum production and rolling, making products worth $35 billion per year. The industry spends nearly 7 percent of its product costs on energy, a larger portion than that spent by other industries. The production of primary aluminum produces 6 MMTCE per year from energy, mainly electricity, use. In addition, the basic smelting of alumina utilizes consumable carbon anodes which contribute about 1.5 MMTCE. The process also produces over 4 MMTCE from perfluorocarbons.

The aluminum industry and DOE signed a compact in October 1996, having produced a vision document in 1996. A technology roadmap was published in May 1997. Because of the importance and difficulty of developing a replacement for the current carbon anodes, a follow-on roadmap, Inert Anode Roadmap, addressing this complex area, was published in February 1998.

The vision and roadmaps identified specific goals adopted by the industry which include:

- Improve the energy efficiency of the smelting process by 13 percent within 10 years and by 27 percent in the longer term.
- Eliminate (process-produced) CO_2 emissions in the long term.
- Develop new uses for wastes/byproducts to reduce waste emissions and improve efficiency and costs.

R&D Challenges. The aluminum industry roadmap organizes technology needs into three categories: Primary (including recycling) Aluminum Production; Semi-Fabrication Production (subdivided into Casting and Rolling/Extrusion); and Finished Products. (DOE will be supporting the first two categories; finished products are left for private sector R&D). They are further prioritized and categorized into short-, mid-, and long-term needs. DOE's overlaid priorities stress the smelting portion of primary aluminum production (since the major of energy use and emissions occur in that process) as well as methods to improve production from recycled aluminum, which only consumes about 5 percent of the energy as primary production.

The main challenge involves eliminating the inherent deficiencies in the traditional Hall-Heroult process. The process involves a carbon anode with molten cryolite (a sodium-aluminum-fluorine compound) as the electrolyte and molten aluminum acting as the cathode in an electrolytic cell. Electric energy plus consuming of the carbon anode leads to conversion of the raw alumina (Al_20_3) to aluminum plus CO_2. Variability in the process causes the emissions of perfluorocarbons. Electricity losses occur for several reasons including anode-cathode spacing requirements, partly due to undulating melt surfaces. The consumable carbon anode is also a major economic expense due to two-three week replacement. Improved cells in the short term leading to a totally new process in the longer term is the principal challenge.

R&D Activities. *Primary (including recycling) Aluminum Production*
Cathode research is investigating wettable TiB_2 cathodes and recent tests showed an 8 percent lower energy consumption over conventional cells. The wettable ceramic cathode, by eliminating the wavy irregular molten surface, allows the anode-to-cathode distance to be decreased, reducing electrical resistance. Research is continuing on materials, scaling issues, stability and molten surface motions. If successful, commercialization by industry partners is expected by 2003.

Exploratory research on two advanced cell designs and several advanced anode materials was recently initiated. Statistical design and retrofit tests will be used to determine the most promising anode-cathode coupling and geometry. A retrofit advanced cell system will also require R&D on cell sensors and controls, advanced sidewall materials, new designs for cell heat control and management, as well as Bayer process improvements.

Other cell research including investigation of advanced sensors using fiber optic probes and laser-based Raman spectra analytical techniques, probe coating materials to survive cryolite melt temperatures, sensors to detect and reduce chloride salts in molten aluminum, and dynamic modeling to enable better control of cell and electric power load levels are all necessary to achieve significant cell improvements, stability, and reliability.

Some 800,000 pounds of aluminum salt cake (spent salt fluxes, residue oxides, dross, etc.) could be saved and aluminum (and its energy content) and other byproducts reclaimed through reprocessing, which would provide major stimulus to aluminum recycling as well aid primary production. Four advanced processes have been examined and concentration is on

an electrodialysis technique as the most promising. Hydrometallurgical processes to improve the purity of nonmetallic byproducts (NMP) is also underway. Converting NMP to fiber insulation is in early commercialization by industry while research on alternative byproducts and electrodialysis is expected to reach pilot demonstrations by 2000-2001.

Several aluminum companies (Reynolds Metal Company, Aluminum Company of America (ALCOA), Alcon Aluminum Corporation, Kaiser Aluminum Corporation), other companies, ORNL, ANL, Carnegie Mellon University, Massachusetts Institute of Technology (MIT), and several other universities are involved in this program; several companies have developed commercialization plans pending successful R&D results.

Semi-Fabrication

The production of sheet, extrusions, and other intermediate products is a second area with potential for energy, waste, and environmental improvements. An innovative spray forming technology to form sheets, in place of the current ingot casting, as well as near-net-shape products directly from the melt (reducing reheating steps), is under investigation. Better metallurgical and corrosion-resistant properties are possible due to better microstructure control. A linear spray nozzle has been developed and thermomechanical processing studies, microstructural characterization, and mathematical and numerical modeling is underway. Energy savings of 25 percent over ingot casting/hot rolling and cost reductions of over 10 percent are expected. Goals of +/- 2 percent profile flatness and porosity targets of <4 percent have been set. An advanced development unit which can operate in both an experimental and a pilot semi-production mode is expected to start operation by 2000. ALCOA, Air Products and Chemicals, Inc., Carnegie Mellon University, University of California, MIT, and others are involved. It is anticipated that licensing the technology broadly, with royalties back to the government and participants will occur if successful.

An additional method of producing near-net-shapes is an innovative semi-solid material (SSM) process. Cast parts are produced from a slurry kept at a temperature between the solidus and liquidus isotherms exhibiting both solid- and liquid-like behaviors. It can combine the advantages of both liquid metal casting and solid metal forging. This is a longer-term, more advanced technology and the current objective is to achieve a better understanding of the fundamental issues concerning material behavior. Research includes numerical simulation to predict die filling and, ultimately, die design optimization; fluid models modified to account for the two-phase nature, obtaining rheological data needed for the modeling, and the effects of slurry structure on flow behavior and separation. If successful, energy reductions due to lower temperature processing and increased productivity due to shorter solidification times and longer die life will occur; quantified goals await further research. Participants include MIT, Worcester Polytechnic Institute, and ORNL; consortia of over 20 industrial partners are cost-sharing and will share in the research results.

Accomplishments. An early version of a new technology cathode element was tested in a full-scale pre-bake cell in a collaborative project between DOE, Kaiser Aluminum Corporation, and the Reynolds Metals Company at a Kaiser plant. Test results showed an 8 percent energy savings compared to a conventional cathode with no decrease in aluminum

production, although continued research is required to provide the required long-term material strength and longevity.

Steel

Budget: FY98-$9.7M, FY99-$10.5M, FY00-$10.6M

Description, Objectives, and Performers. The steel industry uses about 1.8 quads of energy and emits about 35 MMTCE to produce about 100 million metric tons of steel annually. This energy costs some $7.0 billion annually and represents 20 percent of total production costs. Over 50 percent of new steel production is made from recycled scrap. Steel production is a major generator of carbon dioxide and other pollutants, and the industry has invested more than $6 billion in control equipment in the last two decades.

The industry's vision document "Steel: A National Resource for the Future" was released by the American Iron and Steel Institute (AISI) and Steel Manufacturers Association (SMA) in May 1995; an R&D compact was signed by DOE and the AISI and SMA in May 1995; and a technology roadmap was released by the steel industry, as represented by AISI and SMA, in March 1998. Research priorities emphasize energy efficiency, environmental protection, greater use of recycled steel, reduced capital intensity, less waste production, and improved productivity. Long-term goals of the industry included zero waste production, and recycling of 70 percent of scrap steel.

R&D Challenges. Four key areas were identified by industry: (1) production efficiency, (2) environmental engineering, (3) recycling, and (4) product development. DOE collaborates in the first three of the four areas. A long-term high priority challenge is the ability to develop alternative iron smelting processes that produce liquid iron directly from coal and ore fines or concentrate. This would eliminate the steps of cokemaking and blast furnace ironmaking, in turn leading to much reduced costs, energy consumption, and emissions. Also a major challenge is need to develop net-shape casting processes that could enable the cast surface to become the finished part surface. This requires a degree of consistency and near defect-free continuous cast steel that is not achievable by current technology. The ability to provide real-time optimized computer-based control of the entire process and production cycles, with the necessary improvements in modeling, sensors and controls, to the accuracy necessary for substantial improvement also requires significant advances from today's technology.

R&D Activities. *Production Efficiency*
Research in this area includes advanced process control projects to improve the efficiency and productivity of major pieces of process equipment though better sensors and more rapid and precise control of the process. For example, "Microstructure Engineering in Hot Strip Mills," a computer tool, is being developed by the University of British Columbia and the National Institute of Standards and Technology (NIST) to provide on-line control over the quality and yield of hot-rolled steel. Sandia National Laboratory, Berry Metal Company, and others are developing sensors for the basic-oxygen-furnace (BOF) capable of on-line measurement of off-gas temperature and composition and bath temperature from within existing oxygen blowing lances. Both these technologies are undergoing field testing at Bethlehem Steel's Sparrows Point, Maryland, plant. A temperature measurement technology

using phosphor thermography developed at ORNL is being further developed by ORNL, the University of Tennessee, and Bailey Engineers to assure accurate on-line temperature control of galvannealing furnaces.

Environmental Engineering
Research is aimed at reducing NO_x emissions and increasing efficiency in combustors for various steel processing applications. Typical of the combustors under development is the "VISTA Combustor for Very Low NO_x Emissions in Furnaces and Boilers" which can theoretically reduce NO_x emissions to less than 10 ppm after the second stage. The low-emissions burner can be retrofitted to intermediate-temperature industrial systems to meet environmental standards, increase energy efficiency, and improve mill productivity. The Thermo Power Corporation and John Zink Company are conducting this research.

Recycling
Projects include "Atmospheric Gas Recovery and Regeneration in Heat Treating Operations," a membrane technology for recovering, cleaning, and reusing more than 90 percent of the furnace atmosphere gas discharged in present systems after carburization. The technology also removes air pollutants, avoids the production of waste, and offers the potential for heat recovery from the clean gas. Partners include the Dana Corporation and the State of Minnesota.

Accomplishments. The Burns Harbor Showcase, in May 1998, highlighted the successful implementation of several OIT-supported technologies at an operational steel plant. For example, rolls made of "Nickel-Aluminide Materials for Rolls in Steel Reheat Furnaces" are stronger and more durable than conventional rolls, and are expected to last 10 times longer with less downtime. Their use can save 6 trillion Btus per year in the industry, reduce production costs, and minimize waste. Additional success stories at Burns Harbor focused on the technologies for "Oscillating Combustion" and "Temperature Measurement of Galvanneal Steel."

Licensing agreements for the Direct Ironmaking technology developed by DOE and the American Iron and Steel Institute (AISI) are in the final stages of being signed by a major international equipment supplier to the steel industry. This technology would replace the coke oven/blast furnace process and provide energy savings of up to 25 percent in production of molten pig iron.

Metal Casting

Budget: FY98-$5.5M, FY99-$5.7M, FY00-$5.8M

Description, Objectives, and Performers. In the United States, castings are used to produce 90 percent of all manufactured durable goods and nearly all manufacturing machinery. The United States produces 20 percent of the world's cast products, and shipments are expected to reach 14.9 million tons in 1998, with sales worth $28.3 billion. Metal casting is highly energy-intensive, using 0.25 quads annually; energy expenditures in 1994 were $1.1 billion, equal to 5 percent of the value of that year's shipments. This industry recycles 13.3 million

tons of scrap annually, generating $3.5 billion in cost savings, but spends more than $300 million on pollution control technologies and produces 1.6 MMTCE.

The industry's vision document, "Beyond 2000: A Vision for the American Metal Casting Industry," was printed in September 1995, and a compact between the industry and DOE was signed in October 1995. Seven critical areas were identified: market development; materials technologies; manufacturing technologies; environmental technologies; human resources, education, and training; health and profitability; and partnerships and collaboration. A series of key challenges included reducing energy consumption by 20 percent by 2020. Additional goals relevant to DOE included: developing materials technologies; developing advanced manufacturing technologies to increase productivity 15 percent and reduce average lead times 50 percent; developing environmental technologies to achieve 100 percent recycling of pre- and post-consumer waste, a 75 percent beneficial re-use of foundry by-products, and total elimination of waste streams; and encouraging partnerships and collaborations.

The "Metal Casting Industry's Technology Roadmap Workshop," published in January 1998, identified top priority research needs including the development of low-cost, rapid tooling technology for both making and changing metal casting tooling, and improvement in the ability to produce the desired size and dimension of castings, and developing modeling technology for casting processes to gain precise understanding of how die-casting dies actually fill.

The Cast Metals Coalition (CMC) is a collaborative entity responsible for identifying R&D activities; soliciting and reviewing proposals; recommending proposals to DOE; overseeing cost-share; and managing and evaluating selected projects. The CMC is composed of representatives from the three primary associations representing the metal casting industry: the American Foundrymen's Society, North American Die Casting Association and the Steel Founders' Society of America.

The research is principally performed by universities; utilizing 88 percent of program funds with over 18 universities having been involved.

R&D Challenges. Current metal casting processes are diverse and vulnerable to the stringent environmental regulations and increased global competition. The thermodynamics and fluid flow of molten metal into and throughout molds is a complex dynamic phenomenon with a multiplicity of poorly understood factors. Small variations in internal surfaces, mold materials, initial temperatures and cooling rates, internal geometry, the molten metal's specific properties, and many others can have a significant effect on the end product. Moreover, the energy consumed in the overall process, as well as the imbedded energy in the cast product and waste (including rejects and excess material—hence the importance of near net shape casting) is significant and can be reduced by better understanding of the complex molding process. Inclusions, product characteristics and tolerances, weaknesses, costs, reject rates, throughput, are all factors which affect the capability of the industry. Research in low-cost rapid tool making with superior materials, defect-free and dimensional control of castings, advanced sensing and modeling capabilities, improved design standards, and re-use

of foundry sand and other solid wastes will make the metal casting industry the preferred supplier of near net-shape metal components beyond the year 2000. Projected benefits by the year 2020 include 10 percent market increase, 0.018 quads of energy savings, 100 percent pre- and post-consumer recycling, and 75 percent re-use of foundry by-products.

R&D Activities. The program is co-funding research in the areas of materials technologies, manufacturing technologies, products and markets, and environmental technologies.

In the area of *Materials Technologies*, the program is co-funding fundamental research to advance technology for producing clean, machinable gray iron, and ductile iron parts. By improving machinability, closer tolerances can be obtained between pistons and cylinder walls thereby improving fuel efficiency in automobiles and trucks. In another project, "Improve the Die Life of Die Casting Dies of H-13 Steel," researchers published a database of physical and metallurgical properties of H-13 steel to predict die properties during the heat treating cycle. They also developed a PC-based computer model for use in the die casting industry to optimize mechanical properties with minimal distortion.

In the area of *Manufacturing Technologies*, research is conducted on tools, sensors, and modeling to improve die-cavity filling for higher quality castings, extending die life, and minimization of part distortions for die-casting aluminum, magnesium, and zinc alloys. Guidelines are being developed for advanced casting technologies to produce higher quality, higher integrity castings.

In the area of *Environmental Technologies*, the program co-funded an evaluation of energy use in foundry industry processes including melting, molding, cleaning and finishing, and pollution control. An Energy Manual and Spreadsheet model were developed to assist the industry identify major energy load centers and to identify measures for reducing energy consumption.

In the area of *Products and Markets*, the program is co-funding research in the Development of Database Design Rules for Cast High Alloy Steel Components. These materials have properties which allow casting designers to use thinner walls, which will reduce energy costs in product markets.

Accomplishments. The Lost Foam process advantages of reducing machining, minimizing assembly operations, and reducing solid waste and emissions were never realized due to a lack of knowledge of the process and the absence of proper control measures. The Lost Foam Consortium, funded in part by the program, led to advances in controlling the lost foam process including new procedures introduced in lost foam casting as well as control technologies. These measures have been proven in the foundry in reducing defects and producing higher quality, higher precision lost foam castings. Specific developments include a single stage air gauging system followed by a 30-channel commercial air gauge for rapid determination of pattern dimensions; instruments and transducers for measuring vibrational frequencies and amplitudes; a distortion gauge to determine when and under what conditions pattern distortion occurs; instrumentation for measuring gas permeability of pattern coatings;

and a procedure to measure liquid absorption characteristics of liquid pattern pyrolysis into castings. Since 1990, there has been a significant increase in the use of the process and by 2010, about 29 percent of aluminum castings and 15 percent of iron castings are expected to be cast using lost foam technology, equating to energy savings of 4.6 trillion Btus/year by 2010, environmental savings of 0.45 million tons of waste, and energy cost savings of $16 million.

Forest Products

Budget: FY98-$12.0M, FY99-$12.0M, FY00-$21.1M

Description, Objectives, and Performers. The U.S. forest products industry represents 8 percent of the manufacturing sector's total annual output, and had shipments valued at more than $277 billion in 1995. With 1.6 million employees, the industry is a "top-10" manufacturing employer in 46 States. Although the industry uses renewable biomass fuel for 57 percent of its energy needs, it remains among the most energy-intensive of the Industries of the Future, consuming 3 quads of energy annually at a cost of $8 billion. Pollution abatement measures add about $3 billion annually in both capital and operating expenditures to the industry's production costs. Annual production of hazardous wastes is more than 2l9,000 tons. Emissions of direct carbon equivalents were 36 MMTCE in 1994.

A compact for cooperative research with DOE was signed by the forest products industry in 1994. "Agenda 2020: A Technology Vision and Research Agenda for America's Forest, Wood and Paper Industry," was prepared in November 1994. This vision document defined six areas that were considered high-priority for future R&D efforts: (1) Sustainable forest management, (2) environmental performance, (3) energy performance, (4) improved capital effectiveness, (5) recycling, and (6) sensors and control. Although no formal technology roadmap has yet been published, "Research Pathways" have been defined to specify current and future research needs for each of the high-priority research areas.

R&D Challenges. The forest products industry faces significant R&D challenges to meet changing standards and regulations while remaining economically viable and competitive. The industry's high capital intensity and the resulting economic consequences of equipment replacement tend to limit experimentation, development and application of large, new core technologies. One of the major technical issues facing the paper industry deals with the environmental impact of mills. A zero discharge concept has been envisioned by the industry called "mill closure." Current separation technologies do not adequately control or remove the non-process elements that build up in the reused water streams. Inherently more efficient, safer, and lower cost process technologies and systems are needed. Currently targeted is a replacement technology for the Tomlinson Chemical Recovery Boiler, one of the major components of current paper process technology. Existing recovery boilers are expensive to construct and operate and involve significant environmental and safety issues and costs. Most were constructed during the 1950s and 1960s and are nearing the end of their effective lifetimes; hence, a window of opportunity exists over the next decade in which to introduce major new approaches. Advanced black liquor gasification technologies hold the promise of significant improvements to performance, environmental and safety benefits, and energy and

economic improvements, but will require advances in materials, sensors and controls, and system operating parameters.

R&D Activities. *Sustainable forest management*
R&D is being directed along four different "research pathways" to achieve more productive and environmentally sustainable tree stands: biotechnology, tree physiology, soils, and remote sensing. An example of currently funded research is the use of biotechnology to improve wood properties in loblolly pine and hybrid poplar, is "The Development and Validation of Marker Aided Selection Methods for Wood Property Traits." "Trees Containing Built-In Pulping Catalysts," is studying the natural production of anthraquinone (AQ) by trees. AQ is a pulping catalyst that will reduce the need for commercial catalysts to degrade the lignin and brighten the pulp, lowering the industry's production costs and improving its productivity. Research will be funded in FY 2000 in support of these four research pathways.

Environmental Performance
DOE is currently partnering in a research pathway to develop alternative processes that prevent pollution, such as "A New Freeze Concentration Process for Minimum Effluent Processes in Bleached Pulp Mills," in which volatile and complex contaminants are concentrated in the effluent when the water content of the effluent is removed as ice—the water removed as ice can be reused in the process. A "High Efficiency ClO_2 Delignification" project will also shed light on the fundamental chemistry of chlorine dioxide delignification and reduce the use of chlorine by the industry, lowering industrial emissions. Another pathway identifies employing effective treatment methods, and includes "Reducing Emissions of Volatile Organic Compounds" through an economical biological treatment system for high volume, low concentration gas streams. For the longer term, research is also expected to target understanding margins of environmental safety and source reduction and reuse.

Energy Performance
Research on manufacturing process efficiency and heat recovery includes projects such as "Design and Demonstration of Multiport Cylinder Dryers," involving cylinder redesigns with the potential to increase the drying rate of paper by a factor of 2 over existing cylinder dryers. A pathway for fuel conversion and electricity production includes the project, "Characterization and Conditioning of Tars Produced During Black Liquor Gasification," which addresses one of the technology gaps identified by industry that is currently preventing the commercialization of black liquor gasification, and which could lead to a 10 percent energy improvement over the current combustion process. Research will examine black liquor gasification issues for its potential use in advanced turbines for on-site heat, steam and electrical power while reclaiming process chemicals. Other energy pathways will look at the environmental impact of energy production and utilization and provide the industry with optional methods in such areas as combustion, the wider use of renewable resources, and fuel production and enhancement. Research will be funded in FY 2000 in support of these research pathways.

Capital Effectiveness
This pathway involves research on materials and coatings, and lower-cost process alternatives. If successful, the project, Bleach Plant Capital Reduction with Rapid Bleaching and Simplified Stages," could result in significant savings on capital equipment and reduced discharge of chlorinated organic compounds.

Recycling
Research on the improved separation technology pathway includes the project, "The Removal of Wax and Stickies from Old Corrugated Containers." This effort will permit greater use of fiber obtained from recycled old corrugated containers by effectively removing wax and sticky contaminants during repulping and improving environmental, energy, and economics of the process. For the longer term, research is expected to include new technologies for sludge use and disposal, fiber-fiber bonding, and sorting and collection tools in addition to separation technologies.

Sensors and Controls
Research is undertaken on control devices, process measurement and diagnostics, process and product models, data presentation and interpretation, and control system effectiveness. The "Distributed Web Sensor for On-Line Measurement of Paper Basis Weight" is part of a multi-faceted effort to provide the paper industry with real-time techniques to monitor the entire moving paper web. Nuclear instrumentation will be distributed across the web width to detect beta particles transmitted by the web. The sensor for paper basis weight would improve product quality and productivity for the industry, and reduce its processing wastes. The research project, "Non-Contact Laser Acoustic Sensor for On-Line Measurement of Paper Stiffness," will use laser ultrasonics technology to improve paper uniformity, reduce the use of feedstock and production of waste, and increase energy efficiency, productivity, and paper quality.

Accomplishments. The Black Clawson Company commercialized a breakthrough cleaning technology for paper recycling. This new technology enables papermakers to use even lower grades of recycled paper without compromising the quality of the paper produced. This technology will assist the U.S. forest products industry in meeting its 2000 goal of recovering for recycling 50 percent of all the paper used. In addition, this improved cleaning technology achieves greater efficiency while using less energy. By 2010, it is estimated that the energy used for processing recycled paper will be reduced by 0.1 quads/year, with a corresponding annual CO_2 emissions decrease of 0.6 million tons. The research behind this technology involved a 45 percent industry cost share.

The American Forest and Paper Association (AF&PA) represents the industry—research alliances are underway among OIT, National Laboratories, private organizations, and academic institutions. Task groups established for each of the high-priority R&D areas are responsible for developing the pathways, requesting and evaluating proposals, and recommending research projects to DOE for cost-shared support.

Glass

Budget: FY98-$3.9M, FY99-$4.8M, FY00-$4.8M

Description, Objectives, and Performers. The glass industry produces 21 million tons of consumer goods annually valued at $22 billion. Glass making is highly energy-intensive consuming 170 trillion Btus in 1994, equal to about 15 percent of production costs. Theoretically, glass making requires 2.2 million Btus of energy to melt one ton of glass, but twice that amount is actually used because of inefficiencies and losses. Improvements in processing technologies have helped reduce energy consumption in glass making 25 percent in the last 15 years, and industry's goal is to reduce energy consumption by 50 percent (thus approaching the theoretical energy-use limits) by using more efficient technologies and processing operations, and increasing the use of recycled materials. The environmental impact of Glass making is relatively benign, however the direct carbon emissions from the glass industry are 2.96 MMTCE annually.

The industry is divided into four specialized areas: glass/glass packaging, flat glass, fiberglass, and specialty glass. Recognizing the need for research partnerships and advanced technologies to ensure its future viability, the industry signed a compact with DOE and produced its vision document in 1996, entitled "Glass: A Clear Vision for a Bright Future." More than 60 priorities for R& D were identified at a Glass Technology Roadmap Workshop the following year, based on their potential for saving energy, increasing productivity, and enhancing environmental performance during the glass making process, and on developing innovative uses for glass. A solicitation for proposals has generated more than 50 responses from interested researchers since the workshop, and the R&D collaboration is moving toward implementation.

In addition to reducing energy use 50 percent, goals of the vision document include reducing production costs at least 20 percent below 1995 levels, recovering and recycling 100 percent of consumer glass products in the manufacturing process, lowering air and water emissions a minimum of 20 percent, improving quality control during production, creating innovative products and broadening the marketplace, and increasing supplier-customer partnerships.

The Glass Packaging Institute is a trade association whose members are associated with the glass-container industry. However, there is no organization representing all four segments of the glass industry, and there has never been an organization that focused on technical issues affecting the industry. A Glass Manufacturers Industry Council (GMIC) is in the planning stages, which would serve as an umbrella association to track the industry's collaborative R&D efforts and increase the visibility of glass-related R&D.

R&D Challenges. Current sensors and control systems require significant advances in order to enable energy and cost reductions as well as better product control. In particular, systems must be integrated across the overall process and also improved for both specific and integrating process components in order to improve efficiency. Sensors better able to survive the temperatures and environments in the process are needed to enable real-time control. High temperature refractory and non-refractory materials, beyond those available today and

which do not affect product properties are also required. Lack of understanding of some fundamental process mechanisms influencing particulates also hinders progress..

R&D Activities. The roadmap calls for technological improvements in four areas: production efficiency, energy efficiency and conservation, environmental protection and recycling, and innovative uses for glass. Key priorities of the industry include development of refractory materials, optimization of oxygen fuel, and modeling of furnace operations.

Production Efficiency
The "High-Heat Transfer Low-NO_x Natural Gas Combustion System" will optimize the oxy-fuel system already being implemented by many companies for glass-melting processes. The system offers good heat transfer, increases energy efficiency 20 percent, and enhances process efficiency. The technology involves increasing the flame luminosity by seeding the flame with soot particles. The project partner is AccuTru International Corporation.

Energy Efficiency and Conservation
A "Sensor Technology Advanced Research" effort is underway that will be applicable in all four segments of the glass industry. The new sensor will provide more accuracy, reliability, and ability to withstand thermal shock, and will be long-lived, easily replaced, and interchangeable. Improvements in energy efficiency, product quality, waste minimization, and cost efficiency are expected. The research partner is AccuTru International Corporation.

Environmental Protection
"Glass Furnace Side Port Oxygen Enrichment" technology is being developed that will use a low-cost nitrogen oxide reduction technique on an industrial sideport furnace. (Sideport furnaces are used for 65 percent of U.S. glass production). The system reduces the amount of oxygen available to the flame's high-temperature zone, improves the flame temperature's uniformity, and improves heat transfer to the glass, without interrupting furnace operation or affecting product quality negatively. Several organizations are conducting this research, including the Institute of Gas Technology and Owens-Brockway Glass Container, Inc.

Innovative Uses of Glass
The "Advanced Microwave Processing Concepts" project is developing a Variable Frequency Microwave Furnace and demonstrating that microwave curing will reduce energy, lower costs, and increase production of certain new products such as resins, composites, and adhesives.

Accomplishments. The "Oxy-Fuel Firing,"or "Oxygen-Enriched Combustion System" for glass melting furnaces developed by Praxair, Inc. and OIT has been commercially successful. Companies adopting oxy-fuel firing in place of regenerative-type furnaces have reduced specific fuel use by 48 percent, NO_x emissions by about 70 percent, and particulate emissions by 60 percent, and increased their production rate by 25 percent. The quality of glass produced is more consistent, and furnaces converted to this type of combustion need to be replaced less frequently than regenerative systems. Over 20 percent of glass furnaces have converted.

"Advanced Optical Sortation," developed by Alpine Technology Inc., removes more than 90 percent of ceramic contaminants from waste glass (cullet), and allows glass to be sorted by color. Cullet melts at lower temperatures than virgin materials and provides the industry with energy savings of about 1 million Btus/ton annually. Nearly 100 percent of consumer glass may eventually be recovered with such technology, significantly reducing the environmental impact of such waste.

Chemical

Budget: FY98-$11.6M, FY99-$12.4M, FY00-$12.5M

Description, Objectives, and Performers. The chemical industry is the most diverse of U.S. industries, represented by about 10,000 corporations producing more than 70,000 different products that are classified under eight standard industrial classification codes, and which consume over 6 quads of energy. The products fall into three categories: (1) basic chemicals, (2) chemical products needed in manufacturing processes, and (3) finished chemical products that will be consumed or supplied to other industries. As the world's largest producer of chemicals, $372 billion worth of products were shipped worldwide in 1996, creating one of the largest trade surpluses of any industrial sector ($21.2 billion in 1996).

The industry prepared its vision statement, "Technology Vision 2020: The U.S. Chemical Industry," in 1996. Four technical disciplines were identified as crucial to the chemical industry: new chemical science and engineering technology, supply-chain management, information management systems, and manufacturing and operations. DOE research focuses principally on the first area.

The vision process involved the American Institute of Chemical Engineers, the American Chemical Society, the Chemical Manufacturers Association, The Council for Chemical Research, and the Synthetic Organic Chemical Manufacturers Association, as well as a significant number of companies and research organizations.

The size and complexity of the industry make it impractical to develop a single technology roadmap. To date, under new chemical science and engineering, 3 areas of the industry have been analyzed in depth, and roadmaps have been prepared for computational fluid dynamics (CFD), (1997); the separation technologies (adsorption, crystallization, distillation, extraction, membrane processes, and separative reactors), (1998); and computational chemistry, (1998). Roadmapping is underway for chemical process plant materials of construction, with emphasis on high temperature, corrosive-resistant materials, to be completed in early 1999. Additional areas of high industry priority are catalysis, chemical synthesis, separations for industrial biotechnology, electrotechnology and alternative reaction mechanisms, and chemical measurement. Catalysis impacts about 90 percent of the chemical industry's processes.

R&D Challenges. Current technologies limit the ability to control major processes to the degree needed for significant improvement. In addition, several types of separation technologies, such as distillation require considerable energy. Some processes involve the need for toxic solvents or involve such materials, and alternative feedstock and new processes could lead to major advances. New membranes and catalysts could lead to such advances and the ability to use alternative feedstocks. Advanced mathematical modeling, particularly for multi-phase flows, and better real-time controls along with advanced sensors could enable much of what is still today "art," become a much more highly and accurately controlled process.

R&D Activities. In February 1997, the Department signed a Memorandum of Understanding with the chemical industry for identifying appropriate areas for joint research with the focus on "New Chemical Sciences and Engineering" and the research areas described above.

Computational fluid dynamics (CFD) has become one of the more important engineering and analysis tools for the chemical industry over the past decade. As the result of many new developments, the predictive power of CFD for single-phase flow (for example, a single liquid) for process design and control is undisputed. The use of CFD for multi-phase flows (gas and solid together, for example) is far less well developed, however industry believes the potential value would be at least as great as single-phase flow CFD.

To achieve significant progress in the application of CFD to resolve difficult problems, such as flows in process equipment that cannot be seen, DOE has entered a partnership with seven DOE National Laboratories and industry for the development and commercialization of multi-phase CFD technology. A five-year development effort is envisioned.

Separations science and technology is becoming of increasing interest and importance to the chemical industry. Separations processes represent up to 70 percent of capital and operating costs and account for nearly 45 percent of the energy used in the chemical processing industries. The "Novel Catalytic Membrane Reactor," a source reduction technology being developed by the Department in collaboration with five major companies, will enter pilot-scale test and demonstration in 2000. This technology will minimize waste products while conducting highly exothermic reactions. Targeted applications include alkylations, carbonylations, hydrogenation, ethoxylations, and others. Current feasibility studies indicate that the Novel Reactor can achieve a twenty-fold improvement in the ratio of desired product to waste product compared to current technology. In addition to saving energy, reducing or eliminating waste disposal, and increasing product quality, the technology is also expected to increase yields and decrease the cost of raw materials.

Collaboration is underway between DOE's Office of Science and DOE's Office of Energy Efficiency and Renewable Energy in nearly a dozen Small Business Innovation Research projects for basic research in new and advanced membrane separation technologies. Two additional topic areas—reactive separations and alternative reaction conditions—are planned to be added.

In the electrochemical field, Los Alamos National Laboratory is performing research on the chemistry of chlor-alkali electrochemical reactors. These consume around 2 percent of the total electric power generated in the United States. The research could result in a new electrochemical reactor that reduces the total electric power consumption by the chlor-alkali industry by 30 percent and reduce CO_2 emissions from U.S. electric power generation by 0.6 percent.

In the catalysis field, the "Low Temperature, Aqueous Phase Catalytic Gasification" project has recently undergone a successful full-scale demonstration at the DuPont plant in Beaumont, Texas. The system is a catalytic process for destroying organic contaminants in industrial process streams and for producing clean water and a fuel gas. The process is an alternative to the deep-well injection of these wastes, and negotiations are underway between Battelle Memorial Institute and DuPont to optimize the application for future commercialization.

Accomplishments. The "Membrane Vapor Recovery System, VapoSep" for the recovery of VOCs from air was awarded the 34th Kirkpatrick Chemical Engineering Achievement Award, by the American Institute of Chemical Engineers in 1997. This membrane system is already becoming widely used in the chemical, petrochemical, and pharmaceutical industries.

The "Novel Membrane-based Process for Producing Lactate Esters" received high recognition during this past year as winner of the 1998 Discover Magazine Award for Technology of the Year, winner of the 1998 Green Chemistry Challenge Award, and winner of the 1997 Thiele Award for Engineering. Developed by Argonne National Laboratory in collaboration with NTEC, Inc., this technology is an entirely new process for the production of marketable nontoxic solvents. This process has the potential for replacing 80 percent of the 3.8 million tons of halogenated toxic solvents used annually in the United States with biomass-based solvents.

Mining

Budget: FY98-$0.0M, FY99-$2.0M, FY00-$3.0M

Description, Objectives, and Performers. Essentially all manufacturing starts with raw materials which must be mined. Mining (including hardrock and coal mining) occurs in all 50 States, contributing $39 billion per year in economic value. Mining operations consume almost 0.9 quads of energy annually and at the same time represent over 20 percent of the Nation's energy supply, including more than half of the energy used in electricity generation.

R&D Challenges. The key R&D challenges are being identified during the development of the industry technology roadmap.

R&D Activities. The mining industry developed a vision, "The Future Begins with Mining," and in May 1998, the National Mining Association signed a compact with DOE. In FY 1998 and FY 1999, technology roadmaps will be developed and priority technology needs identified. Research based on those roadmaps will be initiated based on competitions to be held in FY 1999 and FY 2000.

Accomplishments. As a new program start, accomplishments beyond the planning stage have not yet occurred.

Agriculture

Budget: FY98-$0.0M, FY99-$2.0M, FY00-$4.0M

Description, Objectives, and Performers. Agriculture represents about 14 percent of the U.S. GDP with exports worth $60 billion providing a trade surplus of $36 billion. The agriculture industry is extremely broad and diverse and has traditionally focused on producing wide varieties of food, feed, and fiber. Trees and plant matter have the potential to reduce fossil fuel consumption, as well as climate change effects, through their substitution for petroleum as feedstocks for producing products such as paints, plastics, and adhesives. These also provide additional markets for the agricultural industry, and it is believed that 0.35 quads of energy could be saved by 2020.

In 1995, a Memorandum of Understanding was signed by the Secretaries of DOE and the United States Department of Agriculture (USDA) to cooperate and coordinate technology research, development, transfer, utilization, and commercialization. The agriculture industry's first vision, "Plant/Crop-Based Renewable Resources 2020," was published in 1998, focusing on plant-based renewable resources as a long-range goal. A compact was signed by representatives of the U.S. agricultural, forestry, chemical communities, DOE, and USDA. This was the first time that this diverse set of American companies, nonprofit groups, trade associations, and academic institutions came together for a shared vision of the future for this emerging industry. The goal stated in the vision document is "to provide continued economic growth, healthy standards of living, and strong national security through the development of plant/crop-based renewable resources that are a viable alternative to the current dependence on non-renewable, diminishing fossil fuels."

The targets set in the vision document include:

- At least 10 percent of basic chemical building blocks to be derived from plant-based renewables by 2020 (a five-fold increase).
- Plant-based systems to produce renewable feedstocks with efficient conversion processes for selected products by 2020.
- Collaborative partnerships among industrial stakeholders, growers and producers, academia, and Federal and State governments to help develop commercial applications and revitalize rural areas.

R&D Challenges. While the overall technology roadmap is still under development, there is a need to identify genetic metabolisms and to be able to understand their pathways in order to effectively convert agricultural and forestry raw materials into chemical intermediates, in competition with hydrocarbons. To produce bio-based products, an understanding is required of how the fundamental properties of and variations in the agricultural raw materials relate to

the industrial process needs. Increasing the productivity of fermentors while reducing size, and increasing the efficiency of the separations process are also difficult technological steps.

R&D Activities. A primary barrier to using plant-based materials as feedstocks is the need to fit carbohydrate chemistry into processes based on hydrocarbons, that is, fossil fuels. Short-term R&D will call for modifying processes in order to economically use existing plant and crop materials. Longer-term R&D will apply recent advances in biotechnology to selected processing opportunities. Specific R&D goals are being developed in the technology roadmap to be completed this summer. A solicitation will be issued to select projects for FY 1999 funding based on the priorities identified in the roadmap.

Based on prior research (in the chemical program), a collaboration between ORNL, ANL, and industry is examining modifying *Escherichia coli* strands for the production of succinic acid from biomass. This could lead to an efficient biomass conversion process, reducing petrochemical feedstocks and energy, and sequestering CO_2 into commodity products.

Accomplishments. As a new program, accomplishments beyond the planning stage have not yet occurred.

Petroleum Refining

Budget: FY98-$3.0M, FY99-$0.0M, FY00-$1.0M

Description, Objectives, and Performers. The refining industry is the largest single industrial energy user, consuming 6 quads (over 25 percent of all manufacturing energy), but is also a major energy supplier vital to energy security. It also produces 180 million tons of waste and has the highest pollution abatement costs as a percent of sales, nearly 4 percent.

An initial phase of research was terminated in FY 1998 due to the industry's inability to reach consensus; prior research on catalytic cracking, fouling, combustion, and biodesulfurization have been, or are being, completed. Recent developments in the industry have led them to reconsider, however, and a vision document is expected in FY 1999. Future collaboration with DOE is expected based on direct and indirect energy efficiency technologies.

R&D Challenges. A new industry-developed vision and technology roadmap will identify the key technology needs and challenges.

R&D Activities. Prior activities have or are being completed while a new program will be initiated in FY 1999 and FY 2000.

Accomplishments. Accomplishments from the earlier program included major advances in fouling minimization in heat exchangers which have a significant effect on the energy efficiency of refineries. Equipment fouling is responsible for 0.2 quads of energy and $2 billion in operating and maintenance costs each year. Argonne National Laboratory has developed a methodology to predict fouling rates and threshold fouling conditions, thus improving operations. A high-temperature, high pressure fouling unit was also developed

and Argonne assisted two oil refining companies in mitigating fouling in hydrotreating and crude preheat units.

Crosscutting Technologies

Budget: FY98-$40.8M, FY99-$48.0M, FY00-$55.3M

Background

There are several enabling or supporting technology areas which have been identified as key or priority needs in multiple industry roadmaps. (Some, such as Advanced Turbine Systems and Combined Heat and Power for on-site industrial use, contribute directly to other strategic goals and are hence described under those goals.) The industry roadmaps have assessed future material needs; combustion processes, either for steam or heat or in the process itself; advanced sensors and controls, particularly real time measurements in hostile environments to improve process quality and productivity; and energy and environmental issues.

In addition, the vast number of factories and plants across the United States, operating diverse manufacturing processes and production systems, producing enormous numbers of materials and products, requires that an effective system be developed and utilized to ensure the rapid adoption of new technologies, advanced techniques, and best practices. Without integrating such approaches as part of an overall R&D results deployment system, many technologies are slow to be adopted and some wither. Small businesses and factories are particularly prone to being even unaware of the potential of energy efficient technologies and practices. By providing demonstrations of selected emerging technologies, showcasing and documenting advances and economic advantages that can be obtained, and developing and actively providing tools and information through collaborations with industry, stakeholders can accelerate the reduction in energy use and emissions, and reduce carbon emissions over the next decade which would otherwise be lost.

Linkage to CNES Goals and Objectives

The program is in direct support of CNES goal and objective:

- CNES Goal I, Objective 2 - Significantly increase energy efficiency in the transportation, industrial and buildings sectors by 2010.

The goal of the program is to produce a 25 percent improvement in energy efficiency and 30 percent reduction in emissions for the vision industries by 2020. The strategy to achieve this, in addition to focusing resources on the most energy and waste intensive industries, is to partner with and across industries, and align industry and government resources to areas of greatest need.

Program Description

Research and development is undertaken on critical crosscutting technologies, identified in multiple industry roadmaps, focusing on sensors and controls and combustion processes as well as on advanced industrial materials such as engineered ceramics, intermetallic alloys, and

membrane materials that have applications in many industries. Financial support is also provided, through competitive solicitations, to inventors and small businesses, and through State governments to local industries for developing inventions, innovations, and testing and demonstrating new technologies that emphasize applications to the Industries of the Future. Information dissemination, training, and showcasing advanced energy efficiency technologies help enable the completion of the development cycle and the continuing development by the private sector.

Enabling Technologies

Budget: FY98-$14.5M, FY99-$19.2M, FY00-$22.0M

Description, Objectives, and Performers. The technology base R&D, needed by multiple industries form the link to the more fundamental basic research supported by the DOE Office of Science. These enabling technologies also have relationships to R&D performed by FE and other DOE programs, and, at times, other agencies. Coordination of materials research is accomplished through the DOE Energy Materials Coordinating Committee (EMaCC) through the exchange of planning and budgetary information and through bimonthly technical meetings on selected topics involving DOE and major contractors. Department program managers also participate in information and coordination activities under the Materials Technology (MatTec) subcommittee of the National Science and Technology Council (NSTC) Committee on Civilian Industrial Technology. In addition, enabling technology results may be applicable to other industries beyond the Industries of the Future portfolio. Where the requirements are sufficiently defined and specific to a given industry, they are part of that industry's portfolio.

R&D Challenges. *Engineered Ceramics*
U.S. industry has a critical need for materials that are lightweight, strong, tough, corrosion resistant, and capable of performing at high temperatures. The availability of such materials will enable substantial increases in energy efficiency, reduction in emissions (such as NO_x, particulates, CO_2, and heat), and a decrease in life cycle costs. Advanced materials developed to date have not provided adequate durability and reliability for many key industrial applications. In the early 1990s, continuous fiber ceramic composites were at a very early stage of development and much too immature of a technology for industry to utilize. A study conducted by DOE concluded that investing in the development of these materials could provide substantial benefits to the U.S. industrial sector.

Advanced Industrial Materials
According to the National Materials Advisory Board, corrosion of metals in the United States costs about 4 percent of the gross domestic product. Using current methods of corrosion prevention on existing alloys could save about 15 percent of that cost, but development of new, corrosion resistant materials, particularly with high temperature fatigue resistance, could save even more. It is estimated that energy and production losses of 10 percent result from scheduled down time for maintenance and repair. Another huge energy consuming process is separations, predominantly done by distillation or cryogenic recrystallization. New, more robust, membrane materials for high temperature chemical separations could save at least half the energy currently used for separations by the U.S. industrial sector.

Combustion Technologies
Fossil fuel combustion in boilers, furnaces, and process heaters is still at much lower efficiencies than is possible and can be improved through better fundamental understanding, modeling techniques, and real-time sensing and control of both existing and additional variables, particularly on large scale units. Oscillating combustion requires additional understanding and development for applications beyond its initial use. Reduction of emissions and maximizing the use of multiple fuels also requires such advances.

Sensors and Controls
Most individual industry technology roadmaps have identified advanced sensors and controls as a critical element. It is surprising the number of major process steps that still rely on human operator experience and manual adjustment for process control, for want of capable and reliable sensors and the ability to directly measure (or indirectly infer) the necessary parameters under the high temperatures, harsh and corrosive climates, and high speed nature (e.g. rolling and paper mills) of many processes.

R&D Activities. *Engineered Ceramics*
In the area of advanced materials, engineered ceramics are being tested and developed for high temperature applications. For example, continuous fiber ceramic composite (CFCC) radiant burners will be tested in a glass plant and CFCC immersion tubes will be tested in an aluminum casting plant in 1999. Advanced industrial materials are focusing on advanced intermetallic alloys, with a new class of metal matrix. composites expected by FY 2000. CFCCs, in particular, have the potential for superior high temperature strength, and resistance to fatigue, corrosion, and wear. Research involves materials development and characterization, fabrication and joining techniques, long term testing in various corrosive environments and temperature regimes, and the development of testing methods and data bases to facilitate other technology and engineering development. In 1998, field testing was initiated at several industrial sites to evaluate CFCC radiant burner screens and immersion tube burners. In 1999, standards for use in design and testing will be published. The CFCC program involves collaboration between industry, National Laboratories and universities. The DOE laboratories, led by ORNL, are developing supporting technologies such as material design and processing methods and conducting performance evaluations. Five industry teams comprising 35 members (led by AlliedSignal Composites Inc., McDermott International, Inc., Dow Corning Corporation, General Electric Company, and Textron Inc.) are developing more than 20 applications.

Advanced Industrial Materials
The program concentrates on the development of selected new and improved materials to support critical industry roadmap needs, utilizing prior basic research from SC and elsewhere, and transferring the results to appropriate IOF industry programs for further technology development and demonstration. A major focus area is advanced intermetallic alloys, which have superior high temperature strength, corrosion resistance, and high temperature fatigue resistance. In FY 1998 and FY 1999, emphasis is shifting from nickel aluminide research to other intermetallic alloys, such as iron and titanium aluminides and a

variety of silicide alloys with potential for such uses as molten glass contact applications and corrosive atmospheres found in the chemical and refinery industries.

Continuing research includes methods of developing uniform spherical particles for the powder metallurgy industry and for spray coating metallic components with the intermetallic alloys. The Metals Processing Laboratory User Center (MPlus) at ORNL will be enhanced to support industry and university collaborative efforts. Since designation of the laboratory as a user center, more than 80 projects have been completed or are still active, with enthusiastic industrial response. The project for development of zeolite membranes for para-xylene separations and a project for development of electrochemical reactors for the chloralkali process have been transferred to the Chemical program for further development and demonstration. In FY 1998, the project to develop ultra-strong polymers by magnetic field synthesis will be completed, to be followed by demonstration by the Dow Chemical Company. By FY 2000, the development of a new class of metal matrix composites with superior strength and wear resistance will be completed, in cooperation with Reynold Metals Company and A.P. Green Industries.

Combustion Technologies
Essentially all process industries use combustion either in boilers, furnaces, or process heaters. Industry obtains 85 percent of its energy from the on-site combustion of fuels. In Combustion Technologies, vision and roadmap documents were developed along with long-term goals of improving energy efficiency (20-50 percent reduction in specific fuel consumption in furnaces); reducing emissions (2 ppm NO_x for boilers); maximizing the use of multiple fuels, including waste and renewable fuels; improving reliability (doubling the time between boiler outages); and reducing life cycle costs. Oscillating combustion technology for reducing energy use in steel reheat furnaces is being tested at Bethlehem Steel's Burns Harbor, Indiana, mill. Research is also planned for improved controls and sensors and increased systems integration. Coordination with SC, FE, and other offices is maintained through DOE's Combustion Coordination Group and interfaces are being established with SC's Combustion Strategic Simulation and Modeling activities.

Sensors and Controls
A need for improved sensors and controls has been identified in most of the technology roadmaps produced to date. There is a program goal to have, by 2009, significant advancements in the underlying science and technology of intelligent control systems. The initial focus of the program is on developing improved technology components in sensors, measuring instruments, information processing, and supervisory and communications systems. This focus will later shift toward advancing micro fabrication technologies and integrating components into smart, automated control systems to achieve improved throughput and productivity. Results will be customized and further developed for specific applications in the specific industry programs.

Accomplishments. Nickel aluminide research has been highly successful, with successful demonstrations in steel mill transfer rolls, commercialization as forging dies and heat treating furnace fixtures, and ongoing trials in more than 30 other applications.

Technical Assistance

Budget: FY98-$15.3M, FY99-$18.1M, FY00-$21.3M

Description, Objectives, and Performers. This program will bring the full range of OIT's technical assistance and technologies to thousands of plant sites in an integrated package that is easy for industrial partners to access. A recent, highly successful showcase at Bethlehem Steel's Burns Harbor, Indiana, plant demonstrated a large number of advanced energy-efficient technologies to representatives across the steel and other industries. Sub-divisions of this strategy include the Motor Challenge Program, that has already increased the use of advanced energy-efficient motors at the 3M Corporation; the Steam Challenge, as part of the Motor Challenge, to provide technical assistance on steam and compressed air systems; and the Industrial Assessment Center Program, that has pinpointed and analyzed opportunities in over 7,000 small manufacturing sites for saving energy, reducing pollution, and increasing productivity.

This approach will have an important role in launching new industrial technologies from the research and development stage to the manufacturing plant where the technology can be used to boost the productivity and competitiveness of U.S. industry. The goal of the program is to facilitate and promote the introduction to industry of near-term and emerging energy efficiency, renewable energy, and pollution prevention technologies.

Industry partners have requested a simpler, integrated package of industrial energy efficiency technologies, and technical and financial services—that is both flexible and easy to access. The strategy and implementation plans for this coordinated, integrated delivery approach will concentrate on outreach and technical assistance to IOF companies and plants, however the techniques and technologies are expected to spread across the spectrum of U.S. industry. In addition to deploying specific emerging technologies from the IOF R&D technology portfolio, technology resources are provided from several technical assistance programs.

R&D Challenges. The principal challenge is to enable the vast and diverse U.S. industry to have access to, valid data to assess, and the tools to evaluate, the multiple advanced energy efficiency technologies and techniques that are flowing through and emerging from the R&D pipeline in order to accelerate their adoption in pilot and full scale use.

R&D Activities. The Integrated Delivery Program has two main components:

Plant Utility Activities build upon the highly needed unbiased tools and information that assists plant-level energy efficiency decision-making. Tools such as the Motor Challenge Motor Master+ software, Steam Challenge 3E Plus Insulation software, Compressed Air Challenge Air Master, the Industrial Assessment Center (IAC) self assessment workbook, and the IAC database will be enhanced and delivered to industry through a variety of channels from trade and technical organizations (e.g., the Technical Association of the Pulp and Paper Industry, and the Association of Iron and Steel Engineers) to the Internet.

Technical Assistance Activities - the core of integrated delivery is the development of one-on-one partnerships with individual plants to showcase and adopt a broad spectrum of advanced

energy efficient technologies and techniques. The activities will build upon the successful collaborative showcasing of energy efficient steel production at Bethlehem Steel's Burns Harbor plant, where a spectrum of DOE developed technologies and techniques were shown in operation or through demonstrations and presentations to the rest of the industry and visitors from other industries.

Industry at all levels will be engaged in and exposed to the complete suite of IOF information, tools, and technologies that will help to implement clean, cost-effective strategies, while improving American industry's bottom line. An additional objective of the integrated delivery strategy is to provide a higher level of direct interaction and technical assistance with manufacturing plant personnel than ever before possible, and to positively influence the way energy, waste, and productivity decisions are made. As part of this system, and aimed at small companies and plants, are factory assessments performed by a network of trained university staff and students located around the country to provide evaluations and assistance at the local level.

The IOF Integrated Delivery strategy relies on the tools, services and technology resources of existing key program elements to offer technical assistance:

The *Motor Challenge Program* works in partnership with the electric supplier and controls industry to increase the market penetration of advanced energy efficient motor-driven systems. A key element in the Motor Challenge strategy is to encourage a "systems approach" to how motors, drives and motor-driven equipment are engineered, specified, purchased, and maintained by industry. Starting in FY 1999, and building on the success of the Motor Challenge program as a model, work was started to develop the tools and provide enhanced technical assistance, on steam and compressed air systems.

The *Industrial Assessment Center (IAC) Program* provides assessments to small manufacturers in order to pinpoint and analyze opportunities for cost-effective energy, waste, and productivity savings, and at the same time provides hands-on training to engineering students in energy, waste and productivity management practices. It is also the only program that provides engineering students with both theoretical and practical plant experience. This university-based program serves parts of 43 States through 30 university engineering departments.

Accomplishments. The Motor Challenge Program partnered with the 3M Corporation to optimize and upgrade electric motor systems at a 3M corporate campus facility. The combined savings from this systematic approach are more than $800,000 per year, and the project serves to promote these techniques and technologies to both other 3M plants and other companies.

The Industrial Assessment Center Program has provided industrial assessments to over 7,000 plants. At one plastic molding plant, an IAC team was able to make recommendations that, when implemented, cost-effectively saved the company approximately $134,000 per year, and significantly reduced the amount of waste plastic involved in the process.

Key partners include the 30 universities that currently deliver IAC assessments; numerous trade and professional societies; motor, controls, compressor and boiler manufacturers and distributors; and others that support the Motor Challenge, steam, and compressed air activities, and the IOF companies involved in showcasing and other efforts.

Financial Assistance

Budget: FY98-$11.0M, FY99-$10.7M, FY00-$12.0M

Description, Objectives, and Performers. OIT has traditionally relied on two separate financial assistance programs: (1) the Inventions and Innovation Program and, (2) the National Industrial Competitiveness through Energy, Environment, and Economics (NICE^3) Program. These programs were designed to speed the development of new energy efficient inventions, and to leverage industry and other resources to demonstrate and promote the benefits of advanced energy-efficient industrial technologies. The Inventions and Innovation Program provides "seed" support to private sector individuals and small businesses in the development of new energy efficient technologies. The program was recently re-engineered to be performed through competitive solicitations. The NICE^3 Program provides funding, on a competitive basis, to State and industry partnerships for projects that demonstrate energy efficient, clean production technologies that are emerging or ready for commercialization. In FY 2000, the Financial Assistance Program will provide an integrated delivery of these programs. In this way, selection of the most meritorious ideas and technologies is obtained through competition and an appropriate balance of the portfolio between short and long term technologies can be maintained.

R&D Challenges. These programs comprise competitively selected awards encompassing the entire industrial sector, but emphasize the Industries of the Future (IOF)—the R&D challenges encompass those identified in the collection of IOF technology roadmaps.

R&D Activities. In FY 2000, the Financial Assistance Program will use competitive solicitations for both the Inventions Program and NICE^3 that will, for the first time, be issued on concurrent schedules. The program will continue to provide opportunities for inventors, innovators, and entrepreneurs to help make their energy-related ideas a commercial reality and will also continue to offer (on a competitive basis) cost-shared funding to State and industry partners to demonstrate advances in near-term, energy efficient, and clean manufacturing technologies that are just becoming available for commercialization. By reducing DOE overhead activities, a larger total number of worthy projects can be supported. Also, the new program will better support and target IOF sectors by using competitive solicitations that are designed to encourage and favor participation by energy and waste intensive industrial sectors. The impact of the new program will also be improved by working with regional centers to more effectively leverage local resources, and to better tailor assistance to specific regional/local needs and situations.

Accomplishments. A grant from the Inventions and Innovation Program provided the Helysis Corporation $70,000 to help develop a new technology that would permit the automated production of mold or die blocks in less time, at competitive energy usage, and at lower cost than traditional methods. The new process involved a patented system called

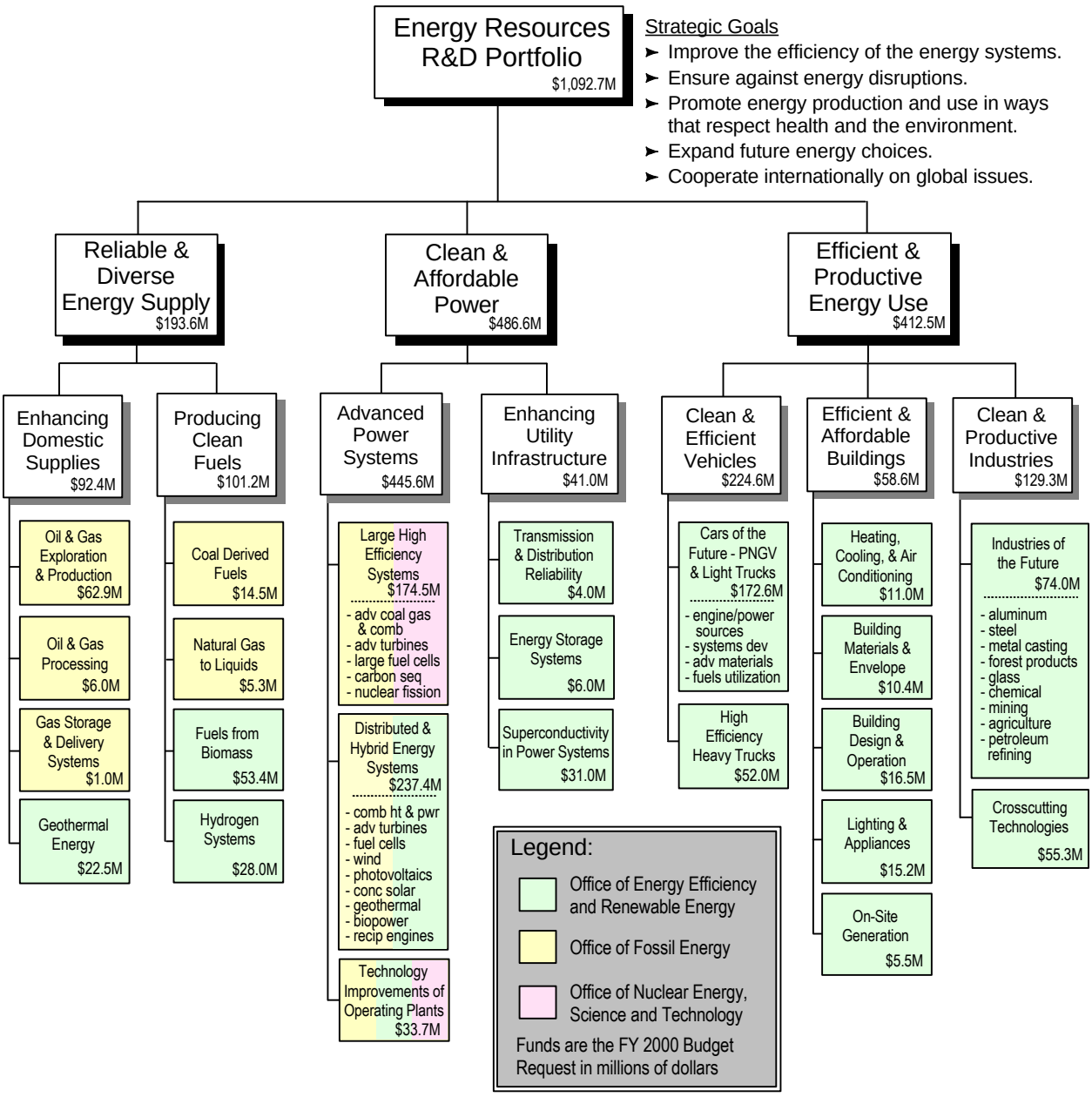
Laminated Object Manufacturing (LOM). Currently, LOM systems are operating in large corporations such as General Motors, Chrysler Corporation and Ford Motor Company, as well as in small pattern makers, government agencies and universities in more than 26 countries around the world.

With the help of a competitive NICE[3] grant, Whyco Technologies, Inc. developed a new plating technology. The Whyco technology uses 15 percent less energy, eliminates more than 255 tons of solid waste per year, and reduces waste water by more than 17,000 gallons per day—resulting in cost savings of more than $500,000 annually. The company has manufactured and sold more than 175 of these systems to other electroplating companies, which are reporting up to a 40 percent increase in plating productivity.

Summary Budget Table (000$)

Clean and Productive Industries Research Areas	FY 1998 Appropriated	FY 1999 Appropriated	FY 2000 Request
Industries of the Future	**53,080**	**57,460**	**74,020**
Aluminum	7,340	8,100	11,180
Steel	9,730	10,530	10,630
Metal Casting	5,480	5,740	5,800
Forest Products	12,040	11,960	21,080
Glass	3,880	4,790	4,830
Chemical	11,610	12,380	12,500
Mining	0	1,980	3,000
Agriculture	0	1,980	4,000
Petroleum Refining	3,000	0	1,000
Crosscutting Technologies	**40,770**	**48,020**	**55,300**
Enabling Technologies	14,470	19,220	22,000
Technical Assistance	15,340	18,100	21,300
Financial Assistance	10,960	10,700	12,000
Total	**93,850**	**105,480**	**129,320**

Chapter 10
Basic Science



Chapter 10
Basic Science

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Overview

The Department of Energy maintains a sizeable portfolio of basic research that underpins DOE's applied R&D missions and explores broad frontiers in fundamental science, leading the Nation in the basic energy and physical sciences. Overall, this chapter addresses the contribution of basic science to the energy R&D mission, that is to say, the contributions of the DOE's Office of Science (SC) to applied energy R&D programs. A companion document to the overall Energy R&D Portfolio addresses the issues and implications of the Department's broader Science Portfolio.

In support of its basic science mission, DOE manages the most extensive and advanced complex of scientific facilities in the world. Such facilities, managed by SC, include powerful accelerators for high energy and nuclear physics, light and neutron beam facilities for the natural and life sciences, electron beam microcharacterization centers, multidisciplinary mission centers, and single purpose research facilities. Beyond DOE-sponsored research, the Department provides access to these facilities for the Nation's professors, students, and public and private-sector researchers.

Within the Department, the basic science programs are funded within SC at a total of $2.5 billion in FY 1998. This budget supports basic science, research facilities, and related infrastructure.

In pursuit of energy goals, research supports, as well as draws from, a broad spectrum of science disciplines. Most of these disciplines contribute directly to the applied energy R&D mission of the Department. These include:

- materials science
- environmental sciences
- fusion/plasma sciences
- energy technology research
- chemical sciences
- high energy and nuclear physics
- biological and biomedical sciences
- computational and math sciences
- engineering sciences
- geosciences
- energy biosciences

The National Laboratories, universities/colleges, and the private sector perform the research.

A distinguishing, general feature of basic science is that it is primarily knowledge rather than application driven. That is to say, one of its main purposes is to explore the complex phenomenon and processes that define our physical world, to determine what factors influence them, and to understand how we may ultimately control them. At this basic level, discoveries and insights usually have broad-reaching, diverse implications for many applied R&D and technology development programs, not just one.

Support for Energy R&D

Although most of the Department's basic science research has broad-based, generic implications for technology programs, some of this research aligns more strongly with particular energy technology applications, depending on the questions and phenomenon that the science addresses and the challenges inherent to the applied R&D area. For example, discoveries in the science of lightweight, high-strength materials, as well as advanced material joining techniques and properties align strongly with applications for next generation, efficient vehicles. To add perspective on how basic science supports applied energy R&D applications, additional examples are provided below in each of the seven other energy R&D areas:

- Enhancing Domestic Supplies
- Producing Clean Fuels
- Advanced Power Systems
- Enhancing Utility Infrastructure
- Clean and Efficient Vehicles
- Efficient and Affordable Buildings
- Clean and Productive Industries

Note that these examples are just that, examples. They are intended to illustrate the strong link that exists between the Department's basic science programs and innovation in DOE's applied energy R&D programs.

Enhancing Domestic Supplies

Examples of basic science that support Enhancing Domestic Supplies are provided below. Most of this research is carried out by the Office of Basic Energy Sciences, the Office of Biological and Environmental Research, and the Office of Computational and Technology Research.

- *Geosciences:* Basic research in Geosciences focuses on improving the level of understanding necessary for advances in, and choices among, current and emerging energy and environmental technologies. Primary research focus areas are geochemistry, geophysics, geomechanics, and hydrology. Additionally, research in chemistry focuses on fundamental molecular-level understanding of chemical interactions and chemical reactions, the development of new analytical tools and methods, and the physical and chemical interactions forming the bases for new membranes for separation processes. These programs also provide the fundamental thermal and physical properties that are the bases of all engineering applications. Research in materials sciences provides the knowledge for new materials impacting domestic supplies in every area from advanced

materials for drill bits to new-concept storage methods. More directly, the basic research within geosciences efforts focuses on:

- Improved fundamental research on mineral-fluid interactions will provide a better understanding of the origin, migration and localization of oil and gas resources, the location and management of geothermal resources, and the control of energy-related wastes in the vadose and saturated groundwater zones.

- New fundamental thermodynamic and physical property information on rocks, minerals, and geologic fluids are needed for resource recovery and contaminant assessment and monitoring.

- New and more sensitive isotopic tracer methods will contribute to evaluation of natural and anthropogenic processes in the geologic environment.

- Improved understanding of hydrologic processes, especially focusing on scaling and heterogeneity of porosity and permeability distributions will form the basis for more robust predictions of flow in reservoirs, aquifers, or in unconfined groundwater.

- Rock physics and geomechanics studies form the foundation for improved geophysical imaging, and for understanding fracture-mediated subsurface transport of fluids.

- *Environmental Sciences:* Within the Office of Biological and Environmental Research, there are research programs on global climate change, advanced sensors, and integrated assessment of the impacts of climate change.

- *Computational Sciences:* Within the Office of Computational and Technology Research, efforts at improving computational tools, developing the 2nd generation Internet, and providing the basis for massively parallel computation are critical to enhancing domestic supplies.

It is worth noting that beyond SC's contributing basic science, the Office of Environmental Management and the Office of Defense Programs both conduct basic research that impacts domestic supplies. The Office of Environmental Management conducts research that provides a sound scientific basis for assessing risks of various supply technologies. And, Defense Programs supports research in computing technology, computational modeling, instrumentation development, and geophysical studies that have both defense and civilian applications.

Producing Clean Fuels

Examples of basic science that support Producing Clean Fuels are provided below. Most of this research is carried out by the Office of Basic Energy Sciences and the Office of Biological and Environmental Research.

Efforts to develop cleaner fuels and reduce carbon emissions draw on many scientific disciplines. For example: biochemistry; catalysis; molecular, cellular and plant biology; structural biology; genome science; and solar photochemistry contribute, because the production of fuels and chemicals by plants and microorganisms and the interconversion of greenhouse gases requires a better understanding of metabolism, of the structure and function of sub-cellular components, and of enzymes. Similarly, the state-of-the-art in biochemistry, molecular biology, and ecology contribute. All of these biological processes are important in understanding the role of microorganisms in sequestering carbon. Improvements in combustion to reduce carbon emissions require a fundamental understanding in chemical dynamics, theoretical chemistry, and physics. Conversion of sunlight to energy requires an understanding in many areas of science, including photochemistry, photosynthesis, metabolism, and solid-state physics. The search for increased efficiency in energy production and use requires fundamental knowledge in ceramics, metals, polymers, solid-state chemistry, and condensed matter physics for materials that can withstand higher temperatures, have lower coefficients of friction, and are stronger and lighter. Enhanced recovery of fuel resources and of disposal of carbon dioxide requires a fundamental understanding of geometric, structural, and hydrologic properties of reservoirs and of multiphase, nonlinear transport of fluids in porous and fractured structures. Cross-cutting programs in nano- and meso-phase materials involve research at the forefront of materials science, chemistry, engineering, surface science, and semiconductor physics.

Office of Science fundamental research areas that underpin the Clean Fuels R&D Portfolio—and other DOE science and technology portfolios—include the following.

- *Microbial Genome Program:* Significant investments have been made in the technology that enables genome sequencing at rates previously unattainable. Capitalizing on these investments, the genomes of microbes that produce methane and hydrogen will be sequenced. This will enable the identification of the key genetic components of the organisms that regulate these gases. Once we identify and understand more fully how the enzymes and organisms operate, we will be able to evaluate the potential use of either the microorganisms or the relevant enzymes to produce methane or hydrogen from either fossil fuels or other carbonaceous sources, including biomass or perhaps even some kinds of waste products. For instance, recently discovered "extremophile" organisms could be used to engineer biological entities that could ingest a feedstock like methane, sequester the carbon dioxide, and give off hydrogen.

- *Microbial Conversion*: Basic research in microbial conversion focuses on examining the metabolism, biochemistry, genetics, and physiology of organisms and consortia of organisms that degrade lignin, cellulose, and/or hemicellulose into potential fuels. The fuels include ethanol, higher alcohols, and methane. While much of the activities involve anaerobic bacteria, fungi are also actively investigated. These studies form the foundation for the efficient conversion of lignocellulosics (biomass) into potential liquid and gaseous fuels, an important component of several technology programs in this portfolio.

- *Plant Biology*: Green plants and some bacteria use photosynthesis to capture solar energy and convert it into chemical energy that fuels metabolism and the biosynthesis of a broad range of storage compounds and structural components. For example, the chemical energy in firewood was the early energy source for mankind, and even today the worldwide combustion of plant biomass generates more energy than any other non-fossil fuel source. As a renewable resource, plant biomass potentially has enormously valuable uses when it is converted into specific materials, fuels, chemical feedstocks and petroleum replacing materials. Basic studies in plant biology are providing new insights into the genetic, metabolic, and enzymatic properties of plants that regulate the production of specific useful chemical compounds and materials. Similarly, studies on the regulation of the photosynthetic process that fuels metabolic biosynthesis are yielding new insights on how bacteria and plants channel photosynthetic energy into the production of renewable biomass materials.

- *Solar Photochemistry:* This research explores fundamental photochemical processes aimed at the capture and conversion of solar energy. This research program encompasses organic and inorganic photochemistry, electron and energy transfer in homogeneous and heterogeneous media, photocatalysis, and photoelectrochemistry. The photosynthetic reaction center is studied as a model for the design of efficient, photoinduced charge separation in biomimetic/ photocatalytic assemblies. The research provides the foundations for future solar technologies in which light-induced, charge-separation processes will convert light energy to chemical energy in such applications as the production of alcohols from carbon dioxide, hydrogen from water, or ammonia from atmospheric nitrogen.

- *Catalysis:* Catalysis is a chemical process found widely in nature and used extensively in industry because it removes energy barriers to chemical reactions. Catalysts used for the refining of petroleum or the manufacture of chemicals are important because they reduce process energy, speed up production, and make possible the manufacture of new materials. Despite their importance, catalytic processes are not sufficiently well understood to allow for rational design of new catalysts. Models for catalytic action are limited in scope and applicability. The Office of Science catalysis program seeks to gain understanding of catalysis at the molecular level to allow the development of general theories and models of catalytic action. The program includes both heterogeneous (multiple phases such as liquid/solid) and homogeneous (single phase) catalysis. Research in heterogeneous catalysis seeks to characterize the role of surface properties on molecular transformations and the structural relationships between oxide surfaces and reaction pathways, especially in the acid and redox catalysts commonly encountered in industrial applications. Research in homogeneous catalysis seeks to characterize the activation and subsequent reactions of carbon-hydrogen bonds and the role of bonding and molecular structure on the catalytic processes. The program constitutes the largest single component of the Nation’s basic research portfolio focused on chemical catalysis.

The Department of Energy's Climate Change Technology Initiative has been developed as a partnership between the technology and research offices at DOE and representatives of the

National Laboratories. A series of workshops have been held to identify basic science needs and opportunities for capturing and sequestering carbon, for fuel cell and hydrogen development, for enhancing the natural carbon cycle, and for biomass conversion. These workshops have included participants from the Offices of Science, Fossil Energy, and Energy Efficiency and Renewable Energy.

Advanced Power Systems

Examples of basic science that support Advanced Power Systems are provided below. Most of this research is carried out by the Office of Basic Energy Sciences, the Office of Biological and Environmental Research, and the Office of Fusion Energy Sciences.

Efforts to develop clean power and reduce carbon emissions draw on many scientific disciplines. For example: electrochemistry; combustion; materials - including welding, joining, and corrosion; photovoltaics and semiconductors; engineering research; geosciences; biology and genomics; and environmental sciences. These and other disciplines contribute, because power production, transmission, and storage as well as the interconversion of greenhouse gases requires a better understanding of the materials and processes that contribute to each phase. Similarly, the state-of-the-art in biochemistry, molecular biology, and ecology will be impacted. All of these biological processes are important, for example, in understanding the role of marine microorganisms in sequestering carbon. Improvements in combustion to reduce carbon emissions require a fundamental understanding in chemical dynamics and theoretical chemistry and physics. The search for increased efficiency in energy production and use requires fundamental knowledge in ceramics, metals, polymers, solid-state chemistry, and condensed matter physics for materials that can withstand higher temperatures, have lower coefficients of friction, and are stronger and lighter. Enhanced recovery of fuel resources, the disposition of nuclear power and other transuranic waste, and the disposal of carbon dioxide require a fundamental understanding of geometric, structural, and hydrologic properties of reservoirs and of multi-phase, nonlinear transport of fluids in porous and fractured structures. Cross-cutting programs in nano- and meso-phase materials involve research at the forefront of materials science, chemistry, engineering, surface science, and semiconductor physics. And efforts to understand fusion plasma science and concepts for engineering plasma confinement may someday make commercial nuclear fusion a reality.

Contributions to Advanced Power Systems include the following research areas:

- *Electrochemistry:* Fundamental research is supported in areas critical to understanding the underlying limitations in the performance of non-automotive electrochemical energy storage systems. Areas of research include the characterization of anode, cathode, and electrolyte systems and their interactions. The broad spectrum of research includes fundamental studies of composite electrode structures, failure and degradation of active electrode materials, and thin film electrodes, electrolytes, and interfaces. The aim is providing knowledge that will lead to improvements in battery size, weight, life, and recharge cycles.

- *Combustion:* Basic research in combustion provides knowledge on the rates and energetics of chemical reactions and on the interactions of fluid dynamics and chemistry. This knowledge is required by combustion models used for the design and optimization of energy-efficient, reduced-emission combustion devices. Knowledge gained consists of measured properties as well as theoretical constructs for the reliable prediction or extrapolation of such properties. SC supports the operation of the Combustion Research Facility (CRF) at Sandia National Laboratories, California, where collocated research, supported by SC, the Office of Energy Efficiency and Renewable Energy (EE), the Office of Fossil Energy (FE), and industry, is conducted in a highly collaborative environment.

- *Photovoltaics and Semiconductors:* Semiconducting materials underpin virtually the entire “high tech” industry worldwide. They comprise the building blocks and components for several technologies within this portfolio, including photovoltaics, sensors, power electronics, and high speed computational systems. Research within this area includes synthesis of new and tailored semiconductor materials; characterization of structure, electronic structure, and stability of semiconductors; investigations of surfaces and interfaces; the influence of light on the behavior and properties of semiconductor materials; theory and modeling of properties and behavior; and the operation of facilities that support such research.

- *Ceramic Materials:* Ceramic materials play an integral role in the utility, automotive, and other energy-intensive industries. A fundamental understanding of their complex microstructure and behavior is essential for their successful implementation. The ceramic sciences research addresses the scientific issues underlying the synthesis, processing, behavior, and characterization of ceramic and non-metallic glassy materials. Focus areas include synthesis, processing, reactivity, and physical and mechanical properties, with emphasis on elevated temperature behavior. The technological areas impacted include high temperature structural materials (e.g., high temperature monolithic and composite ceramics and ceramic coatings), energy storage materials (e.g., solid electrolytes, batteries, and ultracapacitors), energy conversion materials (e.g., fuel cells), hazardous waste storage materials (glasses and ceramics), sensors, and environmentally benign synthesis techniques.

- *Radiation Materials:* There are 71 nuclear power reactors in the United States that are over 20 years old. The time-dependent radiation-induced embrittlement of aging steel containment vessels and structural members defines a critical safety and environmental problem for these on-line facilities. Their continued safe operation requires a better predictive "early warning" or "retirement for cause" model for their behavior. Therefore, the Office of Science supported research in radiation materials includes synergistic relationships between neutron, proton, and ion irradiation with defects, composition, and physical and mechanical behaviors in metals, ceramics, intermetallics, polymers, and semiconductors. Emphasis is on surface modification, modeling of radiation induced damage, cascade formation, property changes, design of radiation-resistant materials, irradiation induced stress-corrosion cracking, changes in grain boundary microchemistry, crack tip phenomena, and evaluation of spallation neutron and high energy proton

damage. There are three additional distinct motivations for SC activities in radiation materials sciences: (1) the safe containment, over many-generations, of radioactive wastes requires valid predictive models for their time-dependent degradation under conditions including self-irradiation, heat, and the time-dependent production of radio-decay products (this work supports the Department's efforts in Environmental Management); (2) the development of fusion reactors will require an understanding and a modeling of the radiation induced behavior of insulator and first wall component candidate materials such as silicon carbide, high-chromium ferritic-martensitic steels, and vanadium; and (3) the energetic-ion-induced surface modification and implantation of metals, ceramics, polymers, and semiconductors is a continuously evolving science as well as an important technology that in turn underpins all energy conversion and conservation technologies.

- *High Temperature Superconducting Materials:* Research into the development of improved superconductors that can be used in the generation, transmission, utilization, and storage of electric power using high-T_c superconductors contributes to the efficient utilization of energy. Therefore, basic research is performed on the theory, synthesis, processing, structure, and physical properties of high temperature superconducting materials including the discovery of new classes of superconducting materials.

- *Intermetallics:* Intermetallic compounds are metal to metal compounds with definite stoichiometry. Intermetallic alloys made from these compounds constitute a unique class of high-temperature structural materials that posses the desired properties of high strength, oxidation and corrosion resistance, low density, and a high melting point. Such properties make them attractive as constituents for gas turbine engines, high-temperature coatings, and in dies and molds for ceramic and metallurgical processing. Intermetallic compounds may also be used in a variety of electromagnetic areas including both hard and soft magnets, superconductor, semiconductor, and optical applications.

- *Materials Welding and Joining:* Materials welding and joining are critical fabrication technologies that are used extensively in all energy, automotive, environmental, and electronic technologies. Weld failures are the most frequent reason for unscheduled and sometimes catastrophic outages in power plants with the cost of replacement power often exceeding $1 million dollars per day. Welding represents 10 percent of the cost of construction and 20 percent of the maintenance costs for a 500 megawatt fossil-fueled electric power plant. SC supported basic research includes understanding the microstructure and defects that develop as a consequence of temperature gradients; solid-state phase transformations in weld heat affected zones; thermal processes as applied to gas metal arc welding; molten metal droplet formation; plasma and arc physics; laser welding of automotive aluminum alloys; time-resolved X-ray absorption spectroscopy to directly determine rate of transformation of one phase to another phase under the highly-nonisothermal conditions that prevail during welding; welding of Al, Ti, and thin plates; coupling welding science and fracture mechanics modeling in response to the Northridge California earthquake experience; and critical issues in the non-welding joining of ceramics and dissimilar materials.

- *Corrosion:* The importance of the scientific understanding of corrosion is emphasized by the estimate that corrosion in the United States has an economic cost of 4 percent of the gross domestic product. Corrosion damage limits the performance of all energy conversion technologies. The basic research underlying the science of corrosion focuses on the formation, properties, and breakdown of passivating films; on a wide array of electrochemical phenomena involved in aqueous corrosion such as pitting and crevice corrosion; on high-temperature gaseous corrosion; and on new techniques to identify and study corrosion.

- *Engineering Research:* The SC Engineering Program supports fundamental research on broad, generic topics in energy related engineering topics. This includes research on fractals and porous media transport, nonlinear waves, traveling wave convection in fluid mixtures, wave turbulence interactions, multi-phase systems, gas and solids problems, the effect of different Reynolds numbers on turbulence, mixing and transport, gas-liquid flow in pipelines, lubricated transport of viscous materials, the rheology of concentrated suspensions, macrostatistical hydrodynamics, heat/mass transfer enhancement in separated and vortex flows, effect of forced and natural convection on solidification of binary mixtures, interfacial area and transfer in two-phase flow, and various diagnostics for analyzing fluids. An emphasis of the research is on complicated fluid dynamics because fluids are a part of most energy-related systems including pipelines, manufacturing processing, hydraulic systems, planes, trains, automobiles, ships, liquid metal handling, new materials synthesis, chaotic wave motion, weather prediction, environmental issues, and biological systems.

- *Geosciences:* Both geophysical and geochemical information is significant for current and future energy technologies, particularly geothermal energy, oil and gas, and understanding the disposition of wastes generated by the technological enterprise, including the by-products of nuclear energy. Rock mechanics, fracture, and fluid flow encompasses research on the response of rock to stress and the role of fluid flow as a cause and/or effect. The prediction and interpretation of rock response offers unique challenges because the scales involved range from the microscopic to hundreds of kilometers and from seconds to geologic times. The properties of rock are dominated by extreme heterogeneity, pressure dependence, the presence of natural fracture systems, and the coupling between thermomechanical properties, fluid flow, and geochemical processes. Geochemical research is supported in rock-fluid interactions to provide fundamental information on the governing mechanisms and rates of reactive geochemical processes that concentrate, transport, modify, and emplace energy resources and the by-products of energy use within the Earth's shallow crust. Other research in the Geosciences is focused on gaining a better understanding of the fundamental biological, chemical, geological, and physical processes that must be marshalled for the development and advancement of new, effective, and efficient processes for the remediation and restoration of contaminated sites. Research advances will continue to be made from pore to field scales, on genes and proteins used in bioremediation, in non-destructive, real-time measurement techniques, in overcoming physico-chemical impediments to bacterial mobility in the subsurface, on species interaction and response of microbial ecology to

contamination, and in understanding microbial processes for altering the chemical state of metallic and radionuclide contaminants.

- *Fusion Energy Sciences:* Research is focused on fusion plasma science and engineering concepts and supporting science for plasma confinement. SC maintains a large research program aimed at unlocking the secrets to this potentially limitless supply of clean energy. Supporting computational sciences are developed within the Office of Computational and Technology Research. Materials and superconductivity research are critical to various confinement concepts.

- *Biology/Genomics:* The microbial genome program capitalizes on DNA sequencing technology from the human genome program to determine the complete DNA sequence of microbes with potential environmental, energy, or commercial applications. While the program has a principal emphasis on DNA sequencing it includes research on microbial diversity, to identify a broader array of potentially useful microbes; and novel strategies and tools for characterizing, manipulating, and modeling entire reaction pathways or regulatory networks of microbes or groups of microbes to maximize the usefulness of these newly characterized microbes.

- *Structural Biology:* Understanding and predicting the complex relationship between the DNA sequence of a gene and the structure and function of the protein it encodes is a critical first step in being able to reengineer genes and proteins for use in developing new strategies for improving or developing new fuels, reducing pollution from fuel use, and cleaning up the environment. Therefore, SC supports basic research in structural biology including instrumentation research and research that cuts across basic, molecular, and computational biology. For example, studies of inverse protein folding provide an understanding of the rules that proteins follow to acquire the three dimensional structures that give them their biological function while Proteomics research provides information that will lead to an understanding of the structure, function, and interactions of all proteins encoded by an organism's genome.

- *Environmental Sciences:* Research in the environmental sciences is focused on understanding the basic chemical, physical, and biological processes of the Earth's atmosphere, land, and oceans and how these processes may be affected by energy production and use, primarily the emission of carbon dioxide from fossil fuel combustion. A major part of the research is designed to provide the data that will enable an objective assessment of the potential for, and consequences of, global warming. Emphasis is given to understanding the radiation balance from the surface of the Earth to the top of the atmosphere (including the role of clouds) and on enhancing the quantitative models necessary to predict possible climate change at global and regional scales. The Atmospheric Radiation Measurement (ARM) program works to produce the experimental and modeling results that will be necessary to resolve the greatest uncertainty in climate prediction—the role of clouds and solar radiation. Climate modeling using massively-parallel supercomputers will simulate climate change, predict climate, and evaluate model uncertainties due to changes in atmospheric concentrations of greenhouse

gases on decade to century time scales. The Carbon Cycle program studies the natural carbon cycle and assesses the potential impacts of climate change on terrestrial systems.

Unique facilities at the Environmental Molecular Sciences Laboratory such as the Molecular Science Computing Facility, the High-Field Mass Spectrometry Facility, and the High-Field Magnetic Resonance Facility will be used to conduct a wide variety of molecular-level environmental science research, including movement of contaminants in subsurface groundwater and vadose zone sediments and atmospheric chemical reactions that contribute to global warming.

Capitalizing on activities in support of the U.S. Global Change Research Program, and stimulating a partnership between the technology and research offices at DOE and representatives of the National Laboratories, the Climate Change Technology Initiative supports research into the role that the terrestrial biosphere and human activities play on the state and quality of the global climate. The research seeks the understanding necessary to exploit the biosphere's natural processes for use in sequestration of atmospheric carbon dioxide including the roles of marine microorganisms in ocean carbon sequestration and the mechanisms by which forest ecosystems sequester carbon. A series of workshops have been held to identify the basic science needs and opportunities for capturing and sequestering carbon, for fuel cell and hydrogen development, for enhancing the natural carbon cycle, and for biomass conversion. These workshops have included participants from the Offices of Science, Fossil Energy, and Energy Efficiency and Renewable Energy.

In addition to interactions across the Department to develop the Climate Change Technology Initiative, the SC programs maintain significant interactions with other DOE offices and other agencies involved in environmental remediation, e.g., Office of Environmental Management, the Environmental Protection Agency, the Department of Defense, or other partners in the U.S. Global Change Research program.

Enhancing Utility Infrastructure

Examples of basic science that support Utility Infrastructure are provided below. Most of this research is carried out by the Office of Computational and Technology Research and the Office of Basic Energy Sciences.

- *Advanced Computing:* High speed computing and networking capabilities are critical to both modeling and control of the utility infrastructure.

- *Materials Science and Physics:* A wide range of advanced materials and materials processing technologies are required for high-performance low-cost semiconductors, superconductors, high-strength light-weight composites, and corrosion resistant materials. Physical understanding of the properties of these materials aids researchers in improving performance and reducing cost.

- *Power Electronics and Controls:* Research includes the development of advanced topology modeling methodologies and high speed switching devices based on silicon carbide and thin-film diamond which will have higher capacity, lower cost and lower losses.

- *Energy Storage:* Research in this area addresses advanced batteries, supercapacitors, flywheel technologies and their associated materials, and control technologies.

The performance parameters, economics, environmental acceptability and safety of all energy generation, conversion, transmission, and conservation technologies are limited by the performance of available materials. The BES Materials Sciences Program is concerned with understanding and exploiting the synergistic relationship between the synthesis, processing, structure, properties, behavior, in-service performance and lifetime, and recyclability of materials. Such understanding is necessary for the development of technologically and economically desirable new materials and cost-competitive and environmentally acceptable methods for their synthesis, processing, fabrication, quality manufacture, and recycling. The Materials Sciences program funds basic research in metallic glasses (for corrosion resistant, wear resistant, and low magnetic loss behavior); ceramics (energy storage technologies); high temperature superconductivity (for energy generation, transmission, and storage); hard and soft magnets (for low energy loss motors and transformers); and ordered intermetallic alloys (for heat, load, wear, and corrosion resistant applications).

Within the BES Chemical Sciences Program, the Advanced Battery Research program supports fundamental research in areas critical to understanding the underlying limitations in the performance of non-automotive electrochemical energy storage systems. Areas of research include anode, cathode, and electrolyte systems and their interactions with emphasis on improvements in battery size, weight, life, and recharge cycles. Although both primary and secondary battery systems are considered, the greatest emphasis is placed on rechargeable (i.e., secondary) battery systems. The program covers a broad spectrum of research including fundamental studies of composite electrode structures, failure and degradation of active electrode materials, and thin film electrodes, electrolytes, and interfaces. Problems of electrode morphology, corrosion, electrolyte stability, and the transport properties of electrode and electrolyte materials and surface films are also addressed.

In Superconductivity research particularly, the Office of Basic Energy Sciences (BES) plays a significant role. It funds research at the Oak Ridge National Laboratory (ORNL) to work with the 3M Company and develop a novel *ex situ* process for growing superconducting films. This work is conducted in collaboration with the Office of Energy Efficiency and Renewable Energy (EE) Second Generation Wire Initiative. The project included BES funding of $375,000 over 18 months, with a matching amount at ORNL from EE. Over the 18 month project time frame, 3M Company devoted over $1.5 million to research with both ORNL and Los Alamos National Laboratory (LANL) on aspects of the second generation wire initiative. EE and SC superconductivity research is coordinated through several workshop mechanisms, including a Wire Workshop jointly sponsored by EE/SC. The output is a jointly produced, publicly available document describing key science issues identified at the workshop. Teams of EE/BES staff have

also been formed to focus on specific issues. In addition, SC maintains facilities on which advanced energy research can be carried out and a large communication network and computer facilities where information can be shared and simulations and analysis can be done.

Clean and Efficient Vehicles

Examples of basic science that support Clean and Efficient Vehicles are provided below. Most of this research is carried out by the Office of Basic Energy Sciences (BES).

- *Electrochemistry:* Within this topic area, the BES Advanced Battery Research program supports basic research critical to understanding limitations in the performance of electrochemical energy storage systems. Research addresses the characterization of anode, cathode, and electrolyte systems and their interactions, and includes fundamental studies of composite electrode structures, failure and degradation of electrode materials, and thin film electrodes, electrolytes, and interfaces. Close coordination with DOE's Office of Transportation Technologies' (OTT) battery programs is accomplished through joint meetings, program reviews, and strategy sessions.

- *Combustion:* Basic research in combustion provides knowledge on the rates and energetics of chemical reactions and on the interactions of fluid dynamics and chemistry. This knowledge is required by combustion models used for the design and optimization of energy efficient, low emission combustion devices. BES supports the operation of the Combustion Research facility at Sandia National Laboratory, which serves as the focus for the integration with the applied combustion programs in EE. Additionally, the EE Combustion Cooperative Research and Development Agreement (CRADA) is one of two pilot collaboratory projects in the Office of Science sponsored DOE 2000 Initiative.

- *Synthesis and Processing of Advanced Materials:* These essential elements of materials science and engineering deal with the assembly of atoms or molecules to form materials, the manipulation and control of the structure at all levels from the atomic to the macroscopic scale, and the development of processes to produce materials for specific applications. The goal of the basic research ranges from creating new materials, improving the properties of known materials, and improving the forming of metals to the understanding of such phenomena as diffusion, crystal growth, sintering, and phase transitions. Scientific results are translated into useful materials by developing processes capable of producing high quality cost-effective products including light weight alloys for vehicles.

- *Ceramics:* The BES Ceramics program addresses scientific issues related to the synthesis, processing, and characterization of ceramic and non-metallic glassy materials. The OTT technological areas impacted include high temperature structural materials (ceramic coatings), energy storage materials (batteries), energy conversion materials (fuel cells), and sensors.

- *Semiconductors:* This research includes synthesis and characterization of new semiconductor materials, electronic structure and stability studies, investigations of surfaces and interfaces, the influence of light on semiconductor properties, and theory and modeling. Semiconductors are the building blocks for photovoltaics, sensors, power electronics, and high speed computational systems.

- *Welding and Joining Sciences:* Welding and joining are critical fabrication technologies used in the automotive industry. BES research includes studies to understand the microstructure and defects that develop due to temperature gradients, solid-state phase transformations in weld heat affected zones, thermal processes as applied to gas metal arc welding, molten metal droplet formation, plasma and arc physics, laser welding of aluminum alloys, and joining of ceramics and dissimilar materials. These activities are directly related to the Transportation Materials program in OTT.

Many of the OTT/BES integration activities, especially those addressing materials research and development, occur through the Energy Materials Coordinating Committee (EMaCC).

Efficient and Affordable Buildings

Examples of basic science that support Efficient and Affordable Buildings are provided below. Most of this research is carried out by the Office of Basic Energy Sciences.

- *Electrochemistry:* Fundamental research is supported in areas critical to understanding the underlying limitations in the performance of non-automotive electrochemical energy storage systems. Areas of research include the characterization of anode, cathode, and electrolyte systems and their interactions. The broad spectrum of research includes fundamental studies of composite electrode structures, failure and degradation of active electrode materials, and thin film electrodes, electrolytes, and interfaces.

- *Combustion:* Basic research in combustion provides knowledge on the rates and energetics of chemical reactions and on the interactions of fluid dynamics and chemistry. This knowledge is required by combustion models used for the design and optimization of energy-efficient, reduced-emission combustion devices. Knowledge gained consists of measured properties as well as theoretical constructs for the reliable prediction or extrapolation of such properties. BES supports the operation of the Combustion Research Facility (CRF) at Sandia National Laboratories, California, where collocated research, supported by BES, the Office of Energy Efficiency and Renewable Energy, the Office of Fossil Energy, and industry, is conducted in a highly collaborative environment.

- *Ceramic Materials:* Ceramic materials play an integral role in the utility, automotive, and other energy-intensive industries such as the building industry. A fundamental understanding of ceramic materials' complex microstructure and behavior is essential for their successful implementation. BES research addresses the scientific issues underlying the synthesis, processing, behavior, and characterization of ceramic and non-metallic glassy materials. The technological areas impacted include high temperature structural

materials (e.g., high temperature monolithic and composite ceramics and ceramic coatings), energy storage materials (e.g., solid electrolytes, batteries, ultracapacitors), and energy conversion materials (e.g., fuel cells), sensors, and environmentally benign synthesis techniques.

- *Semiconductors:* Semiconducting materials underpin virtually the entire "high tech" industry worldwide. They comprise the building blocks and components for several technologies within this portfolio, including photovoltaics, sensors, power electronics, and high speed computational systems. Research within this area includes synthesis of new and tailored semiconductor materials; characterization of structure, electronic structure, and stability of semiconductors; investigations of surfaces and interfaces; the influence of light on the behavior and properties of semiconductor materials; theory and modeling of properties and behavior; and the operation of facilities that support such research.

Clean and Productive Industries

Examples of basic science that support Clean and Productive Industries are provided below. Most of this research is carried out by the Office of Basic Energy Sciences and the Office of Computational and Technology Research.

- *Combustion:* Basic research in combustion provides knowledge on the rates and energetics of chemical reactions and on the interactions of fluid dynamics and chemistry. This knowledge is required by combustion models used for the design and optimization of energy-efficient, reduced-emission combustion devices for most industrial processes. Knowledge gained consists of measured properties as well as theoretical constructs for the reliable prediction or extrapolation of such properties. The Office of Basic Energy Sciences supports the operation of the Combustion Research Facility (CRF) at Sandia National Laboratories, California, where collocated research, supported by SC, the Office of Energy Efficiency and Renewable Energy, the Office of Fossil Energy, and industry, is conducted in a highly collaborative environment.

- *Catalysis:* Catalysis is a chemical process found widely in nature and used extensively in industry because it removes energy barriers to chemical reactions. Catalysts used for the refining of petroleum or the manufacture of chemicals are important because they reduce process energy, speed up production, and make possible the manufacture of new materials. Despite their importance, catalytic processes are not sufficiently understood to allow for rational design of new catalysts. Models for catalytic action are limited in scope and applicability. The SC catalysis program seeks to gain understanding of catalysis at the molecular level to allow the development of general theories and models of catalytic action. The program includes both heterogeneous (multiple phases such as liquid/solid) and homogeneous (single phase) catalysis. Research in heterogeneous catalysis seeks to characterize the role of surface properties on molecular transformations and the structural relationships between oxide surfaces and reaction pathways, especially in the acid and redox catalysts commonly encountered in industrial applications. Research in

homogeneous catalysis seeks to characterize the activation and subsequent reactions of carbon-hydrogen bonds and the role of bonding and molecular structure on the catalytic processes. The program constitutes the largest single component of the Nation's basic research portfolio focused on chemical catalysis.

- *Synthesis and Processing of Advanced Materials:* These essential elements of materials science and engineering deal with the assembly of atoms or molecules to form materials, the manipulation and control of the structure at all levels from the atomic to the macroscopic scale, and the development of processes to produce materials for specific applications. The goal of the basic research ranges from creating new materials, improving the properties of known materials, and improving the forming of metals to the understanding of such phenomena as diffusion, crystal growth, sintering, and phase transitions. Scientific results are translated into useful materials by developing processes capable of producing high quality cost-effective products including light weight alloys for vehicles.

- *Ceramics:* Ceramic materials play an integral role in the utility, automotive, and other energy-intensive industries. A fundamental understanding of their complex microstructure and behavior is essential for their successful implementation. BES ceramic sciences research addresses the scientific issues underlying the synthesis, processing, behavior, and characterization of ceramic and non-metallic glassy materials. Focus areas include synthesis, processing, reactivity, and physical and mechanical properties, with emphasis on elevated temperature behavior. The technological areas impacted include high temperature structural materials (e.g., high temperature monolithic and composite ceramics and ceramic coatings), energy storage materials (e.g., solid electrolytes, batteries, ultracapacitors), sensors, and environmentally benign synthesis techniques.

- *Intermetallics*: These are metal to metal compounds with definite stoichiometry. Intermetallic alloys made from these compounds constitute a unique class of high-temperature structural materials that posses the desired properties of high strength, oxidation and corrosion resistance, low density, and a high melting point. Such properties make them attractive as constituents for high-temperature coatings and in dies and molds for ceramic and metallurgical processing.

- *Welding and Joining Sciences:* Welding and joining are critical fabrication technologies used in the automotive industry. BES research includes studies to understand the microstructure and defects that develop due to temperature gradients, solid-state phase transformations in weld heat affected zones, thermal processes as applied to gas metal arc welding, molten metal droplet formation, plasma and arc physics, laser welding of aluminum alloys, and joining of ceramics and dissimilar materials.

- *Corrosion:* The importance of the scientific understanding of corrosion is emphasized by the estimate that corrosion in the United States has an economic cost of 4 percent of the gross domestic product. Corrosion damage limits the performance of industrial

processes. The basic research underlying the science of corrosion focuses on the formation, properties, and breakdown of passivating films on a wide array of electrochemical phenomena involved in aqueous corrosion such as pitting and crevice corrosion, on high-temperature gaseous corrosion, and on new techniques to identify and study corrosion.

- *Engineering Research:* The BES Engineering Program supports fundamental research on broad, generic topics in energy related engineering topics. An emphasis of the research is on complicated fluid dynamics because fluids are a part of most energy-related systems and industrial processes, including pipelines, manufacturing processing, hydraulic systems, liquid metal handling, new materials synthesis, chaotic wave motion, environmental issues, and biological systems. Engineering topics include fractals and porous media transport, nonlinear waves, traveling wave convection in fluid mixtures, wave turbulence interactions, multi-phase systems, gas and solids problems, the effect of different Reynolds numbers on turbulence, mixing and transport, gas-liquid flow in pipelines, lubricated transport of viscous materials, the rheology of concentrated suspensions, macrostatistical hydrodynamics, heat/mass transfer enhancement in separated and vortex flows, effect of forced and natural convection on solidification of binary mixtures, interfacial area and transfer in two-phase flow, and various diagnostics for analyzing fluids.

- *Plant Sciences:* Green plants and some bacteria use photosynthesis to capture solar energy and convert it into chemical energy that fuels metabolism and the biosynthesis of a broad range of storage compounds and structural components. For example, the chemical energy in firewood was the early energy source for mankind, and even today the worldwide combustion of plant biomass generates more energy than any other non-fossil fuel source. As a renewable resource, plant biomass potentially has enormously valuable uses when it is converted into specific materials, fuels, chemical feedstocks, and petroleum replacing materials. Basic studies in plant biology are providing new insights into the genetic, metabolic, and enzymatic properties of plants that regulate the production of specific useful chemical compounds and materials. Similarly, studies on the regulation of the photosynthetic process that fuels metabolic biosynthesis are yielding new insights on how bacteria and plants channel photosynthetic energy into the production of renewable biomass materials.

- *Biology/genomics:* The microbial genome program capitalizes on DNA sequencing technology from the human genome program to determine the complete DNA sequence of microbes with potential environmental, energy, or commercial applications. While the program has a principal emphasis on DNA sequencing, it includes research on microbial diversity, to identify a broader array of potentially useful microbes; and novel strategies and tools for characterizing, manipulating, and modeling entire reaction pathways or regulatory networks of microbes or groups of microbes to maximize the usefulness of these newly characterized microbes.

- *Structural Biology:* Understanding and predicting the complex relationship between the DNA sequence of a gene and the structure and function of the protein it encodes is a critical first step in being able to reengineer genes and proteins for use in developing new strategies for improving or developing new fuels, reducing pollution from fuel use, and cleaning up the environment. Therefore, the Office of Science supports basic research in structural biology including instrumentation research and research that cuts across basic, molecular, and computational biology. For example, studies of inverse protein folding provide an understanding of the rules that proteins follow to acquire the three dimensional structures that give them their biological function, while Proteomics research provides information that will lead to an understanding of the structure, function, and interactions of all proteins encoded by an organism's genome.

- *Computational Sciences:* The computational research area provides tools and methods to enable the wide spread use of massively parallel computers and the high speed network connections which underpin the computational needs common to many of the industry vision statements and their need for advanced computational capability for industry process understanding and control.

- *Chemical Sciences:* Research in chemistry focuses on fundamental molecular level understanding of chemical interactions and chemical reactions that provide the basis for new analytical tools and methods and the physical and chemical interactions that support the development of new membranes for separation processes.

- *Materials Science:* Basic research in materials enables technologies underpinning new aluminum alloys, the high rate sheet metal forming of aluminum alloys, and high strength and corrosion resistant intermetallic alloys. Part of this effort is carried out under the Design and Synthesis of Ultrahigh-Temperature Intermetallics project under the distributed DOE Center of Excellence for the Synthesis and Processing of Advanced Materials (CSP). Research is also underway, coordinated and carried out under the Materials Joining project under CSP, on the reliable joining of materials both for on-line repair and for the fabrication of new systems encompassing both metals and ceramics. Additional research involves efforts to advance materials requiring long-lifetime wear resistant surfaces, for example, to form boron nitride and diamond protective films on materials and investigating and understanding how to form oxide films as protective layers to prevent corrosion.

- *Advanced Sensors:* Research is conducted on innovative, more powerful sensors, including the understanding of the chemistry of molecular interactions that generate a chemical or physical response.

- *Computation:* The computational research area provides tools and methods to enable the widespread use of massively parallel computers and the high speed network connections which underpin the computational needs common to many of the industry vision statements and their need for advanced computational capability for industry process understanding and control.

Science Excellence and Research Integration

Recognizing that the basic sciences are the cornerstone for future technology innovation, it is important that DOE's basic science be well integrated with applied technology programs and that research be of the highest caliber. At the same time, consideration of needs and applications does not and should not constrain the scope of scientific inquiry—this is the hallmark of a basic science program and a fundamental tenet for truly crosscutting scientific discovery and innovation.

Consistent with the goal for science excellence, SC implements a highly effective scientific peer review process and is often called upon to conduct peer review for the rest of the Department. Additionally, and over the last few years, the Office of Science has strengthened its process for integration with the applied energy R&D programs, improving coordination and communication across a broad range of areas. Examples of some specific energy technology areas that have benefitted from recent strengthened integration include:

- Office of Energy Efficiency and Renewable Energy's Industries of the Future Program.
- Partnership for a New Generation Vehicle.
- Advanced Computation Initiative, that includes the Office of Energy Efficiency and Renewable Energy as well as the oil and gas industry.
- Advanced Turbine Systems Program.

Thus, with an eye toward research relevance and integration, SC sets strategic research directions through working relationships with other DOE programs, through research workshops involving input from the scientific and technical communities, through the promotion of open information transfer and exchange of ideas between the basic and applied research communities, and, finally, through the sponsorship of selected high-impact research collaborations and partnerships. Individual research projects are funded based on peer review by the members of the scientific community. These approaches to basic research funding have led to hundreds of Cooperative Research and Development Agreements, that extend the basic research to applications and development. In addition, there are many more collaborations between SC researchers and industrial researchers.

The resulting diverse portfolio of basic research programs and the combination of university and laboratory programs supports the institutional capacity for interdisciplinary research needed to solve the problems of energy production and use, and also integrates basic science with applied science and development activities. The Department's National Laboratory system plays a special role in the ability of SC to effectively integrate research and development by providing opportunities to collocate activities at these sites. And, because many researchers are also cofunded by SC as well as the applied energy technology programs, the Office of Science helps guarantee that energy technology development is being conducted with the benefit of advanced

scientific knowledge and that the basic research programs are focused in areas directly relevant to energy systems.

Impacts—Select Examples

Against this backdrop, DOE's basic science programs have contributed substantially to the energy R&D mission of the Department. For example, in the past 50 years, 65 SC-supported researchers have received Nobel Prizes—a total that far surpasses that of any other public or private institution. Sixteen were awarded within the last decade.

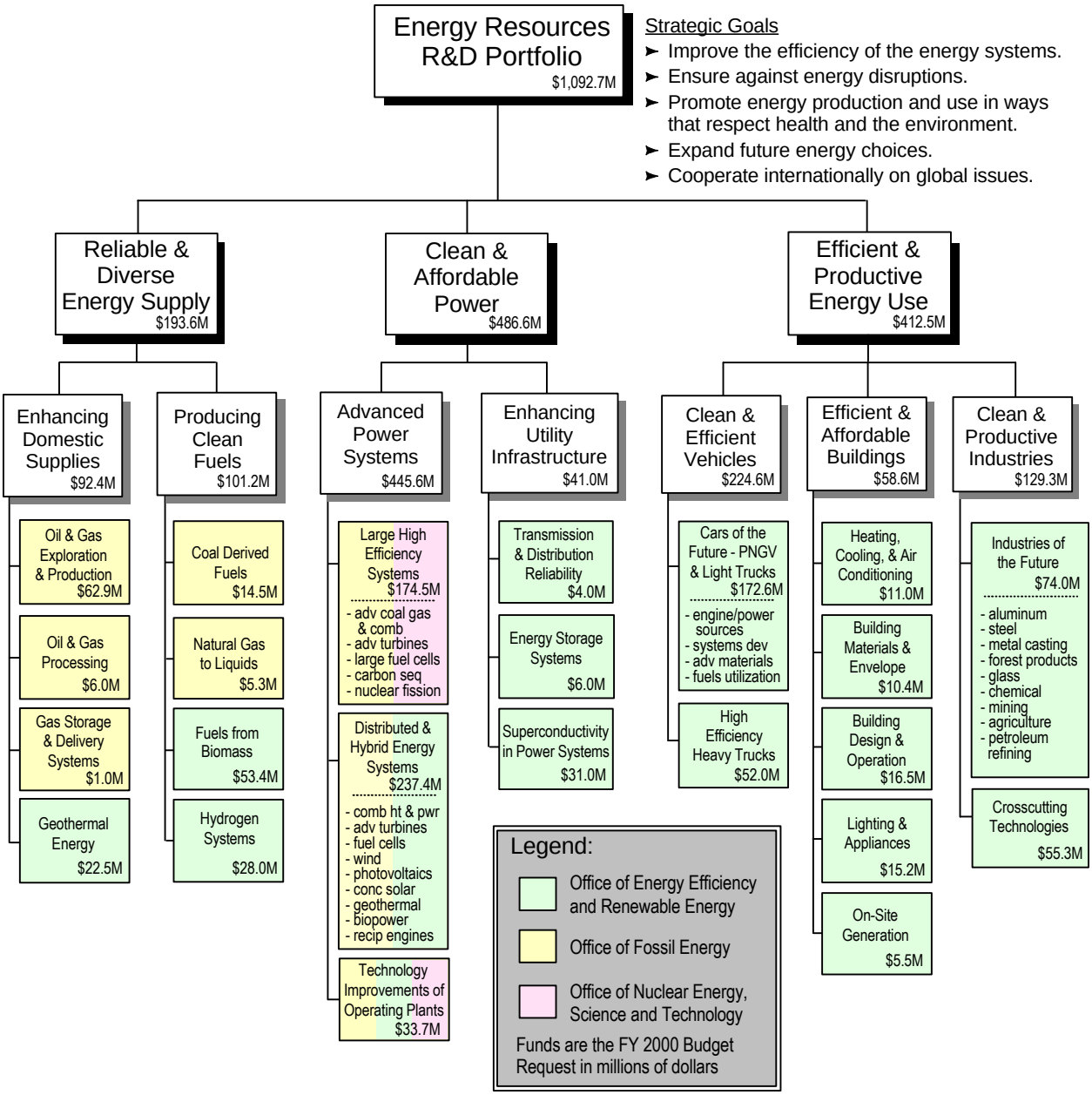
A long term study of R&D 100 Awards, considered the premier indicator of new technologies supported by private and public sector institutions, showed that SC-funded technologies dominate Award winners. During the period from 1963-1996, DOE received 62 percent of all R&D 100 Awards given to the Federal government. SC-funded research has received 177 awards (41 percent of the DOE total/25 percent of the Federal total), making the Office of Science the most frequent recipient in the Federal government. Comparisons with recipients in private industry and academia show similar results.

Below are some select examples that illustrate the energy impacts of SC-funded research in basic science:

- Development of the current generation of high energy and power lithium and lithium ion batteries from research into non-aqueous electrolytes.
- Batteries half the thickness of saran wrap stemming from research into ion transport in glassy solids.
- Improved natural gas separation processes stemming from research into reverse selectivity inorganic membranes.
- Enhanced separation of heavy elements in the nuclear industry from research on actinide separations and related research.
- Ability to produce new, valuable polymers from research into new metallocene catalysts.
- Original discovery of a new class of carbon materials—buckeyballs.
- Potentially new ways to store hydrogen through the discovery of new graphite nanofibers that can store three times their weight of hydrogen.
- Major improvements in the toughness of silicon carbide ceramics.
- Breakthrough processing of aerogel films, ideal insulating materials.

- Design of more reliable joints between ceramics and metals from improved finite element models.
- Research leading to the commercialization of gelcasting for molding near-net shape ceramic parts.
- New and better future diesel engine designs stemming from computational and technology research into models that predict soot generation.
- Discovery of a new marker for efficient combustion.
- Testing and development of nontoxic corrosion inhibitors using a special “vibration pole.”
- Breakthrough levels in energy production from fusion plasma experiments.
- New genetic manipulation techniques to improve the properties of bacteria that are capable of producing methane.
- Lignin depolymerizing enzymes with the potential for an effective “green” technology in pulp and paper production.
- Development of a new catalytic control system for a lean burn engine.
- Development of a photovoltaic cell that holds three world records for efficiency, stemming from collaborative research between EE and SC.
- Improved miniaturization through research into nanowires, “magic structures,” and conductance quantization.
- A tenfold increase in the electrical conductivity of semiconductors through research into gallium injection.
- Improved imaging of pore spaces in sandstone for oil recovery through research into synchrotron x-ray micro tomography.
- Artificial photosynthesis through research into light-matter interactions and proton motive force.
- Improved high temperature superconductors through research into pairing mechanisms and vortex physics.

Appendix
Budget Profiles



Appendix

Budget Profiles (000$)

Energy Resources R&D Portfolio Research Areas	FY 1998 Appropriated	FY 1999 Appropriated	FY 2000 Request
Enhancing Domestic Supplies	**83,187**	**83,600**	**92,400**
Oil and Gas Exploration and Production	59,800	60,400	62,900
Diagnostics and Imaging	19,900	20,400	20,100
Drilling, Completion, and Stimulation	9,100	7,500	7,600
Reservoir Life Extension	21,200	23,300	24,200
Drilling and Production Environmental Management	9,600	8,700	9,000
Gas Hydrates	0	500	2,000
Oil and Gas Processing	5,500	6,200	6,000
Low Quality Gas Upgrading	1,100	1,900	1,600
Air Emissions Detection and Control	4,400	4,300	4,400
Gas Storage and Delivery Systems	1,000	1,000	1,000
Geothermal Energy	16,887	16,000	22,500
Geothermal Exploration	5,600	5,500	7,000
Geothermal Drilling and Completion	6,900	5,000	7,500
Geothermal Reservoir Production	4,387	5,500	8,000
Producing Clean Fuels	**68,274**	**86,312**	**101,243**
Coal Derived Fuels	15,844	15,528	14,500
Transportation Fuels and Chemicals	10,039	8,650	8,300
Solid Fuels and Feedstocks	5,064	5,097	4,000
Advanced Research	741	1,781	2,200
Natural Gas-to-Liquids	6,297	6,784	5,302
Ceramic Membrane Reactor Systems	4,785	5,500	4,000
Thermoacoustic Natural Gas Liquefaction	458	600	600
Novel Conversion Processes	1,054	684	702
Fuels From Biomass	30,327	41,750	53,441
Feedstock Production	2,500	2,800	5,500
Ethanol Production	25,027	35,950	37,441
Biodiesel Production	800	750	1,000
Regional Biomass Energy Program	2,000	2,250	3,500
Integrated Bioenergy Technology R&D	0	0	6,000
Hydrogen Systems	15,806	22,250	28,000
Hydrogen Production	4,737	6,259	8,510
Hydrogen Storage and Use	2,238	2,829	5,590
Technology Validation	6,361	10,993	11,420
Analysis and Outreach	2,470	2,169	2,480

Energy Resources R&D Portfolio Research Areas	FY 1998 Appropriated	FY 1999 Appropriated	FY 2000 Request
Advanced Power Systems	**353,498**	**417,601**	**445,609**
Large High Efficiency Systems	147,989	182,116	174,456
Advanced Coal Gasification and Combustion Systems	61,256	68,526	60,873
- Advanced Coal Combustion	*21,039*	*21,500*	*10,010*
- Pressurized Fluidized Bed Combustion	*17,875*	*14,638*	*12,202*
- Integrated Gasification Combined Cycle	*22,342*	*32,388*	*38,661*
Advanced Gas Turbine Systems	45,000	44,500	41,808
Advanced Large-Scale Fuel Cell Power Systems	40,210	44,200	37,649
Carbon Sequestration	1,523	5,890	9,126
Nuclear Fission Systems	0	19,000	25,000
Distributed and Hybrid Energy Systems	188,344	212,750	237,409
Combined Heat and Power Systems	1,000	1,500	2,000
Advanced Turbine Systems - Industrial and Micro	34,650	51,000	31,300
Distributed Fuel Cell Power Systems (EE)	6,400	0	0
Wind Energy Systems	32,128	33,200	45,600
Photovoltaic Systems	64,691	72,200	93,309
Concentrating Solar Power Technology	16,317	17,000	18,850
Geothermal Systems	5,119	6,000	7,000
Biopower Energy Systems	27,789	31,450	38,950
Reciprocating Engines	250	400	400
Technology Improvement of Operating Plants	17,165	22,735	33,744
Aging Effects in Key Components	5,225	6,225	7,000
Nuclear Power Plants	0	0	5,000
Regulatory Compliance	11,211	13,260	14,744
Hydropower Turbines	729	3,250	7,000
Enhancing Utility Infrastructure	**43,262**	**40,000**	**41,000**
Transmission and Distribution Reliability	1,000	3,000	4,000
Real Time System Control	0	2,500	3,400
Power Electronics	0	0	400
Distributed Resource Integration	0	500	200
High Capacity Transmission Technologies	1,000	0	0
Energy Storage Systems	3,839	4,500	6,000
Integration	1,950	2,200	3,000
Components	1,350	1,400	2,100
Analysis	539	900	900
Superconductivity in Power Systems	31,579	32,500	31,000
The Superconductivity Partnership Initiative	14,000	14,500	14,000
The Second Generation Wire Initiative	8,000	8,000	8,000
Strategic Research	9,579	10,000	9,000
Electric and Magnetic Fields R&D	6,844	0	0

Energy Resources R&D Portfolio Research Areas	FY 1998 Appropriated	FY 1999 Appropriated	FY 2000 Request
Clean and Efficient Vehicles	**169,956**	**181,196**	**224,580**
Cars of the Future - PNGV and Light Trucks	139,066	150,356	172,580
Engine/Power Sources	68,280	96,121	123,180
- Advanced Combustion Engine R&D	*14,818*	*34,175*	*46,800*
- Fuel Cells	*22,614*	*33,501*	*41,380*
- High-Power Batteries for Hybrid-Electric Vehicles	*8,620*	*12,750*	*15,000*
- Power Electronics and Electric Machines	*4,410*	*6,875*	*9,000*
- Electric Vehicle Batteries	*17,818*	*8,820*	*11,000*
Systems Development	45,582	24,815	23,900
Advanced Materials	20,855	22,655	17,000
Fuels Utilization	4,349	6,765	8,500
High Efficiency Heavy Trucks	30,890	30,840	52,000
Heat Engine R&D	3,500	3,500	9,000
Systems Development	1,700	1,500	12,000
Advanced Materials	13,015	14,820	16,000
Fuels Utilization	12,675	11,020	15,000
Efficient and Affordable Buildings	**42,763**	**50,393**	**58,630**
Heating, Cooling, and Air Conditioning	14,650	15,390	11,000
Geothermal Heat Pumps	6,400	6,500	0
Absorption Technologies	5,400	5,910	6,500
Desiccants	2,350	2,480	4,500
Furnaces and Boilers	500	500	0
Building Materials and Envelope	7,187	10,723	10,400
Windows and Glazings	4,959	6,829	6,610
Walls, Roofs, and Foundations	2,228	3,894	3,790
Building Design and Operation	11,811	12,970	16,500
Commercial Buildings	5,000	5,200	8,000
Residential Buildings	6,811	7,770	8,500
Lighting and Appliances	8,115	9,560	15,230
Lighting	2,350	3,100	4,500
Refrigeration	3,140	2,860	3,130
Heat Pump Water Heater and Appliances	0	0	2,100
Solar Water Heating	2,625	3,600	5,500
On-Site Generation	1,000	1,750	5,500
Fuel Cells	1,000	1,750	5,500

Energy Resources R&D Portfolio Research Areas	FY 1998 Appropriated	FY 1999 Appropriated	FY 2000 Request
Clean and Productive Industries	**93,850**	**105,480**	**129,320**
Industries of the Future	53,080	57,460	74,020
Aluminum	7,340	8,100	11,180
Steel	9,730	10,530	10,630
Metal Casting	5,480	5,740	5,800
Forest Products	12,040	11,960	21,080
Glass	3,880	4,790	4,830
Chemical	11,610	12,380	12,500
Mining	0	1,980	3,000
Agriculture	0	1,980	4,000
Petroleum Refining	3,000	0	1,000
Crosscutting Technologies	40,770	48,020	55,300
Enabling Technologies	14,470	19,220	22,000
Technical Assistance	15,340	18,100	21,300
Financial Assistance	10,960	10,700	12,000
Energy Resources R&D Total	**854,790**	**964,582**	**1,092,782**