ENERGY PROGRAMS

at

Oak Ridge National Laboratory

ORNL-6946

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Introduction

Energy availability in a country is of great importance to its economy and to raising and maintaining its standard of living. In 1994, the United States consumed more than 88 quadrillion Btu (quads) of energy and spent about $500 billion on fuels and electricity (Fig. 1.1).

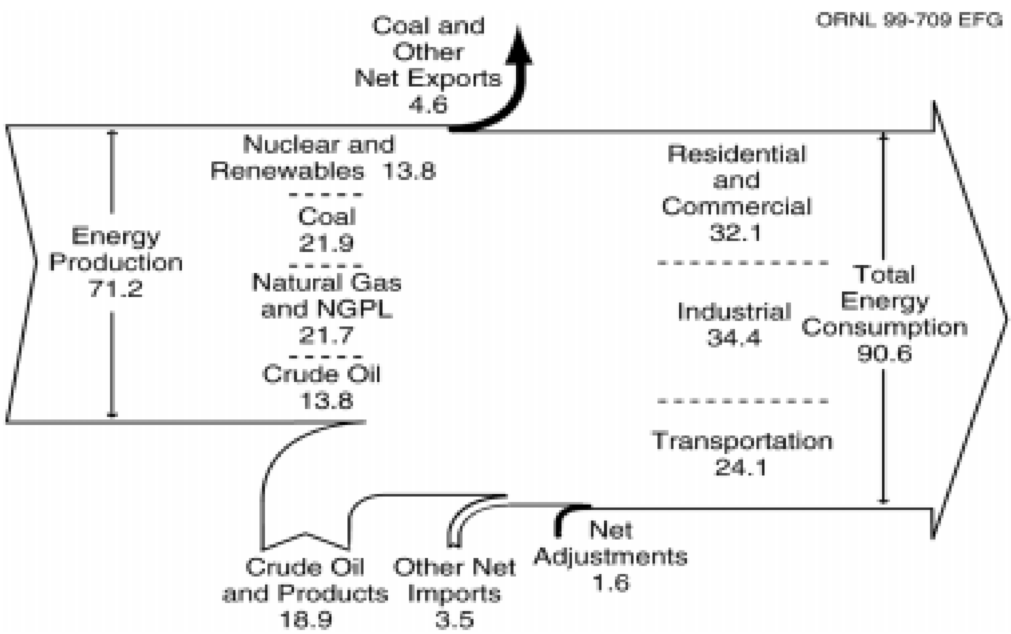

Fig. 1.1. Total U.S. energy production and consumption (in quads) in 1995.
Source: Energy Information Administration (EIA), *Annual Energy Review*, DOE/EIA-0384(95), DOE EIA, Washington, D.C., July 1996.

Fortunately, the United States is well endowed with energy sources, notably fossil fuels, and possesses a considerable nuclear power industry. The United States also has significant renewable energy resources and already exploits much of its hydropower resources, which represent 10% of electricity production. Nevertheless, in 1994, the United States imported about 45% of the petroleum products it consumed, equivalent to about 17 quads of energy. This dependence on imported oil puts the country at risk of energy supply disruptions and oil price shocks. Previous oil shocks may have cost the country as much as $4 billion (in 1993 dollars) between 1973 and 1990.[1] Moreover, the production and use of energy from fossil fuels are major sources of environmental damage.

The corresponding situation in many parts of the world is more challenging. Developing countries are experiencing rapid growth in population, energy demand, and the environmental degradation that often results from industrial development. The near-term depletion of energy resources in response to this rapid growth runs counter to the concept of "sustainable development"—development that meets the needs of today without compromising the ability of future generations to meet their own needs.

Energy research and development (R&D) to improve efficiency and to develop and deploy energy alternatives may be viewed, therefore, as an insurance policy to combat the dangers of oil shocks and environmental pollution and as a means of supporting sustainable development. These considerations guide the energy policy of the United States and of the U.S. Department of Energy (DOE). In its strategic plan, DOE identifies the fostering of "a secure and reliable energy system that is environmentally and economically sustainable" as the first component of its mission.[2] The strategic goal established for energy resources, identified as one of DOE's four businesses, is for "the Department of Energy and its partners [to] promote secure, competitive, and environmentally responsible energy systems that serve the needs of the public."[3]

DOE has also identified four strategic goals for its programs in energy resources:

1. strengthening the economy and raising living standards through improvements in the energy field;
2. protecting the environment by reducing the adverse environmental impacts associated with energy production, distribution, and use;
3. keeping America secure by reducing vulnerabilities to global energy market shocks; and
4. enhancing American competitiveness in a growing world energy market.[4]

Oak Ridge National Laboratory (ORNL) is a major contributor to DOE's mission in energy resources. As described in the *Strategic Laboratory Missions Plan—Phase 1*, ORNL plays a principal role in DOE's energy resources mission area and is a primary performer of DOE-sponsored R&D in energy efficiency.[5] As a multiprogram laboratory, ORNL also plays a principal role in fundamental science and applies special capabilities to support DOE's needs in environmental quality and national security. The Laboratory's R&D programs for improving energy efficiency and making available a wider range of energy sources are complemented and supported by its efforts in fundamental sciences and technology, advanced computing, environmental research, and energy policy and information.

In recognition of ORNL's strengths in energy R&D, DOE recently selected ORNL to lead important studies in the sustainable energy area in preparation for the December 1997 climate change meeting in Kyoto:

- At the request of DOE's Office of Energy Efficiency and Renewable Energy (DOE-EE), ORNL and Lawrence Berkeley National Laboratory (LBNL) coordinated a five-laboratory study of the potential role of energy efficiency improvements in reducing greenhouse gases; the other participants were Argonne National Laboratory (ANL), Pacific Northwest National Laboratory (PNNL), and Sandia National Laboratories (SNL).

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[1] D. L. Greene, D. W. Jones, and P. N. Leiby, *The Outlook for U.S. Oil Dependence,* ORNL-6873, Lockheed Martin Energy Systems, Oak Ridge, Tenn., June 1995.

[2] *U.S. Department of Energy Strategic Plan,* DOE/PO-0053, September 1997.

[3] Ibid., p. 12.

[4] *Research and Development at the U.S. Department of Energy National Laboratories,* Lawrence Berkeley National Laboratory, Berkeley, Calif., September 1997 (a report prepared at the request of the Offices of Policy and Energy Research by a group of the Department's national laboratories).

[5] U.S. Department of Energy, Laboratory Operations Board, *Strategic Laboratory Missions Plan—Phase 1,* DOE, Washington, D.C., July 1996, 1:22.

- ORNL contributed to a similar study of the role of basic science and technology in greenhouse gas emissions reduction for the DOE Office of Energy Research (DOE-ER).
- At the request of Secretary of Energy Federico F. Peña, ORNL and the National Renewable Energy Laboratory (NREL) led a coordinated effort of the 11 DOE national laboratories to develop technology pathways for avoiding greenhouse gas emissions.

1.1 OVERVIEW OF SUSTAINABLE ENERGY PROGRAMS AT ORNL

As described in ORNL's strategic plan, energy production and end-use technologies constitute a major area of R&D emphasis at ORNL.[6] The Laboratory is one of the world's premier centers for R&D on energy production, distribution, and use and on the effects of energy technologies and decisions on society. ORNL applies distinguishing capabilities in materials science, biotechnology, engineering, and technology development and evaluation to transportation systems, biofuels, efficient buildings and building materials, industrial processes, and utilities. ORNL research on fission, fossil, and fusion technologies applies the Laboratory's strengths in physics and engineering to the improvement of existing systems and the development of new science and technology. Unique facilities for energy-related R&D are used both for technology development and for fundamental investigations in the basic energy sciences that underpin the technology work. ORNL's scientific, engineering, environmental, economic, and social science expertise is integrated to supply the information needed in making decisions that ensure a sustainable energy future.

These programs have their roots in ORNL's original nuclear role as part of the World War II Manhattan Project, but they have evolved, meeting and anticipating the changing needs of the United States and the world, to address most areas of energy production and use. Table 1.1 gives a concise review of this evolution, and Sect. 1.2 provides program summaries and goals. Details and recent advances are presented in Sects. 2–5.

The strategic goal for ORNL's energy production and end-use technologies is to provide scientific knowledge, advanced technologies, and assessments that support the production, delivery, and use of reliable, economical energy with minimal adverse environmental impacts. Three objectives have been established to move ORNL toward this goal: (1) provide advanced technologies and materials for biomass, fission, fossil, and fusion energy sources; (2) develop efficiency improvements in the delivery and use of energy for buildings, manufacturing, and transportation; and (3) improve analytical methods for exploring the effects of human activities on the environment.

In working to attain its strategic goal, ORNL conducts energy R&D and analyses in the areas of

- energy efficiency for buildings, industry, transportation, and utilities;
- renewable energy;
- fission energy; and
- fusion energy.

Budgets for ORNL energy programs over the past 5 years are shown in Fig. 1.2, and major program sponsors are listed in Table 1.2. Much of the work of the energy programs is carried out in collaboration with other organizations. Partners in ORNL energy R&D include more than a dozen DOE laboratories and facilities, more than 40 universities, more than 30 industries, and about 35 other nations.

ORNL's support of DOE's missions in science and technology, environmental quality, and national security provides significant advantages to the energy programs. In particular, ORNL's fundamental science and technology programs provide the scientific understanding and technological innovations that underpin the

[6] "Laboratory Strategic Plan," p. 3-1 in *Oak Ridge National Laboratory Institutional Plan: FY 1998–FY 2002,* ORNL/PPA-97/2, Lockheed Martin Energy Research Corp., Oak Ridge, Tenn., January 1998.

Table 1.1. History of sustainable energy programs at ORNL

1943	Graphite reactor built—the first continuously operated reactor.
	Clinton Training School started. Naval reactor program conceived at ORNL. Studies of neutron irradiation effects on materials initiated. Alvin Weinberg's name appears on a patent for the pressurized water reactor (PWR).
1950	Pioneering work on radiation transport leads to start-up of Bulk Shielding Reactor. Low Intensity Test Reactor begins operation. Oak Ridge **School of Reactor Technology** started.
1950–1954	**PUREX** (plutonium and uranium extraction) and **THOREX** (thorium extraction) processes developed.
1952	Ceramics research group created, initially for fission reactor fuel.
1955	ORNL's "Swimming Pool" reactor showcased at United Nations Atoms for Peace conference.
1955–1980	Development and qualification of Zircalloy, the clad material for light-water reactor fuels.
1957	Thermonuclear Experimental Division established. First ORNL **fusion energy** experiment begins.
1958	Relationship between intensity of **neutron doses** and their **genetic effects** explained. Oak Ridge Research Reactor begins operation.
1961	Development of **isotopic heat sources** to power satellites begins.
1962	Health Physics Research Reactor begins operation.
1963	ORNL initiates publication of the journal *Nuclear Safety*.
1964	ORNL becomes first national laboratory to hire **social scientists**. "Water for Peace" **nuclear desalination** concept featured at United Nations conference.
1965	**High Flux Isotope Reactor** (HFIR) and Molten Salt Reactor Experiment begin operation.
1966	Heavy Section Steel Technology program for reactor safety established.
1967	Multidisciplinary seminar on nuclear agro-industrial complex held. Release of computer model ANISN, which becomes world standard for radiation transport and shielding analysis.
1968	Initiation of studies of **atmospheric CO_2 levels**. Start of deciduous forest biome program.
1969–1970	Summer studies on **environmental issues** and the **role of science** in the formation of **public policy**. By end of 1960s, 20% of reactor budget addresses nuclear safety.
1970	ORNL becomes lead laboratory for high-temperature materials and structures in support of the fast breeder reactor program.
	Reduction of energy demand through **energy conservation** is studied. In the early 1970s, proposals are made for improved turbine efficiency, coal gasification, high-temperature batteries, and synthetic fuels.
1971	ORNL studies the environmental impacts of nuclear power plants. In response to the Calvert Cliffs decision and the National Environmental Protection Act (NEPA), the Atomic Energy Commission (AEC) initiates, through ORNL and other laboratories, environmental analysis as part of the licensing process for nuclear power plants. ORNL's role soon expands to NEPA compliance documentation for other agencies.
	Research begins on the **Oak Ridge Tokamak** (ORMAK) in the fusion program. Studies of **solar energy** begin, focusing on enhancement of biological production of hydrogen and methane and on photovoltaics.
1972	Energy conservation studies continue. Formation of **Environmental Sciences Division**. ORNL starts its involvement in preparing **environmental impact statements**—ultimately for fission, fusion, geothermal, solar, fossil fuel, synthetic fuel, and hydropower projects.
1973	ORNL contributes to the AEC report *The Nation's Energy Future*. Molten salt reactor program canceled.
1974	AEC is divided into the Energy Research and Development Administration (ERDA) and the Nuclear Regulatory Commission (NRC). ERDA adds **fossil fuel** and program management responsibility for **energy conservation** to ORNL's energy portfolio. ORNL starts a **building standards** development program. **Energy Division** created, leading to programs on buildings, **appliances**, transportation, and **analyses** of energy issues.

Table 1.1 (continued)

1975	ORNL starts **fossil programs** to address coal, environment, turbines, and advanced materials.
1977	**Transportation Research and Analysis** group started. Improved **heat pump** development begins. Construction begins on **Fusion's** International Fusion Superconducting Magnet Test Facility for **superconducting coil** research. Initial Impurity Studies Experiment tokamak, **ISX-A**, operated and converted to **ISX-B**.
1978	ORNL assigned lead for **coal technology** and nuclear fuel reprocessing and co-lead with Idaho National Engineering Laboratory (later renamed Idaho National Engineering and Environmental Laboratory, INEEL) for hydropower, leading in environmental R&D. Research on **biomass energy**, geothermal energy, and **hydrogen** from plants starts. Energy Conservation Program established (later renamed Energy Efficiency and Renewable Energy Program).
1979	ORNL's **neutral beam injectors** contribute to achievement of record magnetic fusion plasma temperatures in Princeton Large Tokamak (PLT), Princeton Plasma Physics Laboratory.
1970s/1980s	Materials research rises to the forefront with development of new alloys, specialized and composite materials, and techniques for surface modification.
1980	Nearly a quarter of ORNL's budget funds **environmental and health research,** including the ecological effects of energy production.
1980s	ORNL research supports NRC's international cooperative severe accident research program.
1982	ORNL is designated lead participant in NRC's nuclear plant aging research program. ORNL initiates a program to help **developing nations** to assess energy technologies and policies. The Carbon Dioxide Information Analysis Center is formed to compile and disseminate data.
1984	The long-standing **robotics** research program, supporting **fission** and **fusion**, is expanded to include **artificial intelligence** for a wide range of teleoperations.
1985	The **Roof Research Center** is constructed, including climate simulation facilities. A license for a modified nickel aluminide alloy for diesel engines is granted to industry**.**
1986	A license for whisker-reinforced ceramics is granted to ACMC.
1987	**High Temperature Materials Laboratory** opens. **Advanced Toroidal Facility** stellarator begins operation.
1989	The **Center for Global Environmental Studies** is formed and conducts studies of ways to avoid **ozone depletion** and to develop **CFC substitutes**.
1990s	ORNL provides research to support NRC's certification of advanced water reactors.
1991	Total equivalent warming impact (TEWI) concept developed, combining the effects of direct emissions from greenhouse gases with the indirect effects of energy consumption from fossil fuel combustion and electricity generation.
1993	ORNL is instrumental in establishing the C4, or Clean Car Coordinating Committee, precursor to the Partnership for a New Generation of Vehicles, a public-private partnership that breaks new ground for federally funded R&D.
1993–1995	Cancellation of research programs on reprocessing, liquid metal and gas-cooled reactor technology, and space reactor technology.
1994	ORNL is named lead laboratory for mixed oxide (MOX)-fueled reactors for plutonium disposition.
1995	The rolling-assisted biaxially textured substrates (RABiTS) technology for manufacture of high-temperature superconducting wire is developed.
1997	ORNL and the University of Tennessee establish the National Center for Transportation Research.

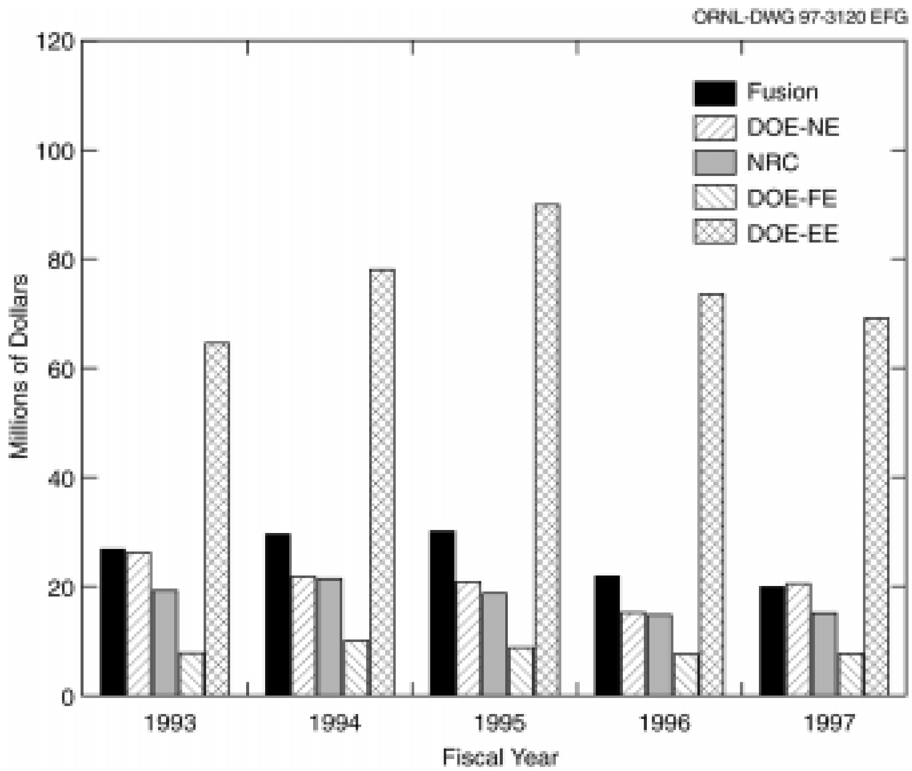

Fig. 1.2. ORNL energy program budgets [new budget authority (BA)] from the U.S. Department of Energy (DOE), the U.S. Department of Defense (DOD) (fission), the Nuclear Regulatory Commission (NRC), and Japan (fission and fusion), FY 1993–FY 1997.

Table 1.2. Major sponsors of ORNL energy programs

U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
Office of Energy Research
Office of Fissile Materials Disposition
Office of Fossil Energy
Office of Nuclear Energy, Science and Technology
Office of Policy and International Affairs
Federal Energy Regulatory Commission
Nuclear Regulatory Agency
U.S. Department of Defense
National Aeronautics and Space Administration
U.S. Agency for International Development
U.S. Department of Transportation
U.S. Department of Agriculture
Electric Power Research Institute

energy programs, and environmental programs at ORNL complement the energy R&D, as shown schematically in Fig. 1.3.

The interweaving of science and technology, energy resources, and environmental R&D that characterizes ORNL's work can be traced to the Laboratory's early years. For example, the development of advanced materials was driven initially by the needs of the fission program. Studies of the effects of neutron irradiation on materials began in 1946, and an interest in the use of ceramics for reactor fuels led to initiation of a program in that area in 1952. Work continued for several decades to meet needs for cladding materials and reactor pressure vessels. Materials development for fusion began in the 1960s and continues today. With the broadening of the ORNL energy programs in the 1970s to include fossil energy and conservation, materials research expanded into new areas, leading to improved steels and new developments in intermetallics and ceramics. Today's science and technology programs are described in Sect. 1.3.

Energy R&D at ORNL has also been a driver for the application of computers to scientific and technical problems. The Oak Ridge Automated Computer and Logical Engine (ORACLE), installed at ORNL in 1953, was among the most powerful computers of its day and was used to analyze radiation and shielding problems. In the 1990s, ORNL once again moved into the forefront of scientific computing with the establishment of its Center for Computational Sciences and acquisition of several powerful Intel Paragon computers that are used for modeling global climate change, predicting the properties of materials, and carrying out a variety of other energy-related computations.

Similarly, environmental programs at ORNL have grown from early concerns about the discharge of radioactive material from wartime experiments to encompass a broad range of energy-related concerns, as described in Sect. 1.4. Ecological research, focused on understanding the processes by which contaminants move through the environment and on identifying the ecological effects of energy production, began in the early 1950s. The release of carbon dioxide (CO_2) that accompanies the burning of fossil fuels has been studied at ORNL since 1968. Today's programs focus on global climate change, environmental contamination, biofuels production, the effects of energy development and use, and resource utilization.

For almost 30 years, ORNL has been assessing the benefits of energy technologies and the risks that they impose on society. ORNL's work in energy policy and information supports policymakers in making decisions on national issues and understanding the environmental, social, and economic implications of these decisions. Current activities in this area are described in Sect. 1.5.

1.2 PROGRAM SUMMARIES AND GOALS

1.2.1 Energy Efficiency and Renewable Energy

1.2.1.1 Program summary

In 1994, almost 55% of the energy consumed in the United States was wasted through inefficiencies in energy transmission and utilization; this represents 47 quads of the 88 quads used. All sectors of energy use contributed; in electricity generation, 20.6 quads were wasted (66% for building electricity use and 34% for industrial electricity use), with 4.2 quads wasted in buildings, 3.4 quads in industry, and 18.7 quads in transportation—at a cost of a few billion dollars per quad. Total energy use in the United States by end-use sector during the past 45 years is shown in Fig. 1.4.

Clearly, energy efficiency improvements offer a great potential for reducing not only the cost but also the environmental impact of energy production and use. Such improvements are also key to supporting the burgeoning economies of developing countries without negatively affecting environmental conditions. Renewable energy sources are important indigenous resources, especially in developing countries. They are important in the near term to reduce greenhouse gas emissions and are essential for a sustainable future.

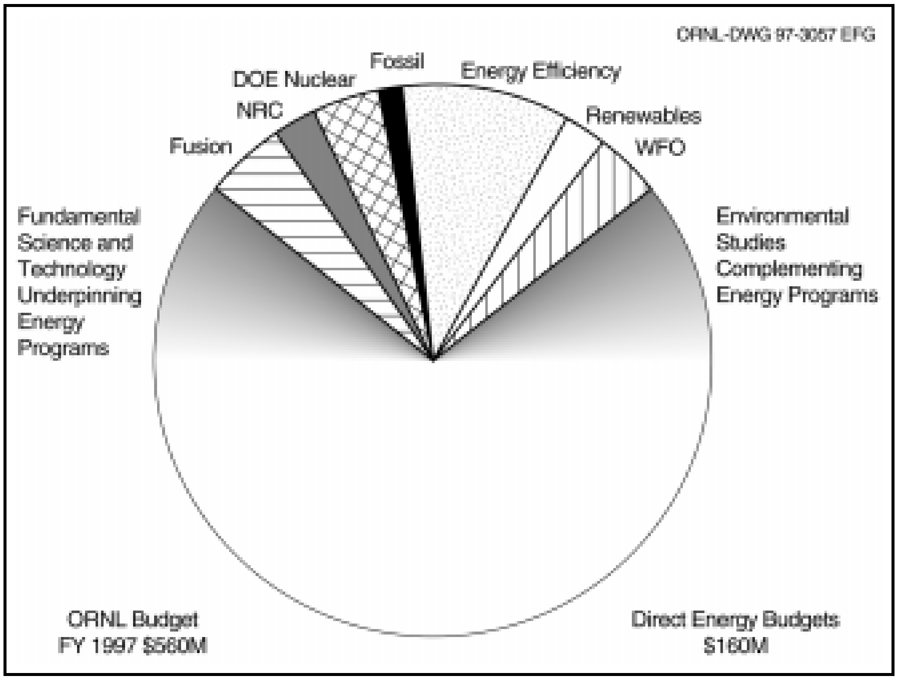

Fig. 1.3. ORNL R&D programs. Specific support for sustainable energy R&D is strengthened by fundamental science and technology programs and by environmental studies. (DOE fission budget includes related DOD funding; fusion budget includes fusion spin-offs.)

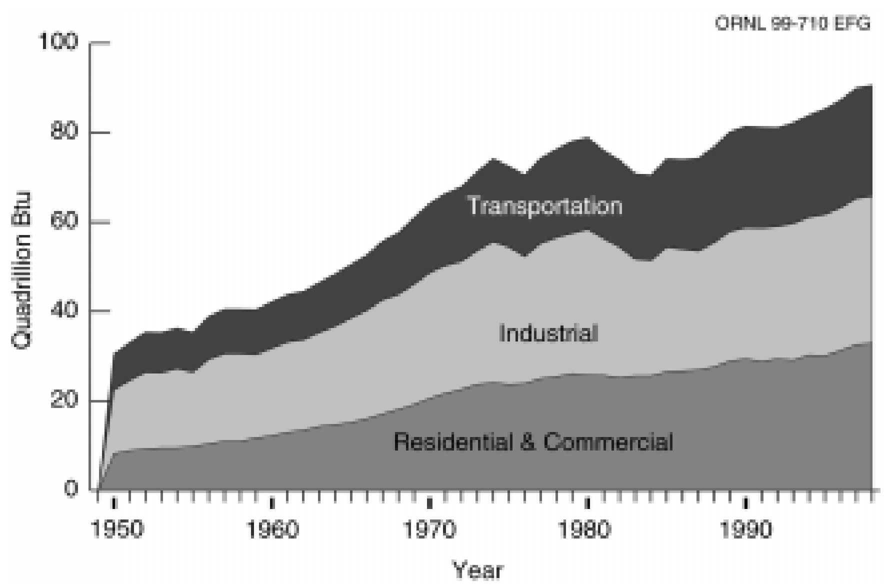

Fig. 1.4. Energy consumption (in quads) by end-use sector, 1949–1997. *Source:* Energy Information Administration, U.S. Department of Energy, *Monthly Energy Review*, DOE/EIA-0035(98/09), September 1998, p. 25.

The ORNL Energy Efficiency and Renewable Energy (EERE) Program conducts R&D for all end-use sectors, primarily for DOE-EE but also for the U.S. Department of Agriculture (USDA), the U.S. Department of Transportation (DOT), and private industry. Its mission is to assist DOE in accelerating the development of sustainable energy technologies in order to create a cleaner environment, a stronger economy, and a more secure future. The program's mission reflects a national commitment to an expansion of the nation's energy resource options and to greater efficiency in every element of energy production and use.

DOE allocations to the ORNL EERE Program for the past 5 years are shown in Fig. 2.3. The DOE funding is complemented by the program's participation in 92 cooperative R&D agreements (CRADAs) over the past several years, with about $46 million in cost-sharing by industrial partners. The total research value of these CRADAs is $82 million.

1.2.1.2 Program goals

Buildings technologies

- Exceed today's state of the art in efficiency by 25% or more with a new generation of ozone-safe heat pumps, chillers, and air conditioners.
- Using available technologies, demonstrate a 1-kWh/day home refrigerator (i.e., operating at half of the energy use of the 1993 national standard).
- Contribute to development of a low-sloped roof, marketable by 2000, with a service life of 30 years and an R-value of 30 (the R-value indicates a material's resistance to heat loss).
- By 2010, develop materials to reduce building energy consumption by 20%.
- Assist in the identification and implementation of cost-effective, energy-efficient retrofits to existing buildings.
- Assist the public and private sectors with the incorporation of innovative technologies and materials in buildings.

Transportation technologies

- In partnership with the University of Tennessee, develop the National Transportation Research Center and apply its resources to addressing national transportation problems through R&D in a cooperative working environment.
- As a member of the Partnership for a New Generation of Vehicles, significantly improve national competitiveness through contributions to fuel efficiency improvements, emissions reductions, the use of ceramic and lightweight materials, and alternative propulsion systems.
- Demonstrate environmentally acceptable, commercially viable biomass-based fuel supply systems, focusing on energy crop development and on fuel production via fluidized-bed reactors and catalysis.
- Contribute to the development of intelligent transportation systems, including analysis of transportation data, analysis of transportation energy use, and annual publication of the *Transportation Data Book.*
- Develop advanced power-train technology for medium- and heavy-duty trucks, including hybrid systems, advanced diesel engines, and natural gas engines, to achieve three times today's fuel economy by 2005, with a significant reduction in criteria pollutant emissions.

Industrial technologies

- Support DOE's "Industries of the Future" initiative in the agricultural, aluminum, chemical, forest products, glass, metal casting, mining, and steel industries through improvements in areas such as
  - the use of advanced materials (e.g., intermetallics and ceramics);
  - bioprocessing and alternative, renewable feedstocks for chemical production;

– cellulosic waste minimization and bioconversion;
– improved heat exchangers and heat pumps;
– advanced turbine systems;
– thermal sciences and microwave applications;
– energy-efficient motors and drive systems; and
– instrumentation, sensors, and controls.

Utility technologies

- Contribute to the preparation of a report on electromagnetic field effects to be delivered to Congress in 1998.
- Develop multiple-meter lengths of high-temperature superconducting, high-current-density, yttrium, barium, and copper oxide (YBCO)–coated tapes using the rolling-assisted, biaxially textured substrates (RABiTS™) process developed at ORNL.
- Contribute to the team effort to demonstrate a 5-MVA high-temperature superconducting transformer and a 30-m, three-phase superconducting power cable in 2000.
- Develop practical applications of the discovery that photosynthesis can occur with Photosystem II activity alone.
- Develop technologies and materials for hydrogen production, storage, and use.
- Develop environmental mitigation practices and "fish-friendly" equipment for hydropower facilities.
- Continue to contribute to international energy information exchanges such as the Greenhouse Gas Technology Information Interchange (GREENTIE), the Center for the Analysis and Dissemination of Demonstrated Energy Technologies (CADDET), and the Heat Pump Program of the International Energy Agency (IEA).
- Develop bioenergy cropping techniques that will result in low-cost, environmentally beneficial, profitable crops for energy production.

1.2.2 Fission Energy

Nuclear energy contributes over 20% of the electrical energy used in the United States and 17% of the world's electricity. It is a major contributor to the "decarbonization" of energy use and can be important in reducing the predicted effects of global warming.

In recent years the U.S. government has shifted its emphasis away from the development of new reactor concepts to focus on efforts to ensure the safety of operating plants and on certification of advanced reactors for the next generation of commercial plants. This shift has been driven by economic competition among energy sources and by public concerns about nuclear safety arising from the accidents at Chernobyl and Three Mile Island. Related issues about the disposition of surplus nuclear weapons material and plutonium from power reactors also require attention.

Consequently, ORNL's research interests have evolved during the past decade. The experience base and the facilities at ORNL give the Laboratory distinctive capabilities for continuing to meet the needs of a number of sponsors. Funding for ORNL's programs in the nuclear area comes from two major sources—DOE and the Nuclear Regulatory Commission (NRC)—with additional funding from industry and other government agencies. Budgets from 1993 through 1997 are shown in Fig. 1.5. The total budget for work in the nuclear area in 1997 was about $15 million from NRC and $21 million from DOE and other sponsors. Funding from NRC is expected to be stable over the next few years, and that from DOE and other sponsors is expected to grow modestly.

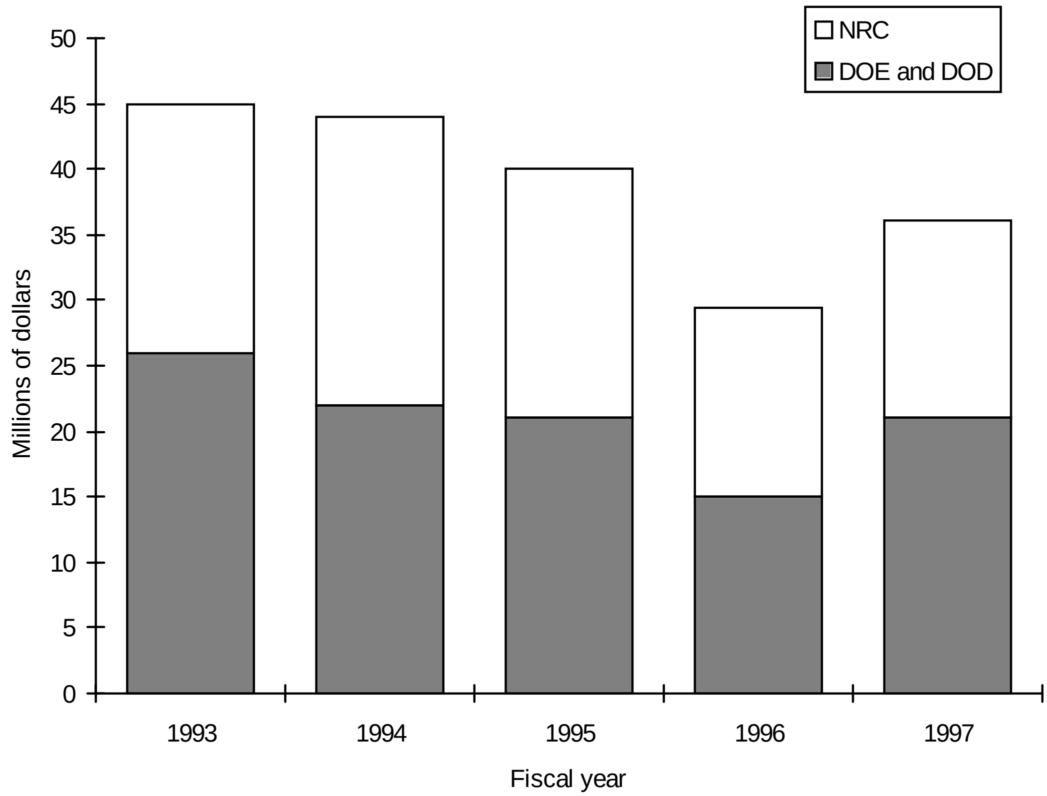

Fig. 1.5. Fission program budgets (new BA) for FY 1993–FY 1997. DOE funding includes support from Japan for materials R&D.

1.2.2.1 Work sponsored by DOE and other organizations

Funding from the DOE Office of Nuclear Energy, Science and Technology (DOE-NE) and the DOE Office of Fissile Materials Disposition (DOE-MD) supports work on radioisotope power systems, mixed-oxide (MOX)-fueled reactors for disposition of fissile materials, and commercial reactor decontamination and decommissioning (D&D) technology. ORNL also expects to contribute to DOE's proposed nuclear energy R&D program. Goals have been established in these areas:

Radioisotope power systems

- Develop the infrastructure to provide a long-term, reliable supply of ^{238}Pu for U.S. customers.
- Provide DOE with a reliable supply of cladding and other key components for radioisotope thermoelectric generators.

Fissile materials disposition

- Define and develop the technology for use of MOX fuels derived from weapons plutonium in U.S. light-water reactors (LWRs), Canadian deuterium uranium (CANDU) reactors, and Russian VVER reactors, and assist DOE in the implementation of reactor-based options for disposition of surplus weapons plutonium.

- Develop and implement alternatives for the disposition of surplus ^{233}U.

Reactor instrumentation and controls

- Support the DOE initiative to address base technology advancements to assure the continued safe, reliable, and economical operation of existing nuclear power plants.

Hazard prediction and assessment capability

- Provide the Defense Special Weapons Agency (DSWA) with the tools needed for real-time assessments and quantification of hazards from accidents or interventions at nuclear facilities.

Advanced technology for D&D

- Apply and extend the experience gained in developing the applications of robotics, remote operations, sensors, and special tooling for DOE environmental remediation to remediation, decontamination, and dismantlement of commercial power reactors and other nuclear or hazardous facilities.

Nuclear energy R&D

- Provide leadership and direction in implementing the DOE-NE initiative to develop proliferation-resistant fuels, high-burnup fuels for spent fuel minimization, increased energy efficiency in nuclear power production to decrease greenhouse emissions from fossil sources, and a base science and technology program for reactor technologies.

Other sponsors include the Electric Power Research Institute (EPRI), which funds projects on reactor instrumentation and controls, and DSWA, which funds accident assessment and scenario analyses for international nuclear facilities.

1.2.2.2 Work sponsored by NRC

Since the 1960s, ORNL has been a leading laboratory in nuclear safety studies. Since its creation in 1974, NRC has been the primary sponsor of this work, which covers many technical areas. There are currently about 45 active projects at ORNL, and support comes from each major NRC office. The primary areas of involvement are as follows:

Reactor Pressure Vessel Integrity

- Support of NRC in the study of reactor pressure vessel (RPV) behavior under prototypical operating and aging conditions.
- Evaluation of methods for assessing margins against failure by fracture under circumstances such as start-up and shut-down cycles and pressurized thermal-shock (PTS) events, through combined analytical and experimental studies.
- Conducting experiments using small- and large-scale specimens characteristic of operating RPVs.
- Experimental exploration of aging effects due to neutron exposure (irradiation embrittlement) and long-term thermal exposure and use of results support development and/or application of regulatory practices.

Primary System Component Aging

- Studies of the aging of primary system components (pumps, valves, and piping) and of methods for detecting, measuring, and analyzing the effects of such aging.
- Development and experimental qualification of non-intrusive measuring techniques.
- Examination of the capabilities of advanced instrumentation and controls (e.g., digital systems) under various environmental conditions.

Severe Accident Modeling

- Study of phenomena and analytical models associated with severe accidents (those with a potential for core damage), with an emphasis on boiling water reactors.
- Formulation of state-of-the-art models that simulate severe accident phenomena and accident progression.
- Development of advanced analysis codes in a manner compatible with existing experimental data and application capability.

Nuclear Material Safety and Safeguards

- Research in support of non-reactor nuclear safety regulation.
- Maintenance of the large and versatile computer code SCALE and improvement of the code for criticality and thermal analyses of various fuel storage and transportation scenarios.
- Preparation of environmental assessments and provision of input for environmental impact statements for fuel cycle facilities (mines, enrichment plants, etc.).

Analysis of Operational Data

- Analysis of licensee event reports (LERs) from all operating nuclear plants to determine through probabilistic risk analyses the severity and root causes of the events and contribute to the identification of accident sequence precursors.

International collaborations

- In nuclear safety work maintain strong interactions with activities in other countries, especially those in Europe and Japan.
- Provide leadership and participation to the European Networks on Evaluation of Steel Components and Advanced Materials Evaluations.
- Active participation in nuclear structures, components, and materials activities of the Nuclear Energy Agency’s Committee on Safety of Nuclear Installations and IAEA’s Nuclear Power and Safety Divisions.

1.2.3 Fossil Energy

1.2.3.1 Program summary

Fossil fuels dominate the energy markets of the world and the United States, accounting for 7000 megatons of oil equivalent (Mtoe) of the world’s 9000-Mtoe/year energy use. Consequently, improvements in the production and use of fossil fuels are of fundamental importance in energy R&D.

Organized in 1974, the ORNL Fossil Energy Program has gained national recognition through achievements in the management of national activities on materials for fossil energy systems, in R&D on priority fossil energy technology needs, and in the integration of these activities with strong fundamental materials research. The Fossil Energy Program carries out R&D for DOE's Assistant Secretary for Fossil Energy (DOE-FE) in the areas of coal, clean coal technology, gas, petroleum, and support to the Strategic Petroleum Reserve. The coal activities include materials R&D, environmental analysis support (EAS), bioprocessing of coal to produce liquid or gaseous fuels, and coal combustion research. Work in support of gas technologies includes activities in the Advanced Turbine Systems Program, primarily on the materials and manufacturing aspects, and in low-cost fabrication methods for solid oxide fuel cell air electrodes. Several activities are contributing to petroleum technologies in the areas of computational tools for seismic analysis, bioconversion for the removal of impurities from heavy oils, and inorganic membranes for separation of hydrogen from refinery purge gases.

The Fossil Energy Program has projects in several ORNL divisions and is responsible for the technical management of all activities in DOE-FE's Advanced Research and Technology Development (AR&TD) Materials Program. The AR&TD Materials Program includes research at other DOE and government laboratories, at universities, and in industrial organizations.

The main activities of the program (see Fig. 1.6) are materials research, EAS, bioprocessing research, combustion research, fuel supply analysis and modeling, and advanced turbine systems. Recent program budgets are shown in Fig. 1.7.

1.2.3.2 Program goals

Materials research

- Develop fiber-reinforced ceramic composites and ceramic membranes for high-temperature and hostile environments.
- Develop and demonstrate the efficacy of porous materials technology as a low-cost fabrication process for the production of air electrodes for the Westinghouse Electric Company's tubular solid oxide fuel cell.
- Develop, in coordination with Pall Corporation, porous iron aluminide filters for removing hot particles from product streams in coal gasification systems.

Environmental analysis support

- Provide environmental technical support to the DOE Federal Energy Technology Center in the preparation of National Environmental Policy Act (NEPA) assessments of site-specific projects, such as coal-fired technologies being demonstrated at the proof-of-concept scale.

Bioprocessing research

- Continue research on the production of molecular hydrogen via photosynthetic water splitting.
- Participate in the Natural Gas and Oil Technology Partnership, supporting joint laboratory-industry projects.

Combustion research

- Provide critical analyses of existing combustion technology options for U.S. industry and government.

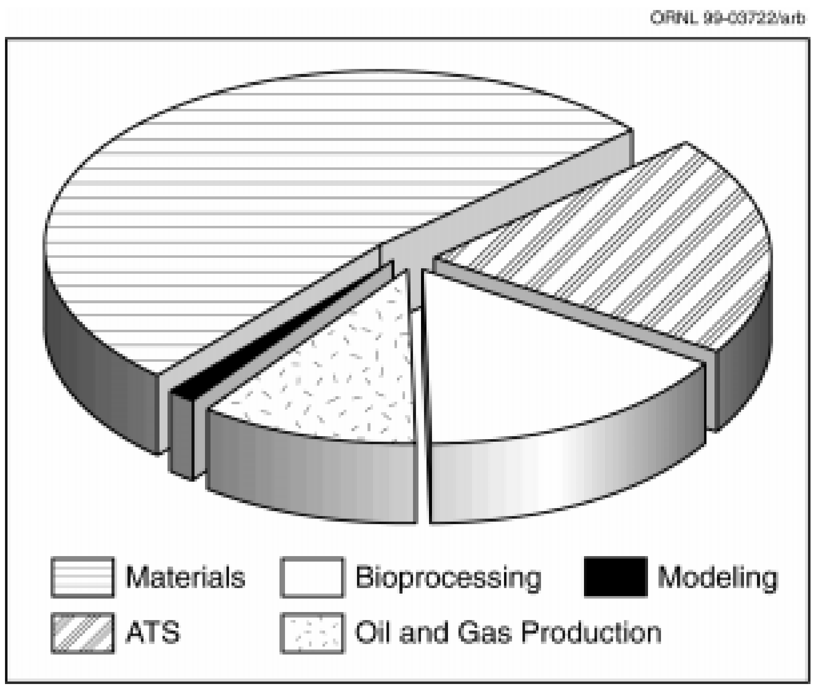

Fig. 1.6. Allocation of FY 1998 funds for the ORNL Fossil Energy Program.

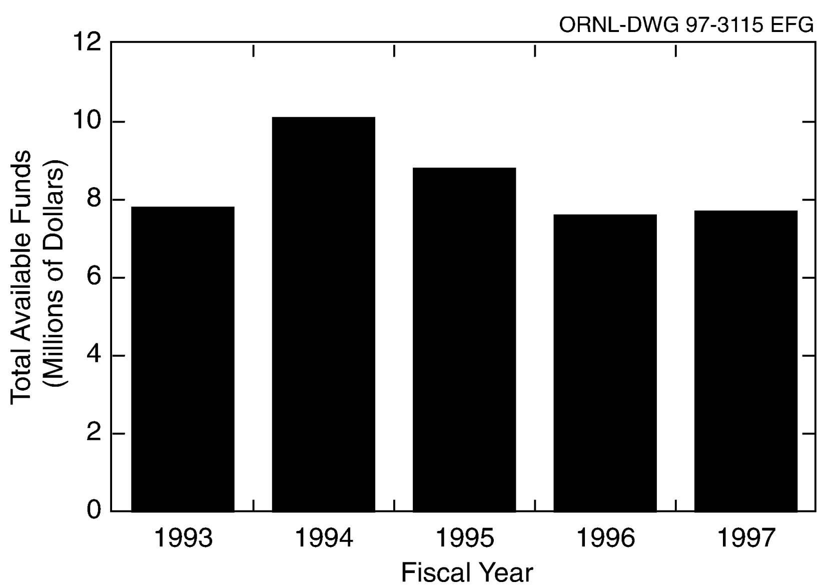

Fig. 1.7. Total funds (new BA) for the Fossil Energy Program, FY 1993–FY 1997.

Fuel supply analysis and modeling

- Develop and test advanced computational tools for three-dimensional (3-D) seismic analysis using the model data set developed under the joint aegis of the U.S. Society of Exploration Geophysicists and the European Association of Exploration Geophysicists to enhance the value to the oil industry of the modeling project conducted by these organizations.

Advanced turbine systems

- Address critical materials and materials manufacturing issues for industrial and utility gas turbines.

1.2.4 Fusion Energy

1.2.4.1 Program summary

The development of practical fusion energy sources is a long-term research goal. Fusion represents a potentially inexhaustible source of energy. As a complement to fission energy, fusion offers potential safety advantages deriving from the low stored energy of fusion power systems, the minimal risk of proliferation associated with fusion fuels, and the substantially smaller volumes of radioactive wastes from the fusion fuel cycle (with no actinides involved). The two approaches to exploiting fusion involve the use of either magnetic fields or inertial effects to confine a plasma (a hot reacting ionized gas).

ORNL is involved in magnetic fusion research. In this approach, a very hot plasma is confined by strong magnets and produces fusion reactions. Plasmas have many other applications, from lighting to materials processing. Consequently, the field of plasma science and technology has great value beyond its importance to fusion energy. ORNL also conducts spin-off research in such areas as semiconductor processing and the application of microwaves and cryogenic pellets to industrial needs.

The DOE-ER Office of Fusion Energy Sciences (OFES) sponsors the bulk of the ORNL fusion energy sciences and technology program; the Japan Atomic Energy Research Institute (JAERI) supports materials irradiation research. Today, 20% of the budget of ORNL's Fusion Energy Division is from other sponsors for spin-offs from the program. Recent budgets, including funding for spin-off R&D, are shown in Fig. 1.8.

A continuing strength of the ORNL program is the effective integration of capabilities in theory, computer modeling, plasma experiments, plasma and nuclear technologies, materials, and engineering. The ORNL program is also one of the most collaborative in the world, involving 6 U.S. laboratories, 8 U.S. universities, and 13 institutions in other nations.

In recent years, the U.S. magnetic fusion program has undergone substantial reductions as its focus has shifted from neart-term development of fusion as an energy source to concentrate on fusion energy sciences. This shift has had a profound effect on the scale and scope of the ORNL program. Of greatest significance has been the elimination of an in-house plasma experimental program, which has led to a focus on experiments at other laboratories in the United States and elsewhere.

A second important driver for the ORNL programs has been the International Thermonuclear Experimental Reactor (ITER) as a major world initiative. ORNL has been a substantial contributor to ITER and its predecessor programs; however, the United States has discontinued its participation in the ITER project.

The principal elements of the ORNL fusion program are atomic physics and diagnostics, theory, plasma experiments, plasma technologies, materials, and spin-offs.

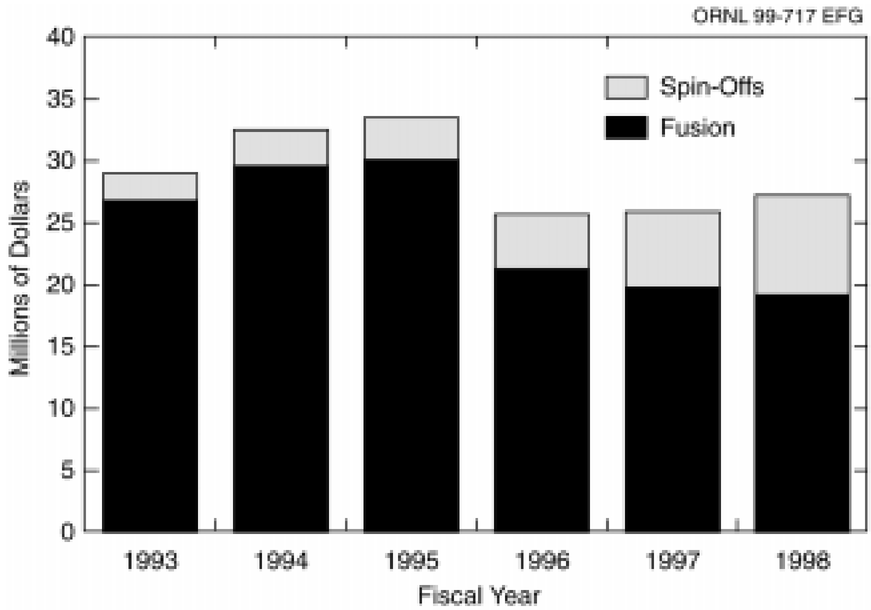

Fig. 1.8. ORNL fusion and fusion spin-off funding (new BA), FY 1993–FY 1998. Following a national restructuring of the program in FY 1996, budgets have stabilized.

1.2.4.2 Program goals

- Explore two complementary approaches to compact stellarators—the National Compact Stellarator Experiment (NCSX) and the Quasi-Omnigeneous Stellarator (QOS).
- Support the development of the spherical torus concept.
- Study and understand boundary physics and transport barriers in toroidal plasma confinement devices.
- Extend the database in fusion-relevant atomic physics for ion-surface interactions.
- Develop innovative, long-pulse-enabling technologies, such as radio-frequency (rf) heating systems and cryogenic pellet fuelers.
- Develop materials resistant to neutron irradiation.
- Become involved in the inertial confinement program.
- Strengthen the role that ORNL plays in plasma processing with the microelectronics sector.

1.3 FUNDAMENTAL SCIENCE AND TECHNOLOGY

DOE-ER has a broad science and technology mission that includes advancing scientific knowledge and stewardship of unique national research facilities. An important component of this mission is providing the fundamental scientific underpinning for the nation's energy technology portfolio. Among the goals of DOE-ER are the following:

- Enable the United States to uphold and enhance its world leadership in science, mathematics, and engineering needed by all sectors of the nation to enhance energy productivity and ensure reliable energy services while preserving human and environmental health and safety.

- Provide the best and most advanced scientific research facilities and infrastructure to advance science, improve existing energy options, and create new energy choices.[7]

The DOE-ER programs at ORNL include work in the following areas:

- studies of the fundamental structure of materials, which have led to the development of superalloys, tougher ceramics, intermetallics, and improved high-temperature superconductors;
- research on biochemical and thermochemical processes important to the exploitation of biofuels and waste materials, which has produced an understanding of how the enzyme Rubisco works;
- atomic and molecular physics and plasma physics, supporting advances in understanding the public safety of nuclear energy and leading to specific applications in catalysis, combustion, semiconductor processing, and fusion energy;
- high-performance computing, which has been essential to advances in 3-D seismic measurements of oil fields, in understanding plasmas in magnetic fusion experiments, and in facilitating the creation of "materials by design";
- fundamental neutron science, leading to improved understanding of the characteristics, processing, and development of energy-related materials and isotopes;
- chemical sciences, supporting the operation of the High Flux Isotope Reactor (HFIR, shown in Fig. 1.9) and research exploring the separation of mixtures, the advancement of analytical techniques, the physical and chemical properties of actinides, advanced battery technologies, and systems related to chemical conversions;
- geophysics, focusing on fundamental geochemical processes that control the transport of matter and energy in the earth's crust;
- engineering research that includes the development, demonstration, and application of remote systems, robotics, teleoperation, and related aspects of intelligent machines, with implications for energy exploration, environmental remediation, and transportation;
- biological sciences, addressing the need to understand complex biological systems and including functional genomics, mutagenesis induced by radiation and chemicals, biochemistry, toxicology and risk analysis, and nuclear medicine; and
- nuclear physics, emphasizing basic research on nuclear structure and nuclear astrophysics.

The coordination of basic research and applied development programs at ORNL accelerates both science and technology. Many of these programs involve collaboration across

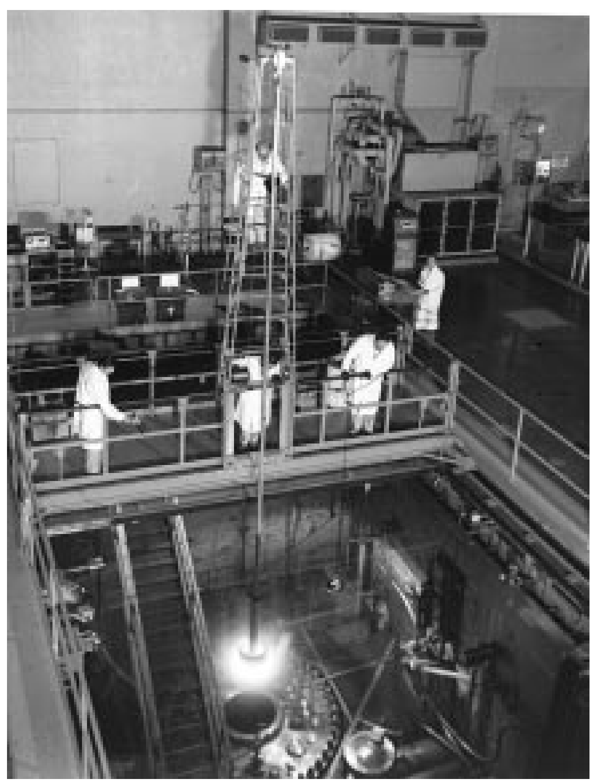

Fig. 1.9. Fuel element being removed from HFIR.

[7] "Energy Supply Research and Development," *Department of Energy FY 1998 Congressional Budget Request,* February 1997, p. 346.

organizational and geographic boundaries; many also draw on the capabilities provided by ORNL's 16 designated user facilities.[8]

1.4 ENVIRONMENTAL PROGRAMS

The effects of energy on the environment have been a focus of research at ORNL since work was undertaken during World War II to address concerns about the discharge of radioactive material from experiments. Radiation ecology issues gained prominence in the 1950s, with studies of radioactivity paths in plants and animals conducted using radioactive tracer isotopes produced at ORNL.

In the 1960s, ORNL's role broadened to include national and international environmental and social issues. Studies of CO_2 levels in the atmosphere began in 1968 and were expanded in 1976, pinpointing the role of the oceans in absorbing CO_2 from the atmosphere. Also in 1968, ORNL established a deciduous forest biome program that included studies of photosynthesis, transpiration, soil decomposition, and nutrient cycling in forest systems in the eastern United States. Research on large-scale forest ecosystems was initiated—a forerunner of today's programs on acidic deposition, biomass energy production, and global climate change. The formation of the Environmental Sciences Division in 1972 brought together capabilities in basic and applied research, environmental assessments, environmental engineering, and advanced technology demonstration to assess and predict the effects of environmental changes.

In 1978, ORNL began supplying technical guidance on forestry research to a new DOE biomass program, and by the end of 1980, nearly a quarter of ORNL's budget was devoted to environmental and health research. Researchers were working to understand the processes by which contaminants move through the environment and to identify the ecological effects of energy production. ORNL also contributed to the development of integrated assessment techniques for examining the interaction of proposed energy facilities with population bases, water supplies, ecosystems, air pollution dispersion potential, and other factors.

Expanding hydrologic and geothermal expertise was applied to DOE's needs in waste management. Risk assessments of energy technologies and industrial processes were undertaken, drawing on computer modeling and advanced instrumentation such as laser optics. Computer modeling was also used to study the effects of CO_2 accumulation in the atmosphere.

In 1982, the Carbon Dioxide Information Analysis Center began operations, and ORNL assumed full program responsibility for DOE's Short Rotation Woody Crops Program, which was expanded in 1984 to include the development of herbaceous crops for biomass energy. Acid rain studies that began in the early 1980s examined the consequences of prolonged exposure of ecosystems to rain polluted by sulfur and nitrogen oxides, ozone, and other materials. A link between acidic cloud water and reduced growth in high-elevation trees was established.

The Center for Global Environmental Studies was formed in 1989. In the early 1990s, ORNL researchers began studying ways to avoid ozone depletion, including the development of replacements for chlorofluorocarbons (CFCs). Global warming policy discussions have benefitted from ORNL's research; a multilaboratory study, conducted at the request of Congress, reviewed options for encouraging the private sector to mitigate, adapt to, and prevent global climate change. ORNL also contributed to the development of the total equivalent warming impact (TEWI) index for determining the global warming impacts of alternative technologies.

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[8]ORNL's guest and user facilities are the following: Atomic Physics–Tandem Accelerator, Bioprocessing Research and Development Facility, Buildings Technology Center, Computational Center for Industrial Innovation, High Flux Isotope Reactor, High-Temperature Materials Laboratory, Holifield Radioactive Ion Beam Facility, Laboratory for Comparative and Functional Genomics, Metals Processing Laboratory User Center, Metrology R&D Laboratory, Oak Ridge Centers for Manufacturing Technology, Oak Ridge Electron Linear Accelerator, Oak Ridge National Environmental Research Park, Shared Research Equipment Program, and Surface Modification and Characterization Research Center.

Also during the early 1990s, ORNL co-led a major study on estimating fuel cycle externalities (costs that are not accounted for by energy producers and consumers). The ultimate objective of the framework developed in this study is to translate the effects of fuel cycles into monetary terms and to determine the extent to which these effects are reflected in the price of electric power. Results for a variety of energy sources are being published by McGraw-Hill in a multivolume series of reports.

Today, ORNL's environmental programs focus on global change, environmental contamination, effects of energy development and use, and resource utilization. Environmental process research seeks to understand the parameters that control the movement of contaminants and nutrients in natural and human-affected systems. Research on the dynamics of ecosystems makes use of large-scale field experiments at the 22,500-acre Oak Ridge National Environmental Research Park (NERP) coupled with empirical, theoretical, modeling, and data systems research to predict the response of ecosystems to global change. Basic and applied research to develop and demonstrate environmental technology for remediation of contaminated environments is a continuing research focus. Work is in progress to create linkages with ORNL's expertise in functional genomics to explore the plant and microbial genomes for enhanced energy applications in biofuels and new applications in industry and commerce.

1.5 ENERGY POLICY AND INFORMATION

ORNL's work in assessing the benefits of energy technologies and the risks that they impose on society can be traced to the passage of NEPA in 1969, which established the use of environmental impact statements (EISs) by federal agencies. In 1971, the Calvert Cliffs decision required the Atomic Energy Commission (AEC) to complete 92 EISs in about a year. The AEC turned to its national laboratories, including ORNL, for assistance with this task. Staff working on these documents formed the nucleus of the Energy Division, established in 1974.

ORNL has examined the socioeconomic as well as the environmental impacts of nuclear power (fission and magnetic fusion) and of non-nuclear energy projects (geothermal, solar, fossil, synthetic-fuel, biomass conversion, and hydropower). ORNL also maintains one of the most extensive and authoritative complexes of scientific data and information analysis centers in the United States, and much of the effort in this area is focused on energy and its impacts on human health and the environment.

Today, ORNL researchers develop and apply tools to estimate the risks that energy production and use impose on ecological systems and integrate the resulting information with economic and policy factors to facilitate sound environmental decision making. ORNL performs policy analyses and assessments; develops decision support tools; assists DOE and other sponsors in evaluating energy-related issues; and collects, analyzes, and disseminates information about energy use, energy technologies and options, and the effects of energy production and use. The work is multidisciplinary, drawing on the skills of ecologists, economists, engineers, geographers, meteorologists, political scientists, sociologists, and computer and information scientists.

2

Energy Efficiency and Renewable Energy Programs

In 1994, almost 55% of the energy consumed in the United States was wasted through inefficiencies in energy transmission and utilization; this represents 47 quads of the 86 quads used. All sectors of energy use contributed: in electricity generation, 20.9 quads were wasted (66% for building electricity use and 34% for industrial electricity use); additionally, 4.2 quads were wasted in buildings, 3.4 quads in industry, and 18.7 quads in transportation—at a cost of a few billion dollars per quad. Total energy use in the United States from 1949 through 1997 is shown in Fig. 2.1. Figure 2.2 shows wasted energy.

Energy efficiency improvements offer great potential for reducing the cost of energy production and use. Such improvements are also key to supporting the burgeoning economies of developing countries without negatively affecting environmental conditions. Renewable energy sources are important indigenous resources, especially in developing countries. The use of renewable energy is important in the near term to reduce greenhouse gas emissions and is essential for a sustainable future.

2.1 HISTORY

The individual energy efficiency and renewable energy programs at ORNL were created following a series of seminars held during the middle and late 1960s that identified the importance of taking a broad view of energy production and end use.

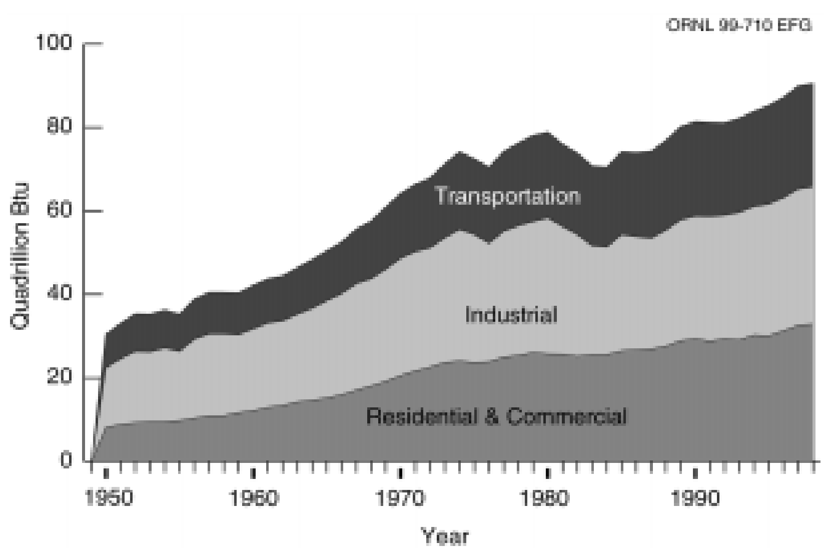

Fig. 2.1. Energy consumption by end-use sector, 1949–1997 (in quads). *Source:* Energy Information Administration, U.S. Department of Energy, *Monthly Energy Review*, DOE/EIA-0035(98/09), September 1998, p. 25.

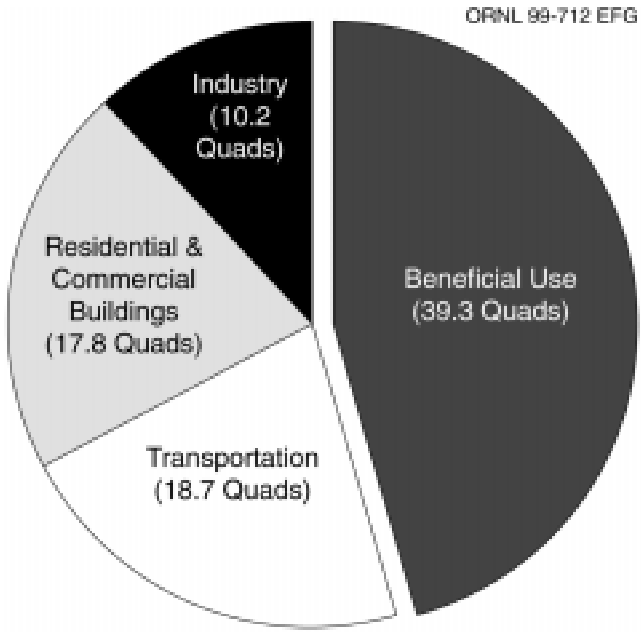

Fig. 2.2. Wasted energy by end-use sector in the United States in 1994 due to inefficiencies in generation, transmission, and use of energy. Less than half the energy consumed in the United States in 1994 resulted in direct beneficial use.

In 1970, ORNL began studies of ways to reduce energy demand by promoting energy conservation (e.g., through better home insulation). Studies were also made of the potential of solar energy, including enhancement of the biological production of hydrogen and methane and improvements to photovoltaic cells.

In the early 1970s, after Congress authorized the Atomic Energy Commission (AEC) to investigate all energy sources, the Laboratory broadened its mission to include R&D on all forms of energy. ORNL proposed work in such areas as improved turbine efficiency, alternative heat disposal methods for power plants, coal gasification, high-temperature batteries, and synthetic fuels from coal and shale to supplement petroleum and natural gas. Although not all of these proposals were funded, they illustrate the keen interest in energy at ORNL during this period.

ORNL contributed to AEC's 1973 report *The Nation's Energy Future*, which advocated research into new technologies and strategies to increase energy supplies by 1980 to eliminate the need to import oil. In 1974, with the creation of the Energy Research and Development Administration (ERDA), energy programs were vigorously promoted, and ORNL's Energy Conservation Program was started, with ORNL acting as program manager for ERDA in several areas. At this time ORNL formed its Energy Division, which has made major contributions to the development of building standards for the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE); to the identification of potential energy savings that can be achieved through technology and policy; to more energy-efficient building equipment, such as heat pumps and air conditioners; and to building envelopes and materials.

In 1977, a Transportation Group was formed to provide analyses and technical support to DOE and DOT on transportation policy issues and to assist in development of intelligent transportation systems. In 1978, the Energy Conservation Program was broadened to include R&D on renewable energy resources, and the program name was changed to Energy Efficiency and Renewable Energy (EERE) Program to reflect this. Research was initiated on biomass, geothermal energy, the production of hydrogen from plants, and improved photovoltaic materials. Also in the late 1970s, work started on the alteration of plant enzymes, both to break down carbohydrates more efficiently and to increase the growth and yield of plants for food and energy production.

In the early 1980s, ORNL researchers studied the benefits and costs of utility and government conservation programs that offered homeowners incentives to reduce electricity use. The Laboratory managed a DOE program to make electric power systems more reliable and efficient. Models were developed to predict how much energy would be used in transportation scenarios that included such elements as smart cars and intelligent highway systems. Bioconversion research was initiated to use microorganisms for converting organic materials—sewage, solid wastes, woody biomass, coal, and corn—into fuels.

In 1985, the Roof Research Center was built, including climate simulation facilities. The complex has been expanded into today's Buildings Technology Center (BTC).

Materials R&D directed toward energy efficiency led to the development of new alloys during the 1980s. Modified nickel aluminide alloys were licensed to industry for use in diesel engines. Silicon carbide whisker–strengthened ceramics were also licensed to industry. The High Temperature Materials Laboratory opened in 1987.

In recent years, the rolling-assisted biaxially textured substrates (RABiTS™) technology was developed for the manufacture of coated, high-temperature superconducting wires. In 1997, members of the team that developed RABiTS received the ORNL Scientist of the Year award and the Lockheed Martin NOVA Award.

2.2 OVERVIEW OF CURRENT PROGRAMS

The ORNL EERE Program addresses all areas of energy efficiency and performs R&D on renewable energy systems, primarily for DOE-EE, but also for USDA, DOT, and private industry. Its mission is to assist DOE in accelerating the development of sustainable energy technologies in buildings, transportation, industry, and utilities in order to create a cleaner environment, a stronger economy, and a more secure future. The program's mission reflects a national commitment to an expansion of the nation's energy resource options and to greater efficiency in every element of energy production and use.

ORNL EERE budgets for the past 5 years are shown in Fig. 2.3. The ORNL EERE Program has participated in 92 CRADAs with a research value of $82 million, including about $46 million in cost sharing by industrial partners.

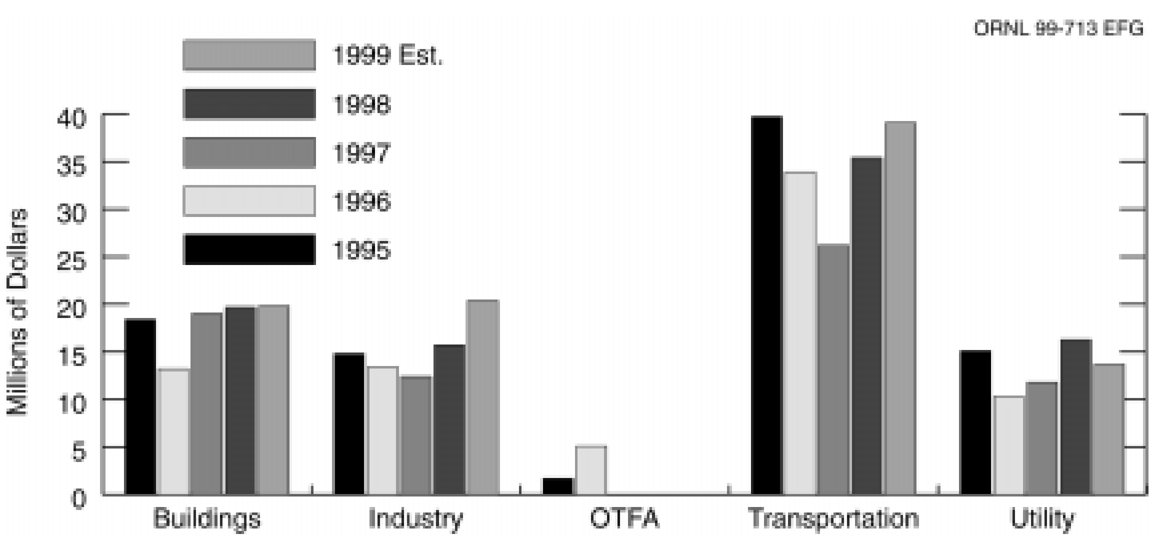

Fig. 2.3. ORNL EERE program budgets (new BA), FY 1995–FY 1999. Funding for technical and financial assistance, identified as OTFA, was recast into other sectors (primarily Buildings) in FY 1997.

2.3 BUILDINGS RESEARCH

The main sponsor of buildings research at ORNL is the DOE-EE Office of Building Technologies, State and Community Programs. Collaborations with federal and local government agencies, industry, and universities are extensive. In these collaborations, inventions from ORNL and other sources are developed into practical applications to save energy and to speed the deployment of energy-saving equipment. The potential for substantial improvements is shown by the 1993 energy use statistics in Table 2.1. Programs encompass

- research on heat pump, chiller, and refrigerator technologies to improve energy efficiency and environmental quality;
- the search for viable alternatives to CFCs, an important part of both equipment and materials research;
- materials research focusing on technologies for CFC-free, high-efficiency, long-lived building insulation;
- building envelope research, examining how buildings function as a system to affect energy efficiency;
- R&D on innovative walls, roofs, foundations, and manufactured houses;
- cost-effective, efficient retrofits to existing buildings; and
- assistance to the public and private sectors with the incorporation of innovative materials and technologies in buildings.

Table 2.1. Residential and commercial energy use (quads) in 1993

End use	Residential	Commercial
Space heating	6.7	1.92
Water heating	2.55	1.1
Space cooling	1.54	1.75
Refrigeration	1.52	0.45
Lighting	1.01	3.74
Clothes drying	0.6	—
Cooking	0.51	0.29
Freezers	0.46	—
Office equipment	—	0.74
Ventilation	—	0.54
Other	3.19	3.02
Total	**18.08**	**13.55**

Source: Energy Information Administration (EIA). *Annual Energy Outlook, 1996* DOE/EIA-0383(96), DOE EIA, Washington, D.C., 1996.

Much of the work is undertaken in the BTC, which provides the U.S. buildings industry with broad access to a unique collection of testing and analysis capabilities. The BTC is housed in a cluster of buildings with over 20,000 ft^2 of space. It has a permanent staff of about 50 people, which is supplemented, typically, by 10 to 20 guest workers.

The centerpiece test facility in the BTC is the large-scale climate simulator (LSCS), where large roof sections are sandwiched between two environmental chambers. The upper climate chamber can simulate any weather condition on earth, while the lower chamber models interior conditions. The LSCS was crucial to the recent ORNL finding that convection currents in attics reduce the effectiveness of loose-fill insulation when there are large indoor-outdoor temperature differences (Fig. 2.4).

Other BTC capabilities include

- the rotatable guarded hot box to test full-size wall, fenestration, roof, and floor systems;
- the roof thermal research apparatus with eight replaceable roof panels, four replaceable wall panels, and a controlled interior;

ORNL-DWG 97-3061 EFG

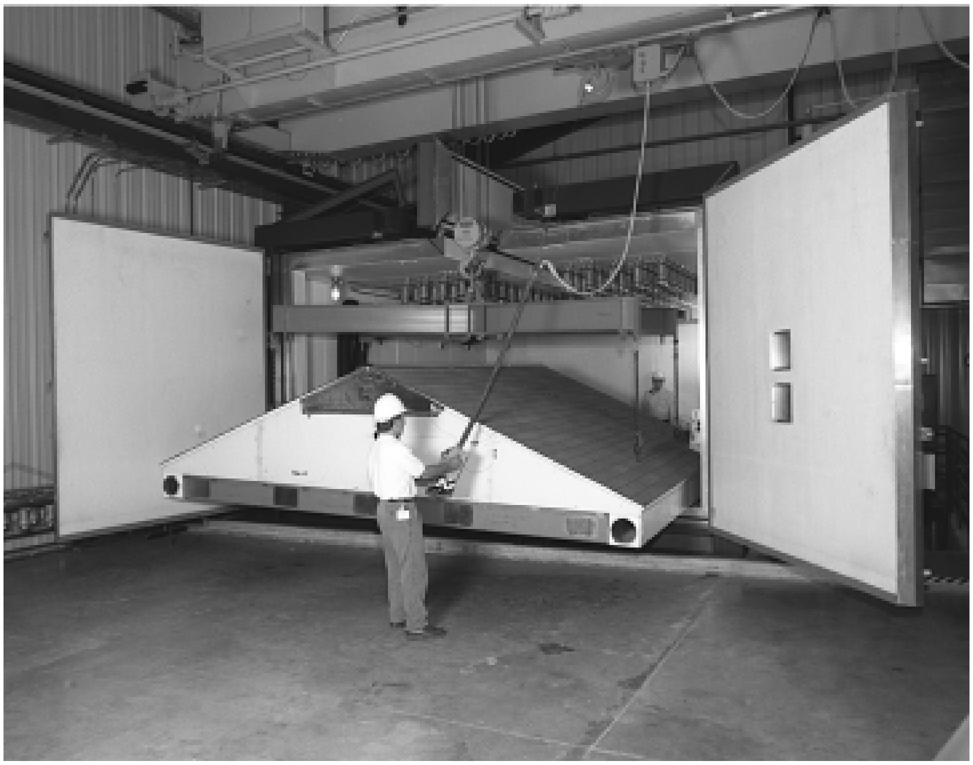

Fig. 2.4. An attic section is placed in the large-scale climate simulator at the BTC.

- two calibrated slab-foundation edges to measure the thermal performance of slab-on-grade;
- the envelope systems research apparatus, which is used to study energy and moisture flow through building envelopes;
- a large two-room (indoor/outdoor) environmental chamber used to simulate temperatures and humidity conditions for the development of air-conditioning, refrigeration, and heat pump technology;
- a small variable, laminar air flow device for analysis of heat exchanger configurations;
- calorimeters and specialized test apparatus for evaluating CFC and hydrofluorocarbon (HFC) replacement refrigerants; and
- a wide array of sensors and data acquisition systems to analyze building performance in the laboratory and in the field.

2.3.1 Building Envelope Systems

ORNL is the lead national laboratory for research on building thermal envelope systems. The research program includes investigation of the thermal efficiency of walls, roofs, and foundations, as well as development of building diagnostics and envelope designs resistant to the adverse consequences of moisture. It also includes the development of mathematical models such as MOIST and MATCH, to predict the transfer of heat and moisture in building envelopes, and field performance studies of envelope systems.

Analysis, modeling, and testing are leading to longer-lasting and more energy-efficient roofs. The program has a goal of developing a low-sloped roof, marketable by the year 2000, with a service life of 30 years and a thermal insulation rating of R-30 (the R-value indicates a material's thermal resistance to heat loss). Dryable roofs are being developed cooperatively with private industry. These roofs are important because they will last longer than current low-slope roofs, potentially saving $12 billion per year in reroofing costs; will result in landfill space savings of 0.2–0.4 billion ft^3 per year; and could reduce peak electrical generation requirements by 900 MW in the southeastern United States.

ORNL studies of the thermal performance of alternative foundation and wall insulation systems resulted in specifications for foundation insulation in the ASHRAE prescriptive standard and the Council of American Building Officials (CABO) Model Energy Code that will lead to energy savings of 0.38–0.45 quads per year by 2010. Several energy-efficient wall and foundation systems with integral insulating capabilities have been developed.

More recently, ORNL researchers have developed a new method of determining the R-value of walls. In contrast to the currently used method, which measures the wall R-value at a “clear wall” point (no corners, studs, windows, etc.), the “whole wall” method takes into account the thermal shorts and breaks introduced by such construction details. The whole wall rating method gives a common basis for comparison of walls of dissimilar construction and materials. The rating method has been used by several manufacturers using the facilities at the BTC.

2.3.2 Building Materials

The goal for building materials improvement is to develop new, cost-competitive materials that can reduce building energy consumption by 20% by 2010. ORNL contributions include

- measurements of the decreasing insulating properties of loose-fill fiberglass attic insulation with increasing temperature differential, caused by convective air loops within the insulation (see Fig. 2.5);
- assessment of the thermal performance and other relevant properties of indigenous materials; and
- improvements to vacuum insulation panels (so-called “superinsulators”), which offer a large advantage over traditional insulators in confined spaces such as the wall-to-roof space in mobile homes (see Fig. 2.6).

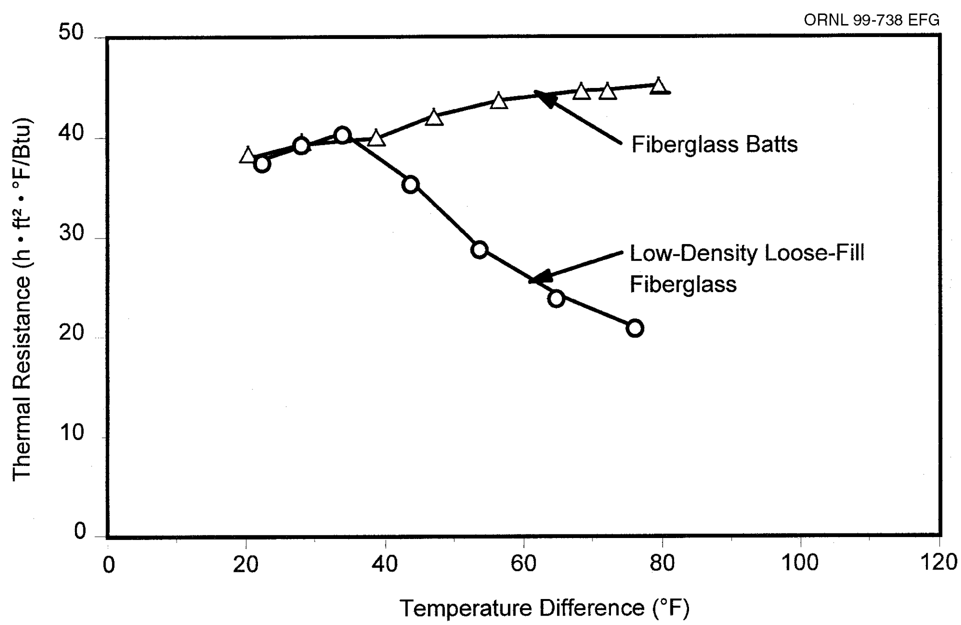

Fig. 2.5. Thermal performance of two types of fiberglass attic insulation over a range of temperature differences. The plot indicates how well the insulation would perform when subjected to a range of differences in indoor and outdoor temperature during a typical heating system.

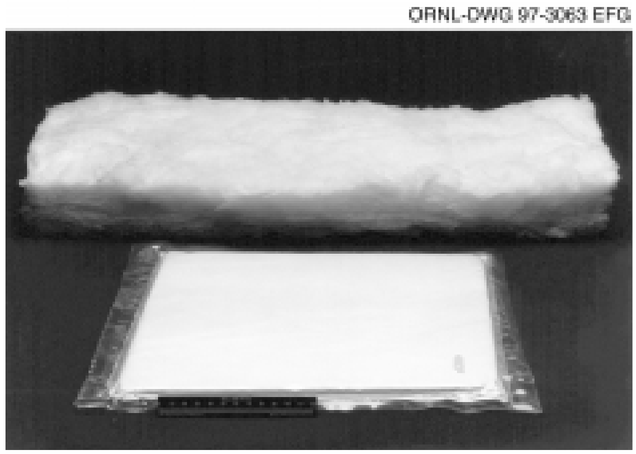

Fig. 2.6. Vacuum insulation panel (*bottom*) and fiberglass batt (*top*).

2.3.3 Existing Buildings Retrofit

The existing buildings retrofit program has focused on four areas of R&D effort:

1. improved and validated energy audits; operation, maintenance, and occupant behavior diagnostics; and energy performance verification procedures;
2. advanced and retrofit technologies;
3. improved methods for educating building owners, operators, and occupants about basic requirements and advanced methods for achieving energy efficiency; and
4. methods for maintaining savings over the long term.

Program efforts since 1985 have led to current savings of 2 trillion Btu/year, with cumulative savings of 10 trillion Btu (worth about $75 million), for a modest level of funding. These energy savings caused a reduction in air emissions of about 32,000 metric tons of carbon equivalent each year (a total of more than 150,000 metric tons). An important indicator of the program's impact is reduced investment requirements for saving energy in the residential sector (see Fig. 2.7).

The National Energy Audit (NEAT) program developed by ORNL for DOE's Weatherization Assistance and Existing Buildings programs is being used by more than 20 states to determine the most cost-effective combination of retrofit measures for single-family homes to increase energy efficiency without decreasing comfort levels. NEAT output also includes an estimated dollar value of projected savings, savings-to-investment ratios, and a list of the quantities of materials necessary to perform the recommended refit. Results of field tests have demonstrated an improvement in energy savings from refits of 25%, compared to the previous typical value of 18%. It is estimated that, for retrofits completed in 1995, NEAT will save $56 million in energy costs over the lifetime of the retrofits.

ORNL collaborated in the design and implementation of DOE's Rebuild America initiative, which has the goal of reducing carbon emissions projected for the year 2000 by 1.7 million metric tons of carbon equivalent. The program has created more than 50 partnerships among local governments, local business groups, and utilities.

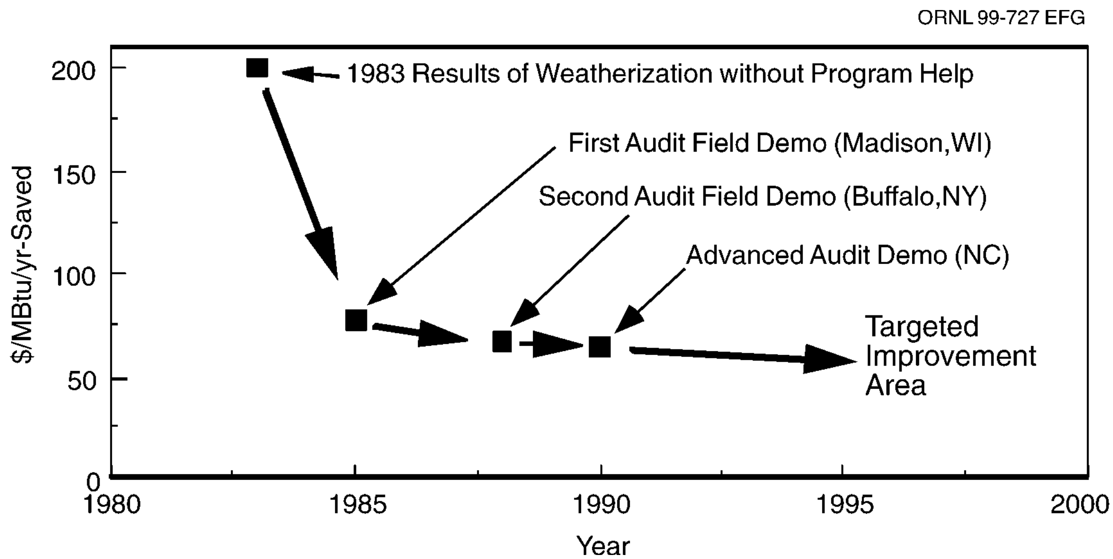

Fig. 2.7. Investment costs for energy in the residential sector have decreased significantly under the Existing Buildings Program.

ORNL assists DOE's Partnerships for Affordable Housing program in its work with Habitat for Humanity International. In a number of initiatives, including technical assistance and training, DOE is helping to institutionalize a process for making Habitat homes more energy- and resource-efficient. Habitat for Humanity has more than 1300 affiliates in the United States, collectively representing one of the nation's largest builders of new and revitalized housing.

2.3.4 Heating and Cooling

The goal of ORNL's heating and cooling R&D is to exceed the 1993 state of the art in efficiency by 25% or more with a new generation of ozone-safe heat pumps and air conditioners.

- ORNL work on electric ground-coupled heat pumps (GCHPs) led to a 25% efficiency improvement over air-source heat pumps of mid-1980s vintage. The GCHP industry has grown significantly since the initial DOE/ORNL research. In 1985, approximately 5000 units were being installed in residences each year. In 1995, the market ranged from 40,000 to 50,000 units a year. A public/private partnership has been formed with the goal of expanding the market to 400,000 units per year by 2000. Assuming an average savings per unit of $350 a year in energy costs, cumulative savings due to GCHPs from 1985 to 1995 are about $90 million.
- ORNL is working with the private sector to develop next-generation, high-efficiency, gas-fired absorption heat pumps. The generator–absorber–heat exchange (GAX) technology should be commercially available before 2000. It promises heating efficiencies at least 50% higher than the best current gas-fired technology. The next improvement will be the Hi-Cool absorption system, which will combine the heating efficiency of GAX with cooling performance better than the best available gas-fired cooling technology. With these improvements, gas-fired heat pumps will be competitive with electric heat pumps in all U.S. climate regions. Progress in absorption heat pumps is shown in Fig. 2.8.
- ORNL has taken the lead in developing the next generation of absorption chillers, known as "triple-effect" chillers. A National Triple-Effect Partnership involving ORNL, DOE, the Gas Research Institute (GRI), and all four U.S. manufacturers of absorption chillers has been formed, with the aim of restoring the United States to a competition-leading position in the large and expanding global market for absorption chillers. Two triple-effect chiller technologies patented by ORNL scientists will soon offer cooling performance 50% more efficient than the best gas chiller technology available in 1995. The Trane

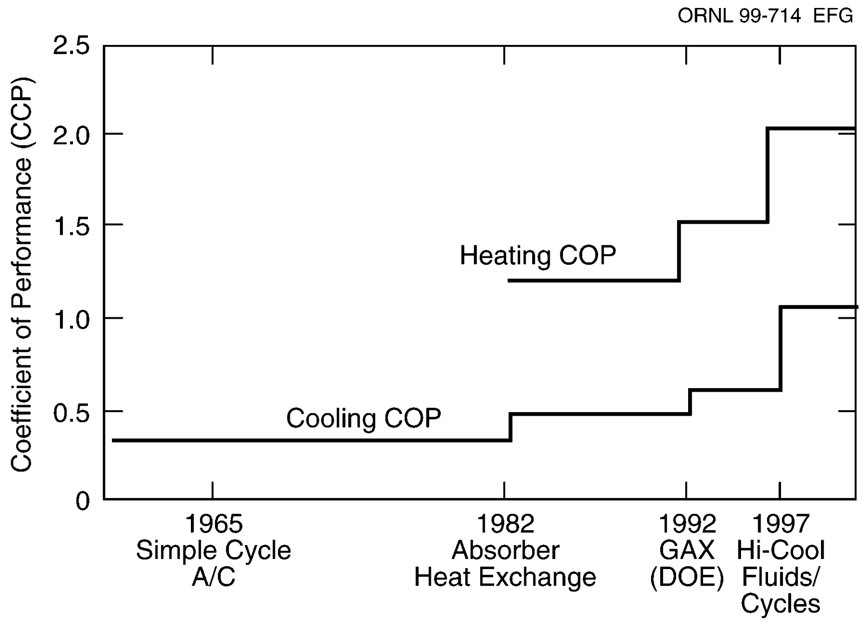

Fig. 2.8. Progress in absorption heat pump efficiency.

Company, supported by GRI, has tested a 400-ton prototype and expects to commercialize it in 1998–1999. York International has developed, through cost-sharing with DOE, a second triple-effect absorption chiller, based on the double-coupled condenser cycle, and anticipates field tests in 1999, with production to follow. A major advantage of both of these products is their use of a "natural" refrigerant (water and lithium bromide) rather than CFCs or hydrochlorofluorocarbons (HCFCs).

- The DOE/ORNL Heat Pump Design Model allows rapid screening of refrigerant and refrigerator circuit options and is widely used by industry. The model showed that the efficiency of single-speed, air-source heat pumps could be increased by more than 50% over levels of the early 1980s through design optimization and the use of more efficient components (compressors, fans, heat exchangers, etc.). The model is estimated to have accelerated the development of high-efficiency systems by 5 years, saving about 0.05 quad.

2.3.5 Refrigeration/Cooling

ORNL has identified and investigated a variety of design changes to supermarket refrigeration systems and home refrigerator/freezer units that have generated significant energy savings.

- In the early 1980s ORNL collaborated with the private sector to develop better supermarket refrigerators by using an unequal parallel compressor rack system and control scheme to modulate compressor capacity to meet a store's changing refrigeration loads. These advances are now incorporated in over 80% of supermarket systems in the United States, resulting in energy savings of about 30%.
- Involvement with the private sector led to the development of a high-efficiency compressor for household refrigerators and ultimately to compressors with energy efficiency ratios as high as 6.0. These compressors were a major contributor to the drop in refrigerator annual energy use from about 1700 kWh/year in 1973 to about 700 kWh/year in 1993 (see Fig. 2.9). The estimated cumulative savings from the use of these compressors in the period from 1980 to 1990 is around 0.85 quad.
- A major current effort, in cooperation with the Association of Home Appliance Manufacturers (AHAM), is the development and demonstration of a CFC-free, 1-kWh/day home refrigerator. The refrigerator incorporates technology that is currently available to the entire industry. The goal was achieved in 1997 using technologies shown in Fig. 2.10.

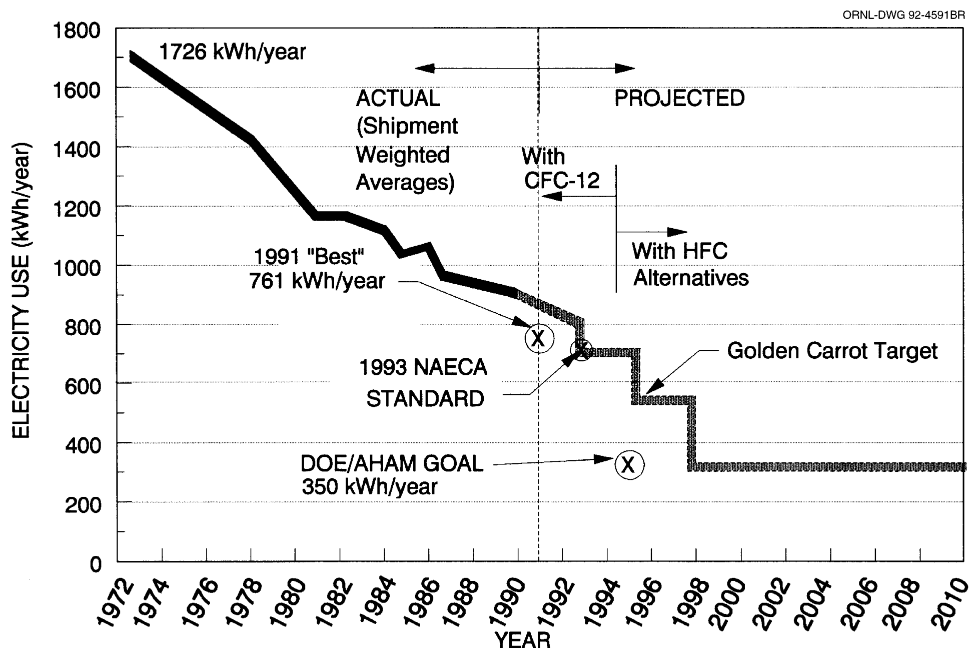

Fig. 2.9. Household refrigerator/freezer energy-efficiency improvements.

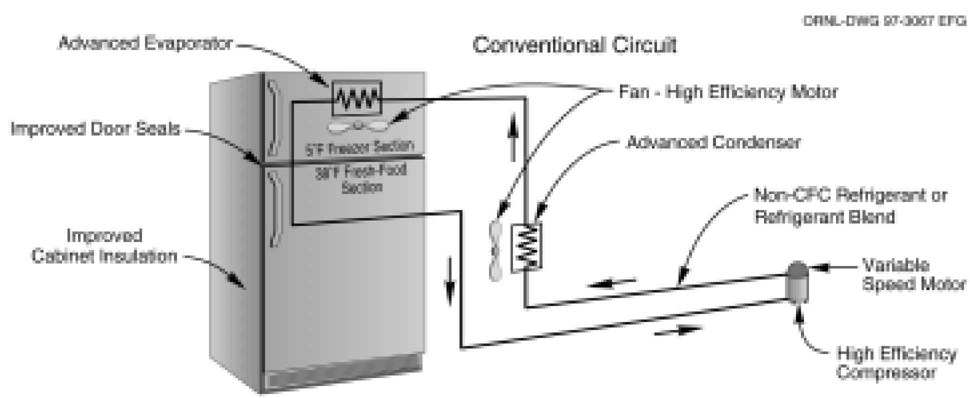

Fig. 2.10. Incorporating high-technology components in a conventional design enables low energy use. A top-freezer unit was chosen because it represents 65% of the current market.

- The liquid-overfeed heat exchange device (see Sect. 2.4.3.5), invented in the course of industry-related research, is being studied for application to residential air conditioners and heat pumps. If used in home air conditioners, it could save consumers some $4 billion and cut CO_2 output by 9 million metric tons each year. Another application, being investigated by a major soft drink producer, is vending machines.
- ORNL is developing advanced air-refrigerant heat exchanger designs for use with HCFC alternative refrigerants and blends in advanced heat pump/central air conditioning systems. To that end, ORNL has initiated efforts with heat exchanger and heat exchanger tubing manufacturers to develop refrigerant side-surfaces and overall configurations to yield the maximum thermal performance with zeotropic blends.
- ORNL has been a leader in identifying, characterizing, and screening CFC alternatives. Staff members received the ASHRAE Best Paper Award in 1990, 1991, and 1992 for CFC alternative screening studies. One paper described the first documented operational performance measurements of refrigeration systems using HFCs, the leading chlorine-free replacement refrigerants. ORNL made a major assessment of the

relative energy efficiencies, associated CO_2 emissions, and net global warming potential of a range of CFC alternatives.

- ORNL won an R&D 100 Award in 1992 for developing the CFC/HCFC ratiometer, a simple-to-use instrument for accurately measuring the percentage of each halogenated compound in refrigerant mixtures.

2.3.6 Support for State and Community Programs

ORNL has long been involved with support for the low-income Weatherization Assistance Program. The Laboratory has also periodically provided assistance to other state and community programs, including the state energy conservation program and DOE's Energy Efficiency and Renewable Energy Network.

The Weatherization Assistance Program is the nation's largest conservation program. The goals of the program are to decrease national energy consumption and to reduce the impact of high fuel costs on low-income households, particularly those of the elderly and handicapped. ORNL has assisted DOE by conducting an evaluation of the program's overall performance, field-testing alternative packages of retrofit measures, evaluating individual retrofit measures for possible inclusion in the program, and developing energy audit tools to guide the selection of retrofit measures for individual dwellings. In 1994, ORNL completed a 3-year, $5 million evaluation of the program. Because the program is implemented by more than 1100 local agencies across the country, the evaluation required an elaborate sampling design and an extensive amount of data.

2.4 TRANSPORTATION RESEARCH

Transportation in the United States consumes about 27% of all energy, including about two-thirds of the oil.[1] Other energy impacts in the transportation area are as follows:

- Motor vehicle and equipment manufacturing is the largest of all U.S. manufacturing industries.
- Petroleum ($45 billion in 1992) and vehicles and parts ($39 billion in 1992) account for slightly more than 10% of U.S. imports, contributing to the trade imbalance.
- Transportation contributes about one-third of U.S. greenhouse gas emissions.

Table 2.2 shows the energy consumption data for various modes of transportation. It is clear that improving the energy efficiency and lessening the environmental impacts of automobile and truck manufacturing and operation could yield significant decreases in atmospheric pollution and the nation's trade deficit.

Recognizing the national importance of these opportunities, ORNL designated transportation as a major initiative in 1991 and joined with other DOE facilities in Oak Ridge (the Oak Ridge Y-12 Plant and the Oak Ridge K-25 Site, now the East Tennessee Technology Park) to form the Oak Ridge Transportation Technologies

Table 2.2. Domestic consumption of transport energy by mode in 1993

Mode	Consumption (quads)	Share of total transportation energy use (%)
Automobiles	9.42	40.85
Light trucks	4.37	18.94
Heavy trucks	3.56	15.44
Air	2.00	8.66
Water	1.47	6.39
Pipeline	0.89	3.86
Off-highway	0.71	3.06
Rail	0.46	2.01
Bus	0.18	0.79
All modes	23.06	100.00

Source: Stacy C. Davis and David N. McFarlin, *Transportation Energy Data Book: Edition 16,* ORNL-6898, Oak Ridge National Laboratory, Oak Ridge, Tenn., 1996.

[1]Energy Information Administration, U.S. Department of Energy, *Monthly Energy Review*, DOE/EIA-0035(98/09), September 1998.

Center (ORTRAN). In a related action, ORNL joined with its principal governmental, academic, and industrial partners in the region to form the Tennessee Technology Coalition, in order to pursue regional and national opportunities in this field.

An important outcome of the latter action has been the creation of the National Transportation Research Center, a partnership between the University of Tennessee and DOE's Oak Ridge complex. The center will serve DOE, DOT, the Department of Defense, and the U.S. transportation industry, all major sponsors of work at ORNL. The Development Corporation of Knox County will construct a research and user facility to house the center; this facility will have more than 50,000 ft^2 of space at an estimated cost of $5 million. Plans are to outfit the center with $10 million of equipment for advanced user facilities, including

- a vehicle emissions laboratory that can measure light-duty vehicle emissions over certification cycles and provide a research tool for automobile makers and federal sponsors,
- a high-speed flywheel propulsion testing facility, and
- laboratories for
  - light-weight transportation materials,
  - intelligent transportation systems (ITS) analysis,
  - new safety systems,
  - advanced military transportation and deployment systems, and
  - packaging materials testing.

The DOE-EE Office of Transportation Technologies (OTT) sponsors programs at ORNL that improve transportation efficiency through research in materials science, ignition and combustion processes, and innovative manufacturing and finishing processes. ORNL provides technologies that enable greater fuel economy and the increased use of alternative fuels for transportation.

2.4.1 Partnership for a New Generation of Vehicles

Recognizing the technology base existing at the national laboratories, representatives from General Motors visited ORNL and other national laboratories in 1991 to identify research topics of mutual interest. Discussions with Ford and Chrysler soon followed. DOE's OTT saw the need for a focal point between the Big Three automakers and the DOE national laboratories and asked ORNL to take the lead in forming the "C4" Committee to give the automakers efficient access to and coordination with representatives of the various laboratories. The Partnership for a New Generation of Vehicles (PNGV), established in September 1993, is the manifestation of this groundbreaking public-private partnership. PNGV has three goals:

1. To significantly improve national competitiveness in manufacturing. Improvements in manufacturing technologies resulting from the partnership's R&D work will be applicable in other manufacturing industries.
2. To implement commercially viable innovations from ongoing research on conventional vehicles, which focuses on fuel efficiency improvements and emissions reductions. The goal ensures that PNGV will build on existing research programs and will apply significant technological advances as they become available.
3. To develop, within 10 years, a commercially viable midsize car with three times the fuel efficiency of today's comparable vehicle without negatively affecting safety, comfort, purchase and operating cost.

ORNL contributions to the PNGV R&D program are shown in Fig. 2.11. Recent work at ORNL has led to two significant developments: (1) catalysts for reduction of nitrogen oxide emissions for lean-burn engine technology, which won the 1997 Vice President's PNGV Award, and (2) the resonant snubber inverter (RSI) for hybrid vehicles. The RSI, shown in Fig. 2.12, is 98% efficient at high speeds and 80% efficient at low speeds and has a power density of 11 kW/kg, exceeding the PNGV goal of 5 kW/kg.

In related work, a multifunction power controller now being developed will replace the large number of individual and complex power electronic circuits in hybrid electric vehicles, greatly reducing the cost of the drive train and increasing the reliability of the vehicles' electronic systems.

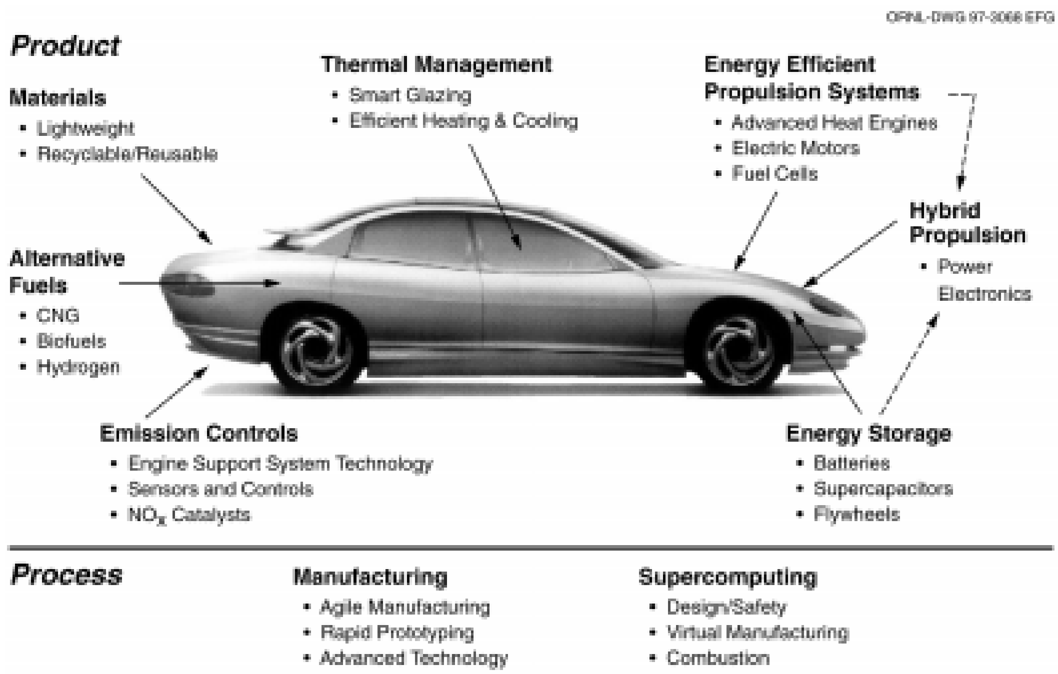

Fig. 2.11. Oak Ridge technologies supporting the Partnership for a New Generation of Vehicles.

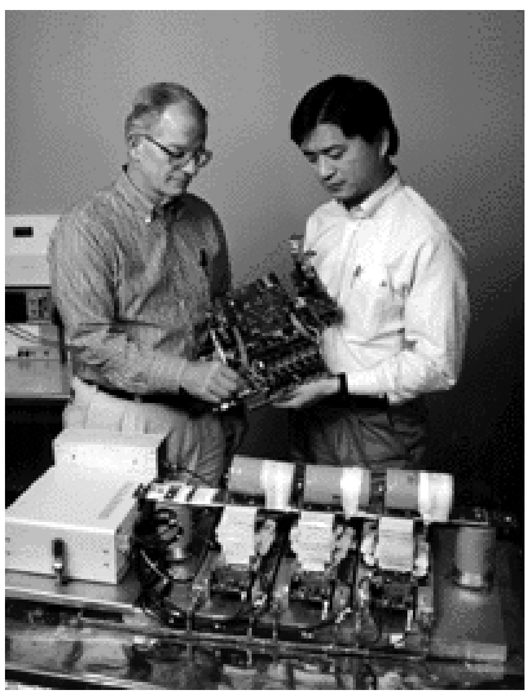

Fig. 2.12. The resonant snubber inverter (RSI), held by two of its inventors, and a conventional inverter, on table. RSIs like the 100-kW unit shown here are smaller and lighter than conventional converters like the 70-kW unit on the table.

2.4.2 Transportation Materials

2.4.2.1 Ceramic materials and processing

ORNL's research on ceramic materials for transportation began in 1983 with the objective of producing reliable ceramics for use in advanced engines (e.g., automotive gas turbines). While this goal has been largely met, cost reductions are needed for wider applications. Therefore, the scope of the program was expanded to providing cost-effective ceramics for near-term applications in conventional engines. In FY 1999, the program will begin studying applications for ceramic materials in the primary industries that are part of DOE's Industries of the Future (see Sect. 2.5).

Most of the work is being performed by the ceramics industry with technology support from government laboratories and universities. Friction and wear studies of new materials are conducted in the ORNL Tribology Laboratory. Successful contributions from ORNL include the following.

- ORNL has developed "whisker-reinforced" ceramics in research coordinated with the DOE-EE Advanced Industrial Materials Program and the DOE-ER Basic Energy Sciences Program. In these materials, ceramics are fused with tiny fibers that stop the spread of potentially shattering cracks, giving good strength at high temperatures without the brittleness of conventional ceramics.
- Silicon carbide whisker-reinforced alumina ceramics developed at ORNL (see Fig. 2.13) have had a major impact on the competitiveness of the U.S. machine cutting tool technology, increasing machining rates by up to 800%. They are also used in numerous automobile parts.
- The application of sintered silicon carbide as a seal face in automotive water pumps was developed in cooperation with the Carborundum Company. These seals exhibit one-half to one-third the failure rate of alumina seals and had obtained 30% of the U.S. market in U.S. vehicles by 1994.
- ORNL has developed silicon nitride piston rings, rocket engine turbine pumps, industrial gas turbines manufactured from in situ–toughened silicon nitride, a gelcasting process for manufacturing ceramic parts, and a gripping device for tensile testing of ceramics.

Products from this research are being manufactured by companies such as Advanced Composite Materials Corporation, AlliedSignal Ceramic Corporation, Carborundum, Chand Kare Technical Ceramics, Coors Ceramics Company, Cercom, Dow Chemical Company, GTE, Hertel Cutting Technology, Instrom Corporation, Kennametal, Keramont Corporation, and Valenite Corporation.

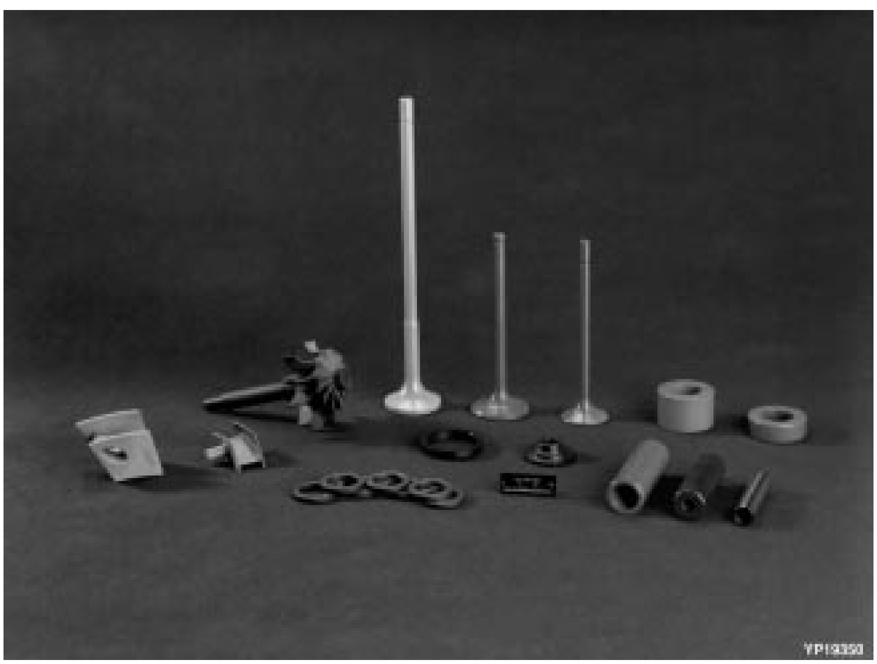

Fig. 2.13. Vehicle components made from silicon carbide whisker-reinforced ceramics.

New efforts are concentrated in two areas: propulsion materials for automotive applications, and propulsion materials for heavy vehicles. In automotive applications, research is geared toward reducing the cost of ceramic components and addresses ceramic manufacturing, ceramic synthesis and processing, nondestructive valuation and inspection, corrosion-resistant coatings methodology and validation, and materials testing and standards. The heavy-vehicle propulsion system materials program is working to develop enabling materials technology to support (1) the use of diesel engines in class 1–3 trucks to achieve a 35% fuel economy improvement over current gasoline-fueled trucks and (2) the development of fuel-flexible LE-55 low-emission, high-efficient diesel engines for class 7–8 trucks.

2.4.2.2 Lightweight materials

It is estimated that a 25% weight reduction in current vehicles would save about 13% of the total U.S. gasoline consumption and would reduce CO_2 emissions by about 100 million tons per year. The challenge is to develop a lightweight material that can be recycled (a PNGV objective), meet safety standards, and have a cost approaching that of steel.

In concert with the U.S. Automotive Materials Partnership (USAMP), ORNL is investigating reliable adhesion technologies for lightweight composite and metal automobile structures. The bonding of similar and dissimilar metals was identified as being of primary importance to the consortium because this would free designers to choose from an expanded menu of low-mass materials. ORNL leads three tasks for this project: developing standardized test procedures for determining the fracture behavior of adhesive joints; generating computer models for predicting joint failures; and developing advanced technologies for designing, curing, and manufacturing adhesive joints. Microwave processing shows promise for increasing the strength of adhesion while lowering the processing time (see Fig. 2.14).

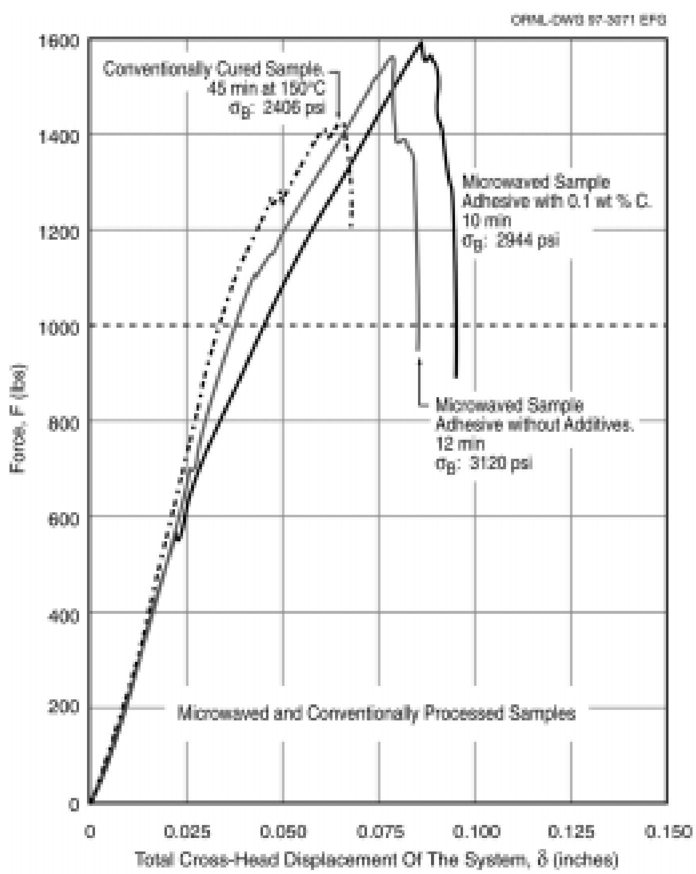

Fig. 2.14. Comparison of microwave processing and conventional processing.

In 1997, ORNL researchers received an R&D 100 award for metal compression forming, a process developed in cooperation with Thompson Aluminum Casting Company of Cleveland (Fig. 2.15). The process makes it possible to create pore-free cast aluminum alloy components with properties comparable to those of forged parts, but at one-third the cost. As a result, cast aluminum alloy parts can be used in safety-critical structural applications that require high tensile strength and ductility and high fatigue strength, particularly for automotive applications. Because cast aluminum components weigh about half as much as steel, cast iron, or ductile iron components, the weight of safety-critical parts of automobiles (e.g., engine mount brackets, steering knuckles, and control arms) can be reduced without sacrificing strength.

In a demonstration project now under way, a major structural assembly will be made of automotive-grade composite components that will be adhesively bonded together. The assembly will be incorporated into a vehicle that will be tested for durability using standard vehicle test procedures. Success will depend on meeting manufacturability time and cost goals so that the technology can be readily incorporated into production lines.

2.4.3 Alternative Fuels

2.4.3.1 Bioenergy feedstock development

Biomass—plant matter—can be converted to alcohol or other liquid fuels to power vehicles, reducing petroleum consumption and greenhouse gas emissions. ORNL manages DOE's Bioenergy Feedstock Development Program (BFDP), a national program for the development and demonstration of environmentally acceptable, commercially viable biomass supply systems based on energy crops. The program's areas of emphasis include

- wood and herbaceous (grasses) energy species;
- environmental research;

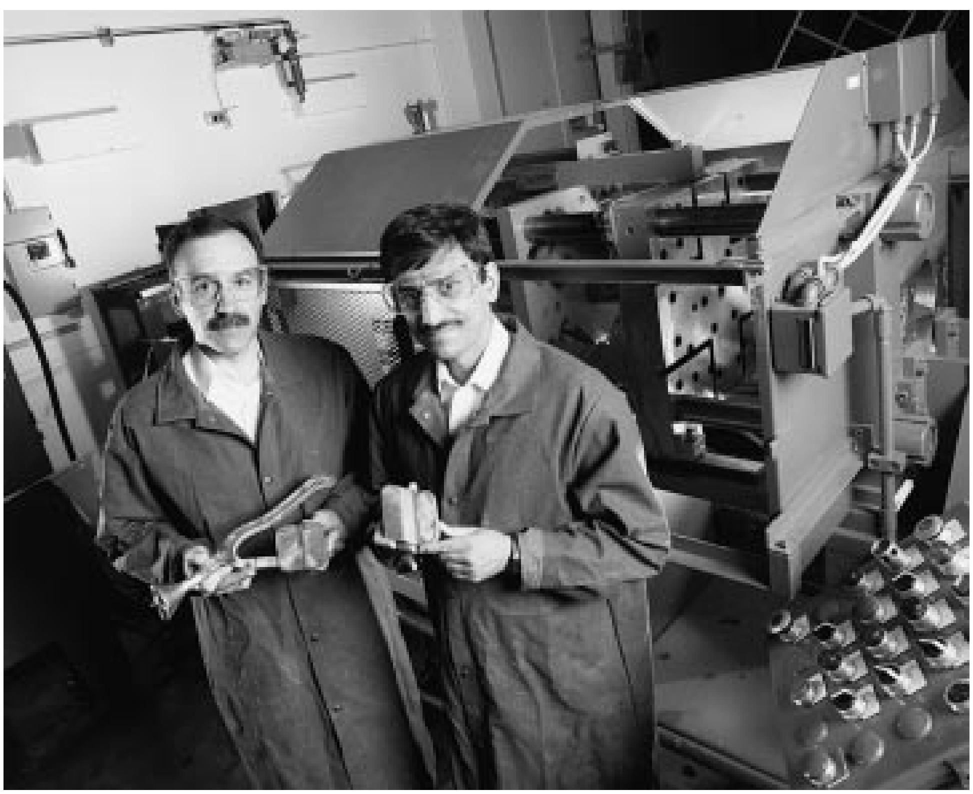

Fig. 2.15. Srinath Viswanathan, of ORNL's M&C Division (on right), and Robert Peurgert, Thompson Aluminum Casting Company, display examples of metal compression forming.

- systems integration and analyses;
- scale-up feasibility and demonstration; and
- data and information management.

The program involves research by universities, USDA, and industry collaborations. It is closely coordinated with research programs at NREL, which is developing new processes for converting plant biomass to fuels.

Though the primary focus has been transportation biofuels, biomass energy is expected to have its largest near-term use in the generation of electricity and the production of pulp fiber. ORNL works with DOE-EE's Offices of Transportation Technologies, Utility Technologies, and Industrial Technologies. Support to the Office of Utility Technologies involves collaborating with NREL, the Electric Power Research Institute (EPRI), individual utilities, and crop producers to evaluate the feasibility of co-firing biomass and coal, or of completely replacing coal feedstocks with biomass. Examples include a project with New York Gas and Electric and other collaborators in New York to investigate the production of willow for co-firing; a project with the Resource Conservation Development District in Iowa to produce switchgrass for co-firing; a project in Minnesota to produce alfalfa for high-protein animal feed and a gasifier feedstock; and a project in Alabama to produce switchgrass for co-firing. The BFDP has many collaborators in the fiber industry working with ORNL and university researchers to improve woody crop production for both fiber and energy. Under optimistic research, development, and demonstration (RD&D) assumptions, substantial amounts of energy crop biomass could be produced by 2015 at reasonable costs (Table 2.3) on farms of the future (Fig. 2.16).

Energy crop development has emphasized selection, characterization, and improvement through breeding and genetic studies. For the Pacific Northwest, Southeast, and North Central regions of the United States, hybrid poplars (a cross of *Populus deltoides* and *P. trichocarpa*) have been bred for increased yield, pest and disease resistance, and drought tolerance. Genetic research on poplars is being conducted by the University of Washington, Mississippi State University, Iowa State University, and the USDA Forest Service. Oregon State University is leading a poplar genetic transformation cooperative while research conducted by ORNL scientists is identifying the genetic and physiological control mechanisms for drought tolerance in hybrid poplars. Willow breeding and crop management research is being conducted by the State University of New York and the USDA Forest Service.

Switchgrass has been selected as the model herbaceous energy crop species. This productive, long-lived plant can be grown across most of the United States east of the driest regions of the Great Plains. Breeding is being conducted at four locations in the United States, and 5-year variety trials have been established in the South at 19 locations. Large-scale field trials began in 1997, with 220 acres planted in Alabama and 20 acres planted in Texas.

Table 2.3. Estimated crop yields, supplies, and costs for biomass energy under optimistic R&D and market assumptions

	Year 2000			Year 2015		
	Willow	Poplar	Switchgrass	Willow	Poplar	Switchgrass
Yield range, dry ton/acre/year	5.0–6.0	4.5–5.0	5.6–6.0	6.8–7.6	5.5–7.7	7.3–7.8
Cost, $/dry ton						
Minimum	*a*	*a*	34	27	33	32
Maximum	*a*	*a*	34	32	34	33
Supply, millions of tons	*a*	*a*	6	27	30	72

Source: Figures derived from unpublished 1997 modeling research of M. E. Walsh et al., Energy Division, ORNL.
[a] While willows and poplars were already being grown as of 1977, it would be impossible to establish new plantings of either for energy use by 2000. Thus, costs and supplies for energy were not estimated.

ORNL-DWG 97-3072 EFG

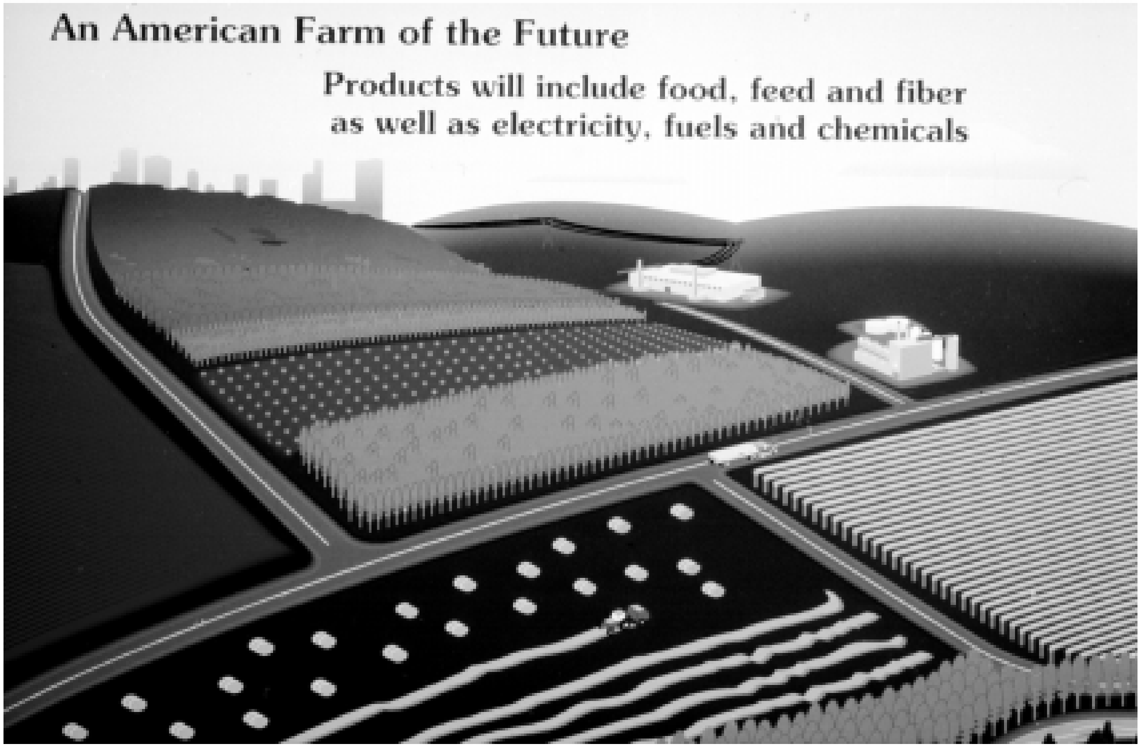

Fig. 2.16. An American farm of the future. Such a farm will supply traditional farm products as well as electricity, fuels, and chemicals.

The BFDP is concerned with environmental effects and the integration of energy crops into the fuel and farm economies. A 1995 study, co-sponsored by the Tennessee Valley Authority, determined the costs and environmental impacts of producing energy crops in the Tennessee Valley and surrounding region. Geographic information system tools are being used to evaluate potential supplies and environmental effects of growing energy crops in the Midwest and the South. Field studies are being conducted on biodiversity effects, nutrient runoff, erosion, and soil carbon changes in response to energy crop production.

2.4.3.2 Alternative fuels utilization

ORNL performs R&D on the implications of alternative fuel use for engines, ignition systems, and emission control systems. A CRADA was set up with General Motors–AC Delco Systems, in which catalysts for natural gas and alcohol fuels are emphasized along with conventional fuels. This R&D includes materials characterization, bench tests, and detailed measurements of catalyst performance on engine test stands. Figure 2.17 shows the catalyst research facilities available to researchers.

2.4.3.3 Bioreactors for alcohol fuel production

A new project uses a fluidized-bed bioreactor to continuously produce alcohols for transportation, separating them from the production by-products. The project staff have been working with industry, and both ethanol producers and suppliers of fermentation agents (enzymes and bacteria) have shown interest in the project. A project under consideration will investigate the conversion of wastepaper to ethanol.

2.4.3.4 Hydrogen production

Hydrogen holds great promise as a renewable, nonpolluting vehicle fuel. The PNGV initiative includes research on materials and infrastructure issues for hydrogen fuels. Current R&D on hydrogen production and storage is funded through DOE's Office of Utility Technologies (see Sect. 2.6.3).

ORNL-DWG 97-3073 EFG

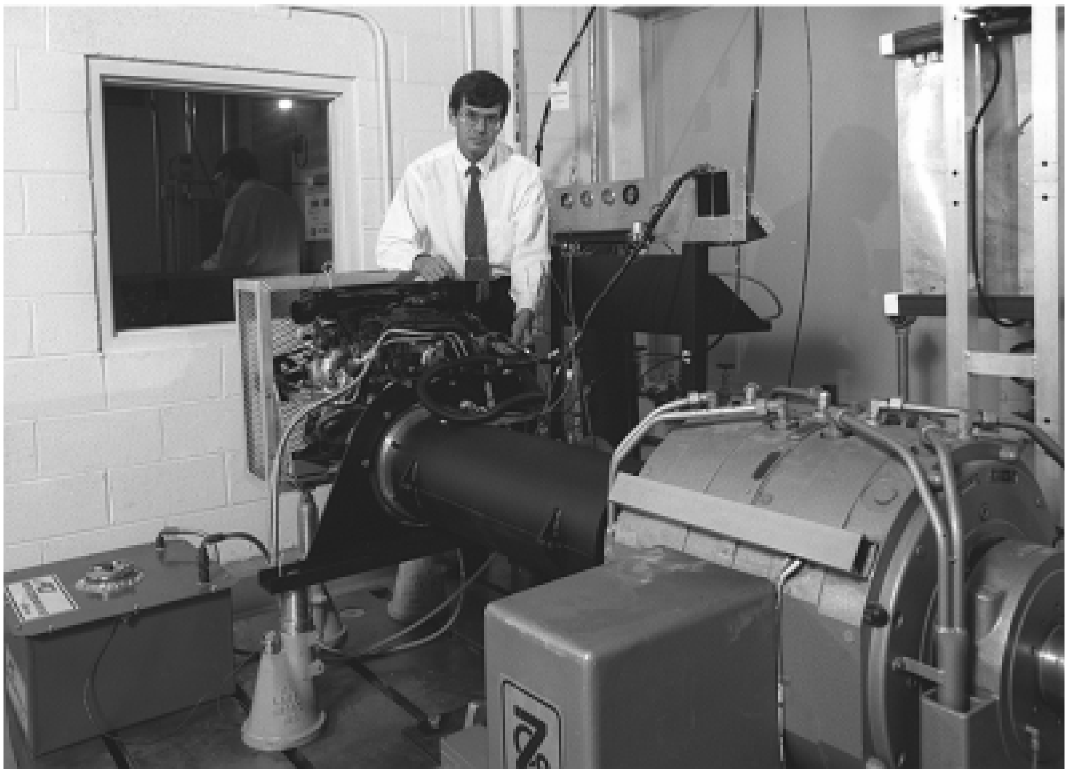

Fig. 2.17. The engine catalyst test facility, Oak Ridge Centers for Manufacturing Technology. The facility can perform automated and precisely controlled testing under steady-state conditions or programmed transient speed/torque profiles, emulating a Federal Test Procedure cycle for vehicles.

2.4.3.5 Cooling cars for less: liquid-overfeed heat exchange

ORNL scientists invented a heat-exchange device that increases the efficiency of automobile air conditioners by 20%, cuts fuel consumption, and could lengthen the life of the cooling unit. The improvement involves adding a simple, inexpensive heat-exchange device to existing designs. The device allows the coils in an air conditioner's evaporator to be "overfed" with liquid coolant, increasing cooling capacity. Any excess liquid coolant is rerouted back into the same heat exchanger for vaporization, protecting the unit's compressor and decreasing its workload, which lowers energy consumption.

The design is compatible with CFC replacements, and a CRADA is under way with DuPont to test the device with various refrigerants. If fully implemented in the U.S. auto industry, it could result in annual savings of 340 million gallons of fuel and cut CO_2 emissions by about 3 million metric tons.

2.4.4 Transportation Data and Policy Analysis

ORNL's Center for Transportation Analysis (CTA) provides support to the DOE-EE Office of Transportation Technologies through analysis of transportation data and energy use related to vehicle and engine research and development, fuel economy, sales and technology trends.

The *Transportation Energy Data Book*, available on the Web at www-cta.ornl.gov/Publications/ Tedb.html, is an annual compendium of statistics characterizing transportation activity and presents information on other factors that influence transportation energy use. For example, Fig. 2.18 shows trends in U.S. petroleum production, consumption, and transportation use over the past 20 years.

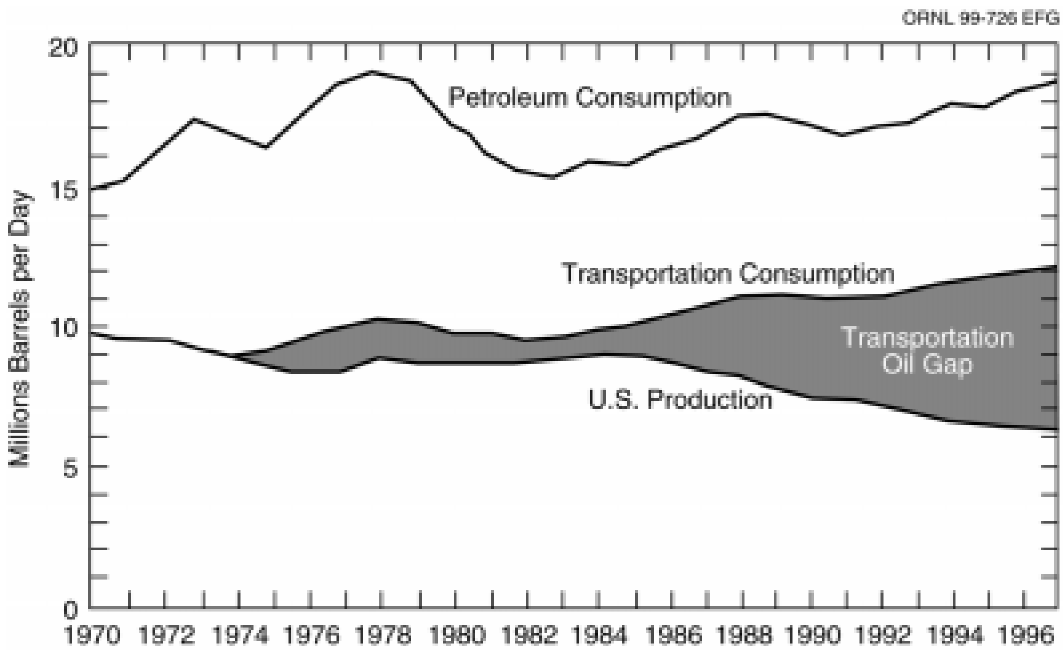

Fig. 2.18. U.S. petroleum production and consumption, 1973–1997.

ORNL also supports the DOE Office of Policy in collaborative efforts to analyze energy policy options related to increasing transportation energy efficiency and the introduction of alternative fuels into the marketplace. A recent study examined the relationship between urban travel and urban spatial structure, showing its importance to designing effective and sustainable vehicle travel reduction policies.

CTA staff have also found that substantial levels of telecommuting can provide a significant decrease in transportation-related petroleum use and emissions, despite offsetting effects such as increased urban sprawl (see Fig. 2.19).

CTA is supporting the Federal Highway Administration in development of intelligent transportation systems (ITS), which will exploit computer technologies and electronic communications to improve the efficiency, productivity, and safety of transportation facilities. CTA staff are

- developing a common location referencing system;
- implementing a prototypic, ORNL-designed Training Center for Advanced Transportation Management Systems—the “control centers” for ITS; and
- contributing to development of traffic simulation, estimation, and prediction models.

2.5 INDUSTRIAL TECHNOLOGIES

The industrial consumption of energy in the United States in 1994 was 33.7 quads—38% of the total energy use. Seven major industries provide materials for the U.S. manufacturing sector and in the process, consume about 27% of the nation’s energy. Table 2.4 shows manufacturing energy use in 1991 for these industries.

The DOE-EE Office of Industrial Technologies (OIT) has developed a strategy called “Industries of the Future” (IOF) to address the needs of the primary industries listed in Table 2.4 and of the agriculture sector. As of FY 1999, the mining industry is included as an IOF industry. ORNL assists in assessments of technology and materials needs for each industry and in development of technology road maps and contributes technological advances to the challenges identified in the assessment activities. Additional support for the IOF strategy and OIT is described in Sects. 2.5.1–2.5.3.

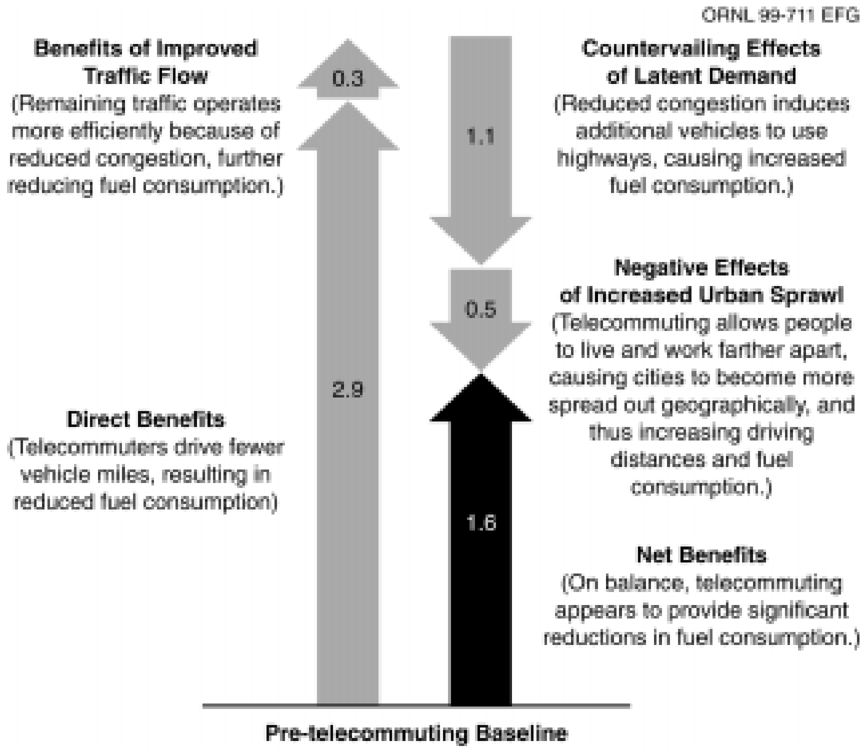

Fig. 2.19. Direct and indirect effects of telecommuting on fuel consumption under DOE "alternative" scenario, 2010. Numbers indicate billions of gallons of gasoline.

Table 2.4. Primary energy consumption by manufacturing, 1994

Industry	Energy use (quads)
Chemicals	5.3
Petroleum refining	6.3
Forest products	3.2
Glass	0.2
Aluminum	0.3
Metal casting	0.4
Steel	3.3
Other	2.7

Note: Primary energy consumption is defined as the consumption of energy that was originally produced off-site or was produced on-site from input materials not classed as energy (e.g., hydrogen produced by electrolysis of brine).

Source: Energy Information Administration (EIA), *Manufacturing Consumption of Energy, 1994*, DOE/EIA-0512(94), DOE EIA, Washington, D.C., December 1997, Table A1, pp. 29–38.

ORNL's goal in research for OIT is to assist U.S. industry in capturing and maintaining global market share through technological improvements. Technological advances from ORNL's work are contributing to improved industrial efficiency through decreased energy consumption, improved product quality, reduced equipment downtime, and decreased waste streams. As industry expenditures on nonproductive costs decrease, resources are made available for market expansion and investment in plant and capital equipment.

For example, ORNL is working with the pulp and paper industry to achieve goals set forth in Agenda 2020, the industry's vision statement. Research topics include developing materials for Kraft recovery boilers, using microwave energy to dry wood, genetic research that can help identify superior strains of trees, biochemical and genetic research to regulate tree growth, analysis of the environmental impacts of high-intensity forest management, and computer modeling of relationships between forest productivity and soil quality.

2.5.1 Advanced Materials and Manufacturing Technologies

The OIT Advanced Industrial Materials (AIM) Program supports the development of new and improved materials and manufacturing techniques leading to a more efficient use of energy in support of the IOF initiative. Work at ORNL focuses on three areas:

1. high-temperature intermetallic and metallic alloys with high ductility, corrosion resistance, and strength;
2. coatings and engineered porous materials; and
3. microwave technology (of interest because of its potential for producing materials with unique properties).

Ordered intermetallic alloys, produced through a cooperative project with the DOE-ER Office of Basic Energy Sciences, represent one of the most successful ORNL inventions resulting from the AIM Program. Among the most useful developments are nickel aluminides, which offer improved performance and savings for high-temperature applications such as forging dies, furnace fixtures, turbocharger rotors, and furnace rollers. ORNL's principal contributions have been in improving the alloy composition and manufacturing processes.

Microwave applications developed at ORNL include ceramic sintering, polymer curing, sterilization, and decontamination. The Vari-Wave™ microwave heating instrument developed by ORNL and Lambda Technologies represents a new concept in microwave ovens used in manufacturing. It dramatically reduces the curing time (from 2 hours to 3 minutes) of adhesives and polymers used in the production of circuit boards and components. It may also have applications in biomedical treatments and in waste remediation, where it could selectively destroy contaminants. The work was initiated through the ORNL Laboratory Directed R&D program and later funded jointly by the AIM Program and DOE-ER. Some of the current research is also funded by the Lightweight Materials Program within the Office of Advanced Automotive Technologies (part of DOE-EE's Office of Transportation Technologies; see Sect. 2.4) through a CRADA, investigating the Vari-Wave as an alternative process for making carbon fiber.

The failure mechanisms of Kraft boiler tubes are being studied in an effort to provide new and/or improved materials for this high-temperature and highly corrosive application. The AIM program is also identifying materials for improved refractories for the glass industry.

2.5.1.1 Continuous fiber ceramic composite

Continuous fiber ceramic composite (CFCC) processing methods are being developed in a program aimed at industrial applications. CFCCs offer stability at high temperatures, resistance to corrosion, and light weight. High-efficiency, high-temperature heat exchangers and gas turbines made with CFCCs could save U.S. industry as much as $2 billion per year in energy costs and reduce emissions. The program is being implemented through joint projects with industry. An example is the program with General Electric to develop Toughened Silcomp™, a product consisting of silicon carbide fibers in a matrix of silicon carbide and silicon made by a melt infiltration process, for use in land-based gas turbines.

2.5.1.2 Thermal sciences research

Thermal sciences research has the goal of expanding the knowledge base that will support efficient energy conversion and utilization in industry. Research on heat transfer processes led to an ORNL invention, the recuperative overfeeding heat exchanger, used in the automobile air conditioner described in Sect. 2.4.3.5. The thermal sciences group has also completed numerous analyses of a magnetic refrigeration cycle, supporting the successful testing of a prototype refrigerator (Fig. 2.20) by the Astronautics Corporation of America. Magnetic refrigeration may be especially useful for large-scale gas liquefaction and for cooling superconducting magnets.

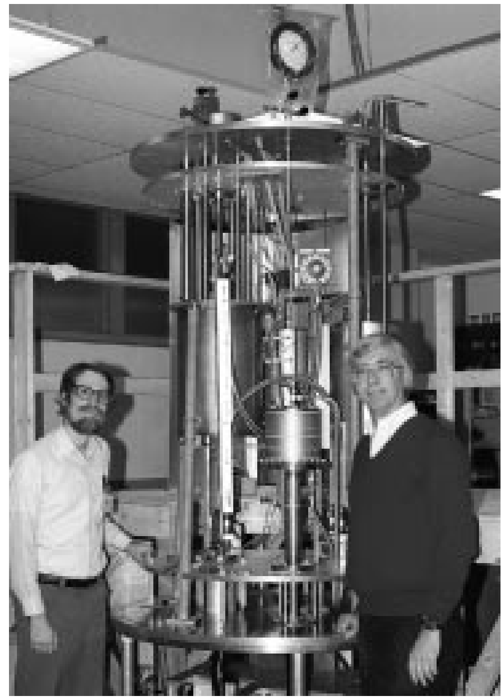

Fig. 2.20. Carl Zinn, Astronautics Corporation of America, and Richard Murphy, ORNL, with the magnetic refrigerator.

2.5.1.3 Alternative feedstocks for industry

More than 90% of the basic feedstocks now used in the production of nonenergy products by the U.S. chemical and refining industries originate from crude oil or natural gas. Work is under way to reduce this use of petroleum products as feedstocks by developing advanced bioprocessing concepts for the separation and processing of industrial chemicals. The focus is on using renewable resources (e.g., corn sugars, woody biomass, or even CO_2 or water) for the production of fuels and chemicals in aqueous, gaseous, and nonaqueous systems.

Much of ORNL's work is undertaken in the Bioprocessing R&D Center. The fluidized-bed bioreactor (FBR) process (see Fig. 2.21) is used to investigate the use of sugars from renewable feedstocks (plant materials and waste paper) as feedstocks for production of chemicals. Two sugars under investigation are ethanol from corn starch and lactic acid. The use of ethanol from corn starch is being studied by Fluor Daniel. Compared to present methods, the FBR approach could save $0.06 per gallon in a new plant owing to reduced downtime and lower capital and operating costs. Thirty million pounds of lactic acid are used each year in the production of food and plastics. The FBR process shows a fourfold increase over conventional methods in volumetric production of lactic acid.

ORNL-DWG 97-3078 EFG

Fig. 2.21. At ORNL's Bioprocessing R&D Center, researchers are exploring less-polluting ways to convert renewable feed-stocks such as cornstarch and wastepaper to chemicals and fuels.

Alternative feedstocks for chemical production are being investigated in a cooperative project involving ORNL's Chemical Technology Division, NREL, ANL, the Idaho National Engineering and Environmental Laboratory (INEEL), and PNNL. The Applied CarboChemicals Company and the Michigan Biotechnology Institute are collaborating with the multilaboratory team. The goal of this project is to displace petroleum with environmentally acceptable renewable feedstocks. The first target is the production of organic acids, particularly succinic acid. A new process developed by the team produces succinic acid by fermenting glucose sugar from corn. After separation and purification, the succinic acid is used as a chemical intermediate that is converted into chemical feedstocks used to make an assortment of products such as plastics, solvents, and fibers. This process will compete with petrochemical methods of production by providing a lower-cost means of obtaining commodity chemicals from renewable resources. Other industrial firms have contributed materials to the project; these include corn feedstocks from A. E. Staley and catalysts from Engelhardt.

2.5.1.4 Pulp and paper processing research

Pulp and paper processing research includes a number of projects involving ORNL and other institutions.

- ORNL is working with Bowater, Ahlstrom, and the Georgia Institute of Technology in investigating the thermal characteristics of the evaporative concentration of black liquors—a critical technology in the pulping process.
- In support of the advanced impulse drying process being developed by the Institute of Paper Science and Technology, ORNL is studying in situ water sensing techniques.
- An environmentally friendly, energy-saving technology for removing ink from waste newspapers (see Fig. 2.22) has been developed, using an enzyme cellulase to treat the fibers.

ORNL is also collaborating in a number of areas addressed by Agenda 2020, a partnership established by DOE and the American Forest and Paper Association as part of the forest products focus area of the IOF. These areas are

- biochemical and molecular regulation of crown architecture to optimize cultural methods and practices for maximum fiber production;
- development and validation of marker-aided selection methods for wood property traits in loblolly pine and hybrid poplars;
- model-based diagnosis of soil limitations in forest productivity, with identification of opportunities for improving soil quality and forest productivity;
- sustainability of high-intensity forest management, focusing on water quality and site nutrient reserves; and
- high-speed microwave treatment for rapid wood drying.

ORNL-DWG 97-3079 EFG

Fig. 2.22. The bioreactor used for separating inked from uninked fibers in old newspaper. Research findings show that the fibers can be separated based on fiber length distribution and strength.

2.5.2 Waste Reduction Technologies

ORNL has evaluated advanced heat exchangers for a number of companies to determine the corrosion resistance of ceramic heat exchanger tubes in a steam-methane reformer atmosphere and to analyze the use of these systems in industrial and hazardous waste incinerators by Babcock and Wilcox, Solar Turbines, and Stone and Webster Engineering Corporation.

Industrial heat pumps with "high-lift" capability are being developed to take industrial reject heat and deliver process heat at up to 260°C (500°F) and process cooling down to –50°C (-58°F). Field testing of prototypes is under way. This work builds on successful commercialization of two earlier concepts: the Brayton cycle solvent recovery heat pump and the ammonia sorber for evacuating refrigerator systems for maintenance. DOE estimates that efficiency improvements from such heat pumps can save up to 1.5 quads of energy ($4 billion at current energy prices) over a 15-year period. Working with ORNL, the Energy Concepts Company has developed and patented a fluid called Alkitrate™ that consists of alkali metal nitrate salts dissolved in water and has low corrosivity. Another company, Rocky Research, has developed a solid/vapor working medium using ammoniated salt compounds. These various working media candidates can be stable at up to 600°F and are generally nontoxic and inexpensive.

DOE's Advanced Turbine Systems Program (co-sponsored by OIT and DOE's Office of Fossil Energy) is aimed at developing ultrahigh-efficiency, clean, cost-competitive gas turbines for utility and industrial markets. ORNL coordinates the materials and manufacturing element of this initiative with the goal of developing materials and manufacturing techniques to withstand turbine inlet temperatures of over 1400°C. Specific performance targets include a system efficiency that will exceed 60% for large-scale utility turbine systems and a 15% decrease in power costs as well as reduced emissions for industrial turbines.

The primary technical issues to be addressed are coatings and process development, turbine airfoil development, ceramics development, single-crystal airfoil manufacturing technology, and materials characterization. A future thrust of this program will involve consideration of the increased utilization of biomass fuels for co-generation and dispersed electricity production.

Motors and drive systems are the backbone of U.S. industrial operations, with more than 40 million motors used for fluid handling and material processing and fabrication. They account for more than 70% of all electricity used by the industrial sector. The OIT Motor Challenge Program involves more than 230 organizations in fostering the development of more efficient electric motor systems. It is estimated that the Motor Challenge will reduce carbon emissions for the year 2000 by almost 10 million metric tons. ORNL supports showcase demonstrations of efficient motors and develops tools and protocols to assist in finding efficiency opportunities and validating the energy savings achieved. ORNL has also developed a computer program, called ORMEL, that can quickly and accurately determine the efficiency of a motor while it is in service.

Cellulosic waste minimization and bioconversion studies at ORNL are focused on modifying biocatalysts to allow economical use of waste paper in fuel and chemical production processes. Other types of lignocellulose that can be converted are municipal wastes, agricultural residues, and grasses.

2.5.3 Evaluation and Analysis

The Energy-Related Inventions Program (ERIP) provides small businesses and independent inventors with technical assessments of their inventions, grants, and education about commercialization. ORNL participates in ERIP by quantifying the program's energy, economic, and environmental impacts. ORNL's most recent ERIP evaluation investigated such questions as the commercial progress of ERIP inventions and spin-off technologies; employment, tax-revenue, and exports effects; energy savings; and environmental benefits. This evaluation indicates that the program has had significant impacts:

- commercialization of at least 129 ERIP technologies, a 23% commercialization rate;
- $763 million (1992 dollars) in sales generated by these 129 technologies through 1992;
- $18.6 million (1992 dollars) for licensed sales of ERIP technologies through 1992;
- an additional $63 million in sales generated by 36 spin-off technologies;
- for every ERIP grant dollar, $2.01 raised by inventors after receipt of the ERIP grant;
- 688 full-time-equivalent jobs directly supported by ERIP technologies in 1992;

- $2.7 million in ERIP-related individual income tax revenues returned to the U.S. Treasury in 1992;
- $531 million (1992 dollars) of energy expenditures saved by three ERIP technologies;
- reduction of carbon emissions by almost 1 million metric tons as the result of three ERIP technologies.

2.6 UTILITY TECHNOLOGIES

Just as coal powered the industrial revolution, so electricity is powering the information era. Electricity production accounted for 37% of the primary energy in the United States in 1993. Given the likelihood of continued growth in the demand for electricity, the nation is faced with ensuring that electricity is delivered efficiently and reliably and that cost-effective renewable resource options are available.

ORNL provides field management (including assistance in engineering and analytical studies and technical support for planning and decision-making) for two programs within DOE's Office of Utility Technologies: electromagnetic field (EMF) effects and high-temperature superconductivity. ORNL also conducts research on hydrogen production, environmental mitigation at hydropower facilities, the effects of electric utility deregulation on the utility industry and consumers, and the physical chemistry of geothermal systems. ORNL studies geothermal heat pumps (see Sect. 2.3.4) to determine their energy, economic, and environmental benefits and participates in international programs coordinated by the International Energy Agency (IEA) that support the development of export markets for energy technologies.

2.6.1 Power Systems Technologies

2.6.1.1 Earlier work

ORNL has previously worked with the DOE power marketing agencies, EPRI, and other interested parties on ways to improve electric systems capacity, flexibility, and efficiency while maintaining high system reliability. The program resulted in the development of real-time control, high-capacity transmission options, and technologies for improving the understanding of transient phenomena and dielectric materials characteristics. ORNL has also provided technical support to groups such as the North American Electric Reliability Council and the Secretary of Energy Advisory Board Task Force on Electric System Reliability, and has studied the need for special services to ensure system reliability in an open, competitive marketplace.

2.6.1.2 EMF effects

ORNL continues to examine the possible health effects of EMFs, a subject of concern to the public. The National Electromagnetic Field Research and Public Information Dissemination (RAPID) Program was established as part of the Energy Policy Act of 1992. This multiagency effort is led by the National Institute of Environmental Health Sciences (NIEHS) and DOE, which has designated ORNL as its lead laboratory for the program. Two booklets addressing common questions and concerns about EMF effects have been published; one is intended to inform the general public; the other addresses workers and workplace concerns. Replication experiments to investigate reported effects of EMF are under way at ORNL, PNNL, the Food and Drug Administration (FDA), and the National Institute for Occupational Safety and Health (NIOSH) facilities. A working group is synthesizing the data and working with NIEHS to prepare a report to be delivered to Congress.

2.6.1.3 High-efficiency electric power inverters

High-efficiency electric power inverters are valuable in many applications, such as electric-hybrid vehicles and any device that uses electricity to power equipment (pumps, fans, compressors, motors, etc.). A lightweight, efficient, reliable dc-to-ac inverter developed in ORNL's Engineering Technology Division (see

Fig. 2.23) has the potential to provide annual savings of $160 million from electric power applications alone. Researchers have also developed advanced, low-cost converter configurations and assessed silicon carbide components for high-voltage, high-current solid-state switches for DOE's Power Systems Program.

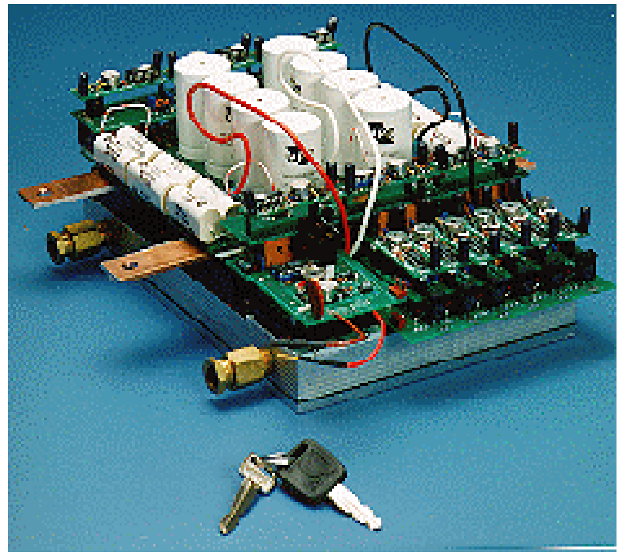

Fig. 2.23. The compact, reliable, lightweight soft-switching inverter developed at ORNL.

2.6.2 Superconductivity Program for Electric Power

DOE's Superconductivity Program for Electric Power is a comprehensive, integrated approach to the development of high-temperature superconducting (HTS) technology for cost-effective use in electric power applications. Estimates of energy savings from the wide application of HTS systems in the United States range from 1 to 2 quads per year. Program activities fall into two categories: basic research on wire and systems technologies and applied research in the Superconductivity Partnership Initiative. ORNL contributes to both areas, including important studies of the mechanisms for current flow in the conductors. The discovery of a "local order of grains," resulting in long-range percolative paths for current flow through a network of small-angle grain boundaries at colony intersections, provides a working model for the microstructure of practical polycrystalline wires.

Powder-in-tube conductors are the most commonly used HTS conductors. ORNL conducts research to improve the "flux pinning" in these conductors, through participation in the Wire Development Group led by American Superconductor Corporation (ASC). ORNL is also working to develop a surface-coated-type bismuth-strontium-calcium-copper oxide (BSCCO) superconducting wire in partnership with ACS.

The performance of coated yttrium-barium-copper oxide (YBCO) conductors is superior to that of BSCCO conductors for applications at higher magnetic fields and liquid nitrogen–level temperatures. Good superconducting performance requires depositing a YBCO film on a textured substrate, which acts as a template for the production of the optimum grain alignment. ORNL has developed techniques for texturing the metal substrates by a rolling and annealing process, followed by deposition of one or more epitaxial buffer layers. The resultant template is described as a rolling-assisted, biaxially textured substrate (RABiTS). Current densities in the superconductor of more than 1 MA/cm^2 have been achieved in short samples. Figure 2.24 shows the current density of YBCO/RABiTS wire at varying magnetic fields.

The principal goals of the ongoing program are to derive precommercial products from RABiTS-based superconducting wires by increasing the conductor length, increasing the engineering current density, and refining deposition techniques. ORNL is collaborating with 3M Company, Southwire Company, Oxford Superconducting Technology, MicroCoating Technologies, EURUS, and ASC on aspects of YBCO wire development. The 3M/Southwire CRADA also includes Los Alamos National Laboratory as a partner.

Applications for HTS components are numerous:

- Motors and generators can be more efficient and lighter.
- Transformers can be more efficient and nonflammable, have lower environmental impact, and be lighter and more fault-tolerant than conventional transformers.
- Transmission and distribution cables can operate at higher current density with lower loss than conventional cables.
- Inductive fault-current controllers will provide increased power system stability, safety, and operate with higher voltage and current capacity than present systems.
- HTS current leads reduce heat losses in low-temperature superconducting applications.

Today, the two main applications projects involving ORNL are conducted under DOE's Superconductivity Partnership Initiatives. ORNL is contributing to the design, production, and testing of a 5-MVA, 13.8-kV, 25-K BSCCO HTS transformer in collaboration with Waukesha Electric Systems, Intermagnetics General Corporation, and Rochester Gas and Electric Corporation, with operation planned in 2000. ORNL is also working with Southwire Company, which is building a 30-m-long three-phase, 13.8-kV, 1250-A cryogenic HTS dielectric cable, to be installed at Southwire's manufacturing plant by the year 2000. A prototype 5-m-long cable system was operational in 1998 (see Fig. 2.25).

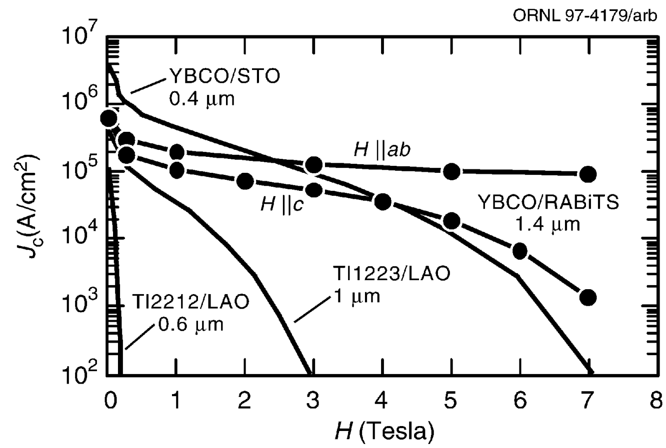

Fig. 2.24. Magnetic field dependence of high current density (J_c) YBCO/RABiTS and other HTS materials at liquid nitrogen temperature.

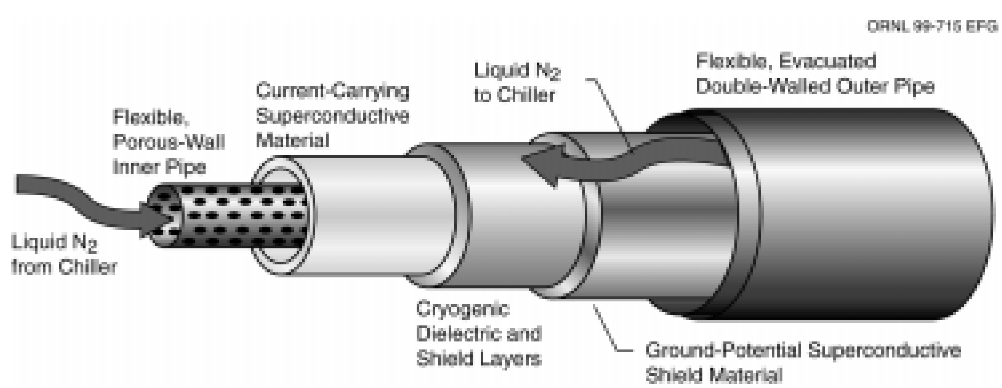

Fig. 2.25. High-temperature superconducting cable section.

2.6.3 Hydrogen Production

Hydrogen as a fuel has three times the energy content of gasoline on an equivalent mass basis. When used as a fuel in a fuel-cell-powered car, it can provide two to three times the energy conversion efficiency of conventional gasoline-fueled, internal combustion engine vehicles. Hydrogen vehicles are benign environmentally, to the extent that the production of the hydrogen is benign. Projects for the DOE-EE Office of Utility Technologies are helping to advance the feasibility of hydrogen as a fuel.

- Investigations of photosynthetic water splitting by algae as a renewable source of elemental hydrogen led to an exciting observation: an alga that performs photosynthesis with only Photosystem II, whereas photosynthesis has been generally assumed to require both Photosystems I and II (see Fig. 2.26). This doubles the theoretical efficiency of hydrogen production.
- ORNL designed a conceptual hydrogen fuel dispensing station. Technical and economic assessments were performed on the infrastructure for such systems, to be used in the evaluation of a demonstration facility.
- An investigation of advanced thermal management technologies for hydrogen storage is under way. The objectives are to develop a heat transfer model to describe hydrogen absorption in fullerenes; to characterize the thermomechanical behavior of the dynamic storage process; and to design practical configurations to thermally manage hydrogen absorption-desorption devices.

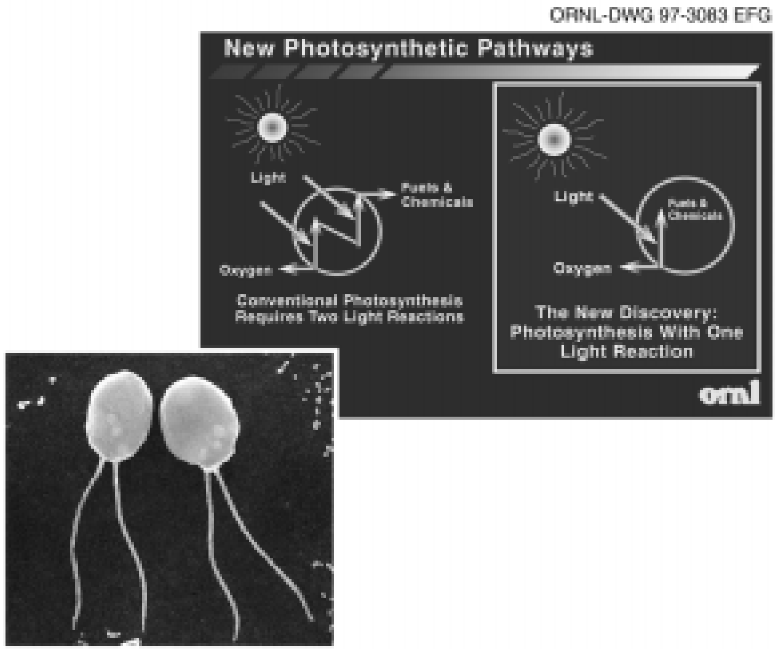

Fig. 2.26. ORNL researchers studying production of renewable hydrogen discovered a new photosynthetic pathway.

- A project to investigate the use of biocatalytic systems to generate hydrogen gas from cellulose, if successful, will provide a method for the biological production of hydrogen from renewable resources, while generating gluconic acid, a commodity chemical, as a by-product.
- In a CRADA with DCH Technology, an ORNL-developed hydrogen sensor is being developed for specific market applications related to the hydrogen economy. The sensor will greatly improve the viability of hydrogen as an energy source by providing the capability to detect and pinpoint hydrogen leaks in production, storage, transport, and utilization.

2.6.4 Renewable Energy Conversion and Environmental Impacts

ORNL provides technical and analytical support to the DOE Office of Utility Technologies in the areas of geothermal energy, biomass energy, hydroelectric power, and other renewables. The Laboratory also supports the DOE Advanced Hydropower Turbine Initiative on ways to improve existing facilities. Since 1978, ORNL has been the lead environmental research and analysis facility for DOE's hydropower program, investigating environmental mitigation practices, fish-bypass systems, environmentally friendly turbines, and the effects of dissolved oxygen in water released from turbines.

2.6.5 Electric Industry Policy Studies

Researchers in ORNL's Energy Division are working with regulators in eight states to support decision-making on electric industry restructuring issues. These issues include the effects of competitive markets on producers and consumers, the integration of transition-cost recovery mechanisms in restructuring plans, and the effects of market power on market operation. Other work related to industry restructuring includes developing tools to simulate the operation of competitive markets for provision of generator-related ancillary services; collecting data on the use of two ancillary services, voltage support and operating reserves; and examining the future of the industry's public obligations in a restructured industry. The researchers are also working with the Ohio Public Utilities Commission in a joint project to examine the effects of alternative ways to reduce electricity-related carbon emissions, and supporting the DOE Task Force on Electric System Reliability.

2.6.6 Support for IEA Programs

Environmentally sound energy technologies represent a major international need and constitute one of the biggest emerging export opportunities for U.S. industry. In total, the world market for renewable energy technologies is estimated at $150 billion annually. The market for energy efficiency goods and services is estimated to be $84 billion annually. These markets offer numerous opportunities for the creation of new U.S. businesses and jobs. By participating in activities of IEA, DOE is able to publicize the availability of U.S. technology solutions that might help both developing and developed countries meet their energy, economic, and environmental goals.

ORNL manages and supports the U.S. involvement in a number of the IEA implementing agreements by providing executive committee members, national team leaders, and operating agents.

- The Greenhouse Gas Technology Information Exchange (GREENTIE) is an intergovernmental information center involving 39 member countries. It was established in 1993 by IEA and the Organization for Economic Cooperation and Development. Its objectives are to identify greenhouse gas mitigation technologies that have a potential for international deployment and to publicize their availability to decision-makers and potential users. GREENTIE's primary product, issued from its center in the Netherlands, is a directory of information about suppliers of products and services for reducing greenhouse gas emissions. GREENTIE Liaison Offices in member countries have the local knowledge needed to identify information sources for greenhouse gas mitigation technologies. They are also on hand to distribute GREENTIE's products and to help users make effective use of GREENTIE's facilities. ORNL serves as the U.S. liaison office.
- The Center for the Analysis and Dissemination of Demonstrated Energy Technologies (CADDET) was formed in 1988 to collect and disseminate information on demonstrated energy-efficient technologies. A key goal is to contribute to an international effort to reduce the adverse environmental impacts of fossil fuel consumption through energy conservation. At the heart of the operation is a computerized register of almost 1700 energy technology demonstration projects, including 358 from the United States. Analysis reports, which compare the technical and economic results of selected projects, are sent quarterly to more than 10,000 subscribers.
- The IEA Heat Pump Program involves R&D and demonstration of heat pumping technologies. ORNL's BTC provides technical and administrative support and chairs the U.S. national team, which is composed of representatives from ORNL, DOE, and the U.S. heat pump industry. The U.S. national team is the designated operating agent for a collaborative project on the thermophysical properties of environmentally acceptable refrigerants. Project goals include providing a reliable source of information on refrigerant properties; determining internationally accepted analysis tools such as equations of state; and enabling better equipment design with environmentally acceptable refrigerants.

2.6.7 Support for International Initiatives

For a decade and a half, ORNL has been developing a base of knowledge and experience with energy and environmental collaboration in developing countries and emerging economies. Since 1982, the Laboratory has led more than 60 projects in more than 30 countries in Africa, Asia, Eastern Europe and the Former Soviet Union, Latin America and the Caribbean, and the Middle East—many of them in association with U.S. and endogenous private-sector firms.

2.6.8 Hydropower

Since 1978, ORNL has had the lead in environmental research and analysis for DOE's hydropower program. Hydropower produces 10% of the nation's total electricity, avoiding substantial greenhouse gas emissions. However, relicensing and other regulatory pressures, and real and perceived environmental effects, are reducing energy production and could lead to a loss of 1000 MW of capacity by 2005. ORNL, in partnership with INEEL and DOE's Idaho Operations Office, has conducted R&D for more than 20 years to address these problems. Current work includes

- a major study of environmental mitigation practices by the hydropower industry, which has included a 1994 report on mechanisms to allow fish to bypass dams;
- designs for turbines that are less damaging to fish; and
- research on population-level effects on fish for DOE, EPRI, and the Pacific Gas and Electric Company through CRADAs.

3

Fission Energy Programs

Nuclear power contributes more than 20% of the electrical energy in the United States and 17% of the world's electricity. It is a major contributor to the decarbonization of energy use and can be important in reducing the predicted effects of global warming.

In recent years, the U.S. government has shifted the emphasis of its nuclear R&D programs from the development of new reactor concepts to a focus on ensuring the safety of operating plants and on certification of advanced reactors for the next generation of commercial plants. This shift has been driven by economic competition among energy sources and by public concerns about nuclear safety arising from the accidents at Chernobyl and Three Mile Island. Related issues about the disposition of surplus nuclear weapons material and plutonium from power reactors also require attention.

ORNL has played a prominent role in nuclear power technology since the 1940s, and its programs in this area have evolved to meet the needs of DOE, NRC, and other sponsors. ORNL's history, experience base, and facilities provide it with the resources to continue as a major contributor to a variety of programs in fission energy.

3.1 HISTORY

ORNL has a long and distinguished history in the nuclear area. The X-10 Graphite Reactor, which began operating in 1943, was the world's first continuously operated fission reactor. The naval reactor program, which led to the development of the pressurized water reactor, was conceived at ORNL in 1946 in conjunction with the Clinton Training School (later the Oak Ridge School of Reactor Technology). Reactors were built at ORNL for R&D on a number of applications, such as electricity production, isotope production, ship and aircraft propulsion, and desalination of sea water. These reactors included the Bulk Shielding Reactor (1950), the ORNL "Swimming Pool Reactor" (showcased at the United Nations "Atoms for Peace" Conference in 1955), the Oak Ridge Research Reactor (1958), the Health Physics Research Reactor (1962), the High Flux Isotope Reactor (HFIR) (1965), and the Molten Salt Reactor Experiment (1965). Only HFIR remains in operation today; it is now being upgraded to enhance its capabilities for neutron science and isotope production.

To support the needs of the fission program, ORNL initiated studies of the effects of neutron irradiation on materials in 1946. Beginning in the early 1950s, work in the Laboratory's Solid State Division revealed the magnitude of radiation-induced changes, which include the displacement of atoms and transmutations with the production of helium and hydrogen. Large increases in funding, starting in the 1970s, supported efforts by the ORNL Metals and Ceramics Division to understand the physical mechanisms that underlie radiation effects for both fission and fusion reactors.

Building on its wartime work in synthesizing and extracting plutonium, ORNL designed and developed two widely used extraction processes: PUREX (for plutonium and uranium extraction at the Savannah River and Hanford sites) and THOREX (for separating thorium, protactinium, and ^{233}U from fission products and each other). This work laid the foundations for nuclear fuel processing throughout the world.

In 1961, ORNL began the development of isotope heat sources for remote applications, including space. This program continues to be a significant part of ORNL's fission portfolio. The Radiation Shielding

Information Center was established in 1962 to to provide in-depth coverage of the radiation transport field; now known as the Radiation Safety Information Computational Center, it collects, organizes, evaluates, and disseminates technical information on shielding and protection from radiation associated with fission and fusion reactors and other sources.

AEC initiated the Heavy Section Steel Technology program at ORNL in 1966 as a key part of its reactor safety research. The program addressed safety and aging aspects of reactor pressure vessels (RPVs). Other projects initiated by the AEC, and later by NRC, addressed reactor systems and components such as piping, pumps, valves, vessel internals, and instrumentation and control (I&C). Reports were prepared to document ORNL's assessments of the status of component and structures technology.[1] Most of this work has been conducted by ORNL's Engineering Technology, Metals and Ceramics, and Instrumentation and Controls Divisions. The products of these programs have been incorporated into regulatory guides, standard review plans, and national consensus codes and standards.

By the end of the 1960s, 20% of the Laboratory's reactor budget was devoted to nuclear safety. Expertise in this area was applied during the 1970s as ORNL became a center for exploring the safety, environmental, and waste disposal challenges of nuclear energy. Researchers operated a nuclear safety pilot plant to test fission product release and fuel transport and a mock-up facility to test fuel bundles for fast breeder reactor and a heat transfer facility to test the behavior of fuel elements during a loss-of-coolant situation. ORNL also devised filters to contain radioactive iodine that might be released in an accident and participated in the design of auxiliary cooling systems for reactors to prevent meltdown.

Since the accidents at Chernobyl and Three Mile Island, NRC and the nuclear industry have placed major emphasis on understanding and modeling core melt phenomena and on developing methods to prevent or mitigate the effects of hypothetical severe accidents. This has led to the development of methods and computer codes for probabilistic risk analysis (PRA), and these in turn are being incorporated into risk-informed approaches to reactor regulation. There are several landmark publications in this area.

Since the 1970s, ORNL has played an important role in the evolution of regulations for fission reactors by maintaining and analyzing large databases of reactor operational data, including all Licensee Event Reports (LERs) required by NRC. Analyses conducted by ORNL have included root cause and PRA assessments to provide an understanding of the severity of events, with a focus on identifying accident sequence precursors.

3.2 OVERVIEW OF CURRENT PROGRAMS

Funding for ORNL R&D in the nuclear area comes from several sources, including DOE, NRC, the Department of Defense (DOD), and industry. EPRI supports projects on reactor I&C, and the Defense Special Weapons Agency funds projects on international reactor safety and proliferation risk. Collaborative activities are extensive and involve other national laboratories, universities, and other nations (e.g., England, France, Germany, Japan, Korea, Russia, Switzerland, Sweden, Ukraine). In 1997, the total budget for work in the nuclear area was about $34 million ($14 million for NRC work and $20 million for DOE and other sponsors).

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[1] Examples of such reports are G. D. Whitman et al., *Technology of Steel Pressure Vessels for Water-Cooled Nuclear Reactors,* ORNL-NSIC-21, ORNL Nuclear Safety Information Center, Union Carbide Corp., Oak Ridge, Tenn., December 1967; and W. B. Cottrell and A. W. Savolainen, *U.S. Reactor Containment Technology,* ORNL-NSIC-5, Vols. 1–2, ORNL Nuclear Safety Information Center, Union Carbide Corp., Oak Ridge, Tenn., August 1965.

3.3 NUCLEAR PROGRAMS FOR DOE AND OTHER SPONSORS

Budgets for fission R&D in recent years are shown in Fig. 3.1. The program involves work on radioisotope power systems, MOX reactor fuels, reactor I&C, international reactor safety and proliferation issues, and robotics for reactor D&D. ORNL also plans to carry out work in support of DOE's Nuclear Energy Research Initiative.

3.3.1 Radioisotope Power Systems

During the last two decades, ORNL has developed materials to meet the severe normal and off-normal requirements of radioisotope power systems for National Aeronautics and Space Administration (NASA) and DOD missions. As part of this effort, ORNL has developed unique, highly efficient manufacturing processes, evaluated the performance of materials, and produced materials for specific missions. Deep space missions that have used ORNL power systems include Voyager 1, Voyager 2, Galileo, Ulysses, and Cassini. Production for the Cassini mission includes carbon-bonded carbon fiber insulators (shown in Fig. 3.2), iridium alloy blanks and foil, and iridium alloy–clad vent sets. The iridium alloy–clad vent sets are used to encapsulate the ^{238}Pu fuel, and the insulators ensure that the iridium alloy remains at a suitable temperature in normal and off-normal conditions.

Continuous improvement in product and manufacturing processes has led to better materials and improved production yields that have substantially lowered production costs. Clad vent sets for the Cassini mission were produced by the Oak Ridge Y-12 Plant under ORNL guidance; the production capability has since been moved to ORNL. This program also developed the ultrasonic technique employed at Los Alamos National Laboratory for inspecting the critical girth weld on the fuel clad. Recently, ORNL developed a new iridium alloy that appears to perform as well as the one used for Cassini but with the advantage of reduced thorium content. Bare rolling of iridium sheet products, which promises higher production yields, has been developed, and bare forming of iridium alloy cups holds the promise of further reducing production costs.

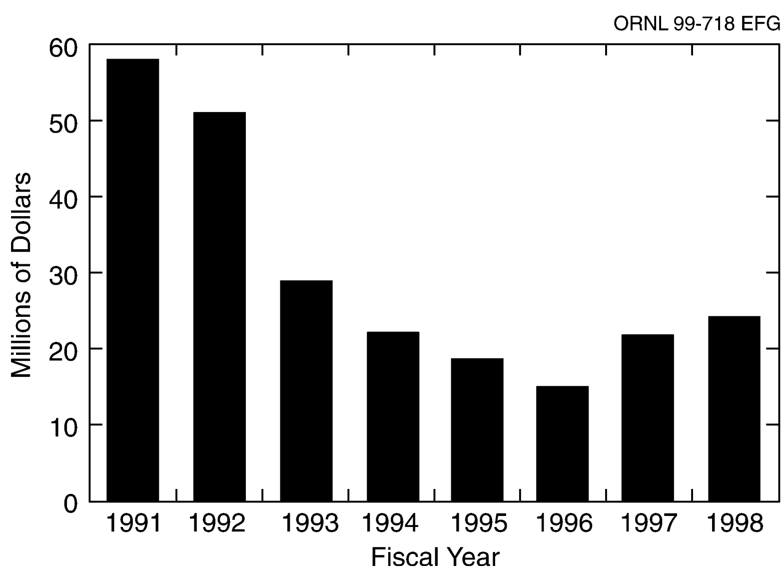

Fig. 3.1. DOE and DOD fission budgets (new BA) for FY 1991–FY 1998.

ORNL has supported DOE requests by proposing additional work on radioisotope power systems. A particularly promising match between envisioned DOE needs and ORNL facilities and infrastructure is the production of a few kilograms of ^{238}Pu each year for space exploration needs. ORNL could use HFIR in conjunction with the Advanced Test Reactor at INEEL to irradiate ^{237}Np targets to produce ^{238}Pu. The target feed material would be stored at ORNL, and the targets would be fabricated and processed in ORNL's Radiochemical Engineering

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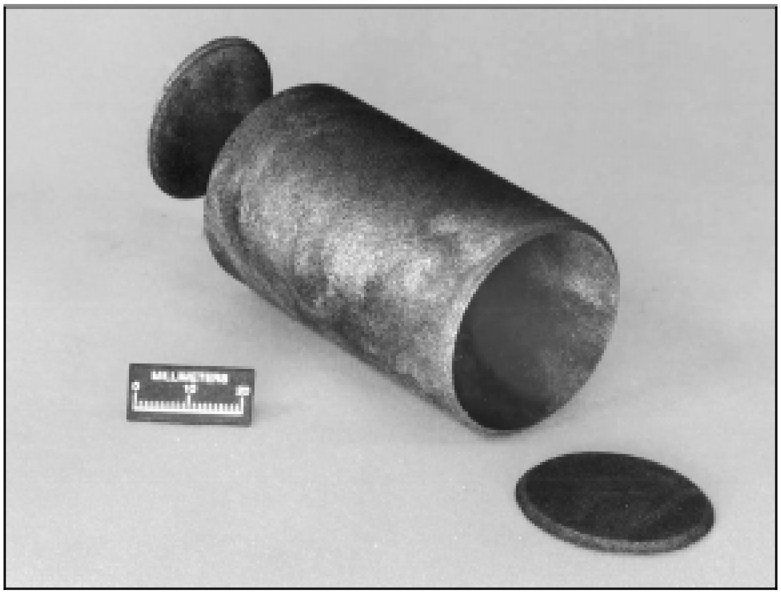

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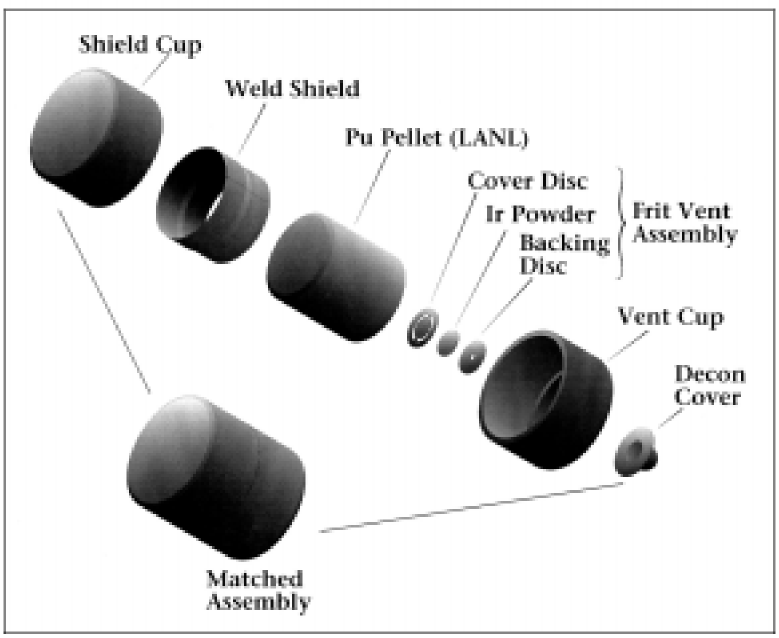

Fig. 3.2. ORNL products for NASA's Cassini mission. *Top,* carbon-bonded carbon fiber insulator sleeve and discs for radioisotope power systems; *bottom,* expanded view of iridium alloy clad vent set.

Development Center (REDC), shown in Fig. 3.3. Chemical processing of irradiated targets would be conducted in hot cells, and targets would be fabricated in a glove box facility near the hot cells.

In addition, ORNL has proposed relocation of assembly and testing activities from the Mound Plant in Ohio to ORNL. If ORNL is selected for this effort, an existing nuclear facility in the Metals and Ceramics Division would be used for the assembly, testing, and handling of radioisotope power systems. Following modification of the facility, glove box, and other enclosed chambers would be installed for assembly operations in controlled environments. Equipment would be installed for various evaluation tests, including vibration resistance, magnetic field generation, and center of gravity.

DOE is preparing an EIS for each of the two potential projects described above, and final decisions are expected in late 1999.

3.3.2 Fissile Materials Disposition

The end of the Cold War created a legacy of surplus fissile materials (primarily weapons-grade plutonium and highly enriched uranium) in the United States and the former Soviet Union. These materials pose a danger to national and international security. During the past few years, the United States and Russia have entered into a series of agreements aimed at securing and safely storing fissile material stockpiles. In September 1998, the two countries announced that each country will dispose of 50 metric tons of surplus weapons-grade plutonium. The United States is pursuing a dual-track approach to rendering the plutonium inaccessible for use in nuclear weapons. One track involves immobilizing the plutonium by combining it with high-level radioactive waste

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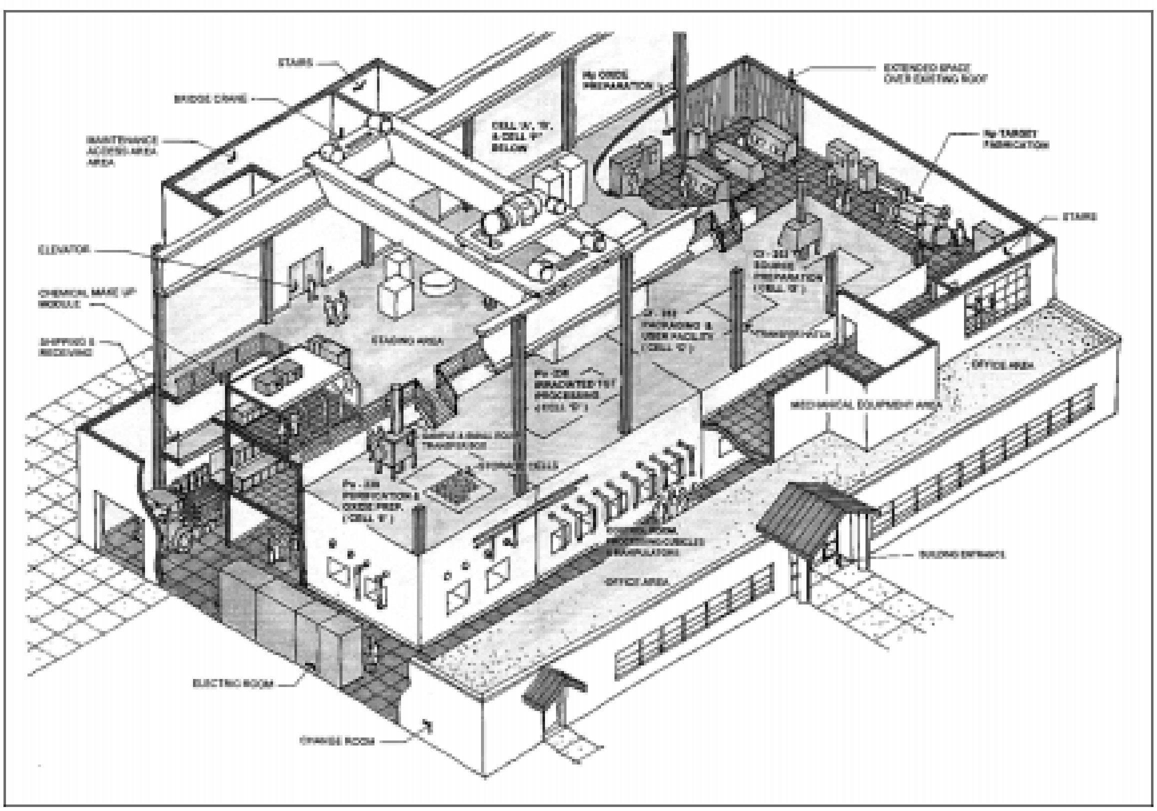

Fig. 3.3. Artist's rendition of the ORNL Radiochemical Engineering Development Center (Building 7930).

in glass or ceramic "logs." The other method, the MOX, or reactor-based, disposition option, converts plutonium into fuel for commercial nuclear reactors. ORNL is DOE's lead laboratory for this reactor-based disposition under the direction and sponsorship of DOE-MD.

Research is under way at ORNL to define, develop, and demonstrate technologies required for implementation of the U.S. MOX disposition option. A key ORNL responsibility is the design and execution of MOX fuel irradiation tests, including the post-irradiation examination of irradiated test fuels at the ORNL Irradiated Fuels Examination Laboratory. Other ORNL roles include evaluation of the neutronic, thermal-hydraulic, and safety implications of the use of weapons-grade MOX in commercial power reactors; the identification and evaluation of power reactor fuel cycles that provide the technical, economic, and strategic flexibility necessary to execute the plutonium disposition campaign; and the design and certification of shipping containers necessary for shipment of fresh MOX fuel. In addition to these activities, ORNL provides staff that advise DOE on both technical and economic issues related to the procurement of a commercial provider of MOX fuel fabrication and light-water reactor (LWR) services.

ORNL is the lead U.S. laboratory in the joint U.S./Russian program to evaluate and develop reactor-based plutonium disposition options and strategies for Russia. ORNL works closely with five Russian research institutes, as well as industrial nuclear fuel cycle entities, nuclear power plant owner/operators, and Russian nuclear safety regulators, on the joint program. ORNL and its Russian partners seek to develop, demonstrate, and license the technologies and facilities required to implement plutonium disposition on three types of reactors: VVER-1000 LWRs, the Russian BN-600 fast reactor, and Canadian deuterium-uranium (CANDU) heavy-water reactors. These activities include evaluation and development of the conversion and purification methods for weapons plutonium; the validation of neutronics, physics, and thermal-hydraulic computational codes; the design and testing of MOX fuels; evaluations of reactor modifications required to accommodate MOX fuel; and the overall economics of plutonium disposal in Russia.

Finally, ORNL is DOE's lead laboratory for ^{233}U disposition. ORNL's responsibilities include the evaluation and development of technologies and options for safe disposition of the U.S. inventory of this material, much of which is currently stored at ORNL.

ORNL receives about $12 to 14 million per year to conduct its technical activities in the Fissile Materials Disposition program. Additional information about ORNL's involvement in the program can be found at http://www.ornl.gov/fmdp.

3.3.3 Reactor Instrumentation and Controls

ORNL has extensive capabilities for developing advanced I&C systems. These capabilities, acquired to support past DOE activities in research reactor development and advanced reactor R&D, are now in demand by industry. In the past few years, ORNL has developed improved control algorithms for overall process control in Babcock & Wilcox commercial power reactors. This work led to an assignment from Duke Power Company to review the design requirements for a new integrated plant control system for Oconee Unit 3, which is based on the ORNL control algorithms, and to provide recommendations for ensuring high reliability of the installed system.

In 1995, ORNL received an R&D 100 award for development of an electromagnetic interference / radio-frequency interference (EMI/RFI) measurement system that is being used to establish the ambient noise fields in nuclear plants. This information is being used by U.S. utilities and NRC to develop criteria for the electrical noise resistance of new digital systems being installed in nuclear plants.

Westinghouse and EPRI have funded a project at ORNL to provide replacement modules for Westinghouse-designed nuclear power plants. The work draws on an ORNL proposal, made several years ago, to use application-specific integrated circuits (ASICs) as a cost-effective means of replacing obsolete analog protection systems in U.S. nuclear plants. This technology could extend the service life of at least 30 nuclear plants with a total capacity of 20,000 MW.

ORNL is also working with EPRI to develop a hydrogen monitor for nuclear plant containment areas. This palladium-based sensor has been tested for hydrogen concentrations between 0.5% and 30% in air. The sensor is being tested for survivability under the postulated post-accident temperature and steam conditions in a reactor containment.

3.3.4 Characterization and Hazard Assessment of World Nuclear Facilities

In 1994, to address a Department of Defense (DOD) need for estimating potential threats to both military and civilian populations resulting from military or terrorist strikes against world nuclear facilities, ORNL initiated a broad range of interrelated activities that have led to products now used throughout DOD for military planning, post-event analysis, and emergency response. The first product, developed with other commercial contractors, was a forward-deployed computer code named HASCAL that calculates the atmospheric dispersion of radiological material as a result of accidents or military incidents at any of the world nuclear facilities (existing commercial and research reactors, enrichment facilities, reprocessing facilities, etc.). ORNL's primary initial contributions in the development of HASCAL were

- development of a complete database of default isotopic inventories at these world facilities and corresponding models for updating the database using known or assumed operating conditions;
- development of health-related data, primarily radiological dose factors, for more than 1100 nuclides that might be dispersed;
- development of atmospheric source terms for ranges of accident and/or incidents for each nuclear facility type; and
- creation of graphical user interfaces for specific user profiles.

The commercial developers were responsible for weather data and models, the atmospheric transport model, nuclear weapon effects models, and overall system integration. Over the last few years the code has been continually upgraded by ORNL and others to include the capability to assess atmospheric dispersions of chemical and biological materials as well as additional dispersal scenarios for radiological sources. The code and related data are now distributed under the name HPAC.

In addition to the ongoing development of HPAC in the areas mentioned above, ORNL is also developing additional capabilities for use in planning, post-event analysis, and emergency response:

- development of nuclear facility vulnerability data based on analysis and experiments to quantify incident (as opposed to accident) fault trees and consequences;
- development of a water transport model for eventual incorporation into HPAC;
- development of a world population database at a 30" × 30" resolution based on integration of various types of satellite data;
- development of a fine-scale worldwide land-cover database for use in HPAC; and
- development of platform-independent, client-server, web-based architectures for HPAC and other DOD products.

This effort has been sponsored by the Defense Threat Reduction Agency (formerly the Defense Special Weapons Agency and before that the Defense Nuclear Agency). HPAC is currently used in all military command centers throughout the world and has been used during the Bosnian conflict, the Atlanta Olympics, the Presidential Inauguration, and studies of Gulf War illness.

3.3.5 Advanced Technologies for Decontamination and Decommissioning

ORNL has led the Robotics Technology Development Program sponsored by DOE's Office of Environmental Management (DOE-EM) since 1993. The robotics and remote operations technologies developed for D&D of DOE-owned nuclear facilities are being applied to several DOE-EM projects, including the recovery of fissile materials from the Molten Salt Reactor Experiment at ORNL, the disassembly of the CP-5 reactor at Argonne National Laboratory, and the decontamination of the ORNL gunite tanks, which contain sludge from spent fuel wastes. Under an agreement between DOE-NE and the Nuclear Power Engineering Corporation (NUPEC) of Japan, ORNL is developing for NUPEC a mobile automated characterization system (MACS) for surveys of floor contamination. The existing ORNL MACS, which has been demonstrated in the CP-5 reactor, is being used to test the NUPEC detector system and will be replicated and adapted to a Japanese specification for NUPEC use. NUPEC will use its MACS to perform contamination surveys at the shut-down Tokai-Mura gas-cooled reactor and later apply it to LWRs. NUPEC has expressed long-term interest in collaborating on other projects, including wall surveys and dismantlement. ORNL will also participate in the Chernobyl Shelter Project in support of PNNL and DOE-NE.

3.3.6 Nuclear Energy R&D

DOE's FY 1999 budget request includes $19 million for a Nuclear Energy Research Initiative (NERI) to address key issues affecting the future of nuclear energy and to preserve the nation's leadership in nuclear science and technology. The objectives of NERI are to develop advanced concepts and achieve scientific breakthroughs in nuclear fission technology that will further enhance nuclear energy as a safe, environmentally sound, and cost-effective means of meeting the world's growing need for electric power; to facilitate the transfer of technology developed for defense-related activities to address technology challenges in the civilian sector; and to encourage international cooperation in addressing nuclear technology issues. ORNL expects to participate in the NERI in the following areas:

- proliferation-resistant reactor and fuel technologies;
- reactors with higher performance and efficiency;
- materials, chemical, computational, and engineering sciences;
- systems and component design development;
- advanced lower-power reactor designs and applications;
- advanced nuclear fuels and fuel systems development;
- advanced instrumentation, controls, and diagnostics; and
- new technologies for nuclear wastes.

3.4 NRC PROGRAMS

Under the terms of a DOE-NRC Memorandum of Understanding established in 1978, ORNL supports NRC in nuclear safety, safeguards, and environmental protection activities by providing analyses and data used in establishing the technical bases for licensing and other regulatory actions and decisions. More than 50 projects are carried out by staff from nine ORNL divisions and two organizations within Lockheed Martin Energy Systems (which manages and operates the Oak Ridge Y-12 Plant for DOE). These projects support all of the major NRC offices. Recent budgets are shown in Fig. 3.4. The major technical emphases of the work

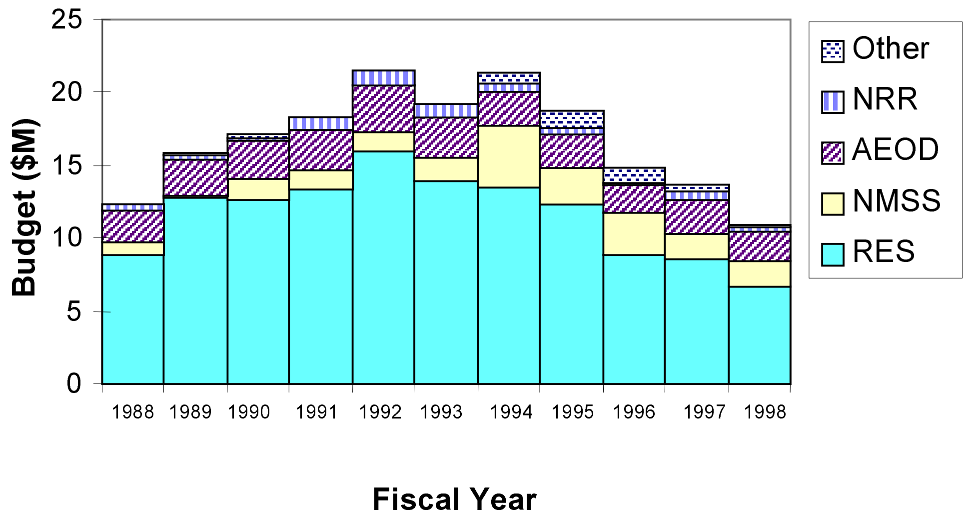

Fig. 3.4. Annual ORNL budgets by NRC office. Data for FY 1998 are estimates.

at ORNL are RPV integrity, aging of power plant components (see Fig. 3.5), severe accident analysis and code development, data analysis and evaluation, and nuclear materials safety and safeguards support.

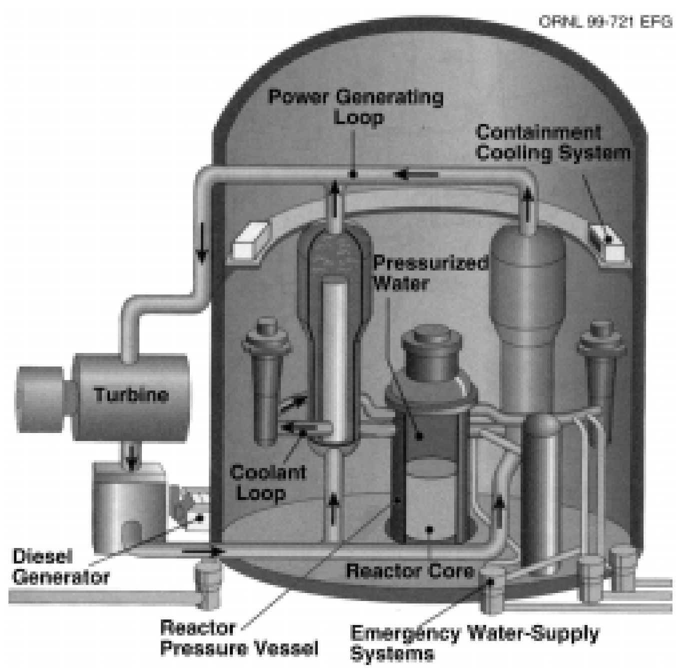

Fig. 3.5. Structures, systems, and components examined in ORNL programs for NRC.

3.4.1 Office of Nuclear Regulatory Research

The NRC Office of Nuclear Regulatory Research is responsible for research, standards development, and the resolution of safety issues for nuclear power plants and other facilities regulated by NRC. ORNL support to this office includes research in several areas: RPV integrity (irradiation embrittlement, fracture mechanics assessment methodology, pressurized thermal-shock assessments, annealing studies, etc.), nuclear plant aging and license renewal issues, severe accident modeling and analysis, I&C technology, and technology supporting advanced reactor certification. ORNL is a leader in the development and application of fracture mechanics technology for nuclear RPVs, in radiation experiments and embrittlement assessments, in boiling-water reactor (BWR) core melt progression analysis, in testing techniques to assess component aging, and in microstructural examination methods. Some of this work is carried out in collaboration with other

DOE laboratories and with researchers in other countries. Figure 3.6 shows a test machine and segments of the RPV from a canceled nuclear plant, from which fracture specimens are fabricated. Experiments are designed to examine prototypical RPV materials, specimen thickness, and loading conditions (e.g., multiaxial strains).

3.4.2 Office of Analysis and Evaluation of Operational Data

The NRC Office of Analysis and Evaluation of Operational Data manages the review, analysis, and evaluation of reactor safety performance and serves as the center for the continuing independent assessment of operational event data. Major ORNL research areas for this office include the review, analysis, and evaluation of operating reactor safety performance data for both U.S. reactors and those in other nations, and assessments of procedures and software tools used by response personnel in the event of a nuclear accident. Major activities are the Sequence Coding Search System (SCSS) database of Licensee Event Report (LER) data, which applies a system for reducing descriptive text in the LERs to coded sequences, and the Accident Sequence Precursor (ASP) program, which evaluates commercial nuclear plant operational data from a risk standpoint.

3.4.3 Office of Nuclear Materials Safety and Safeguards

The NRC Office of Nuclear Materials Safety and Safeguards is responsible for establishing and administering regulations for nuclear materials and ensuring that public health and safety are not endangered by medical and industrial uses of radionuclides. ORNL research areas for this office include criticality safety, shielding and thermal analyses of nuclear fuel facilities and cask designs, environmental review of licensee facilities, review of terminated materials handling license files, and the assessment of regulatory needs and tools for material protection, control, and accountability (MPC&A).

3.4.4 Office of Nuclear Reactor Regulation

The NRC Office of Nuclear Reactor Regulation is responsible for developing, issuing, and enforcing regulations for the safe operation of the nation's commercial nuclear power and research reactors and for assessing applications to construct and operate new reactors. ORNL provides technical assistance to this office in the areas of fuel stability analyses, economic analyses, component assessments, reviews of safety-related systems, nuclear plant license renewal issues, and nuclear reactor licensing actions relative to design basis and severe reactor accident source terms, fission product chemistry, iodine evolution and pH control, and analyses of nuclear plant safety in the event of loss of off-site power.

ORNL 99-719 EFG

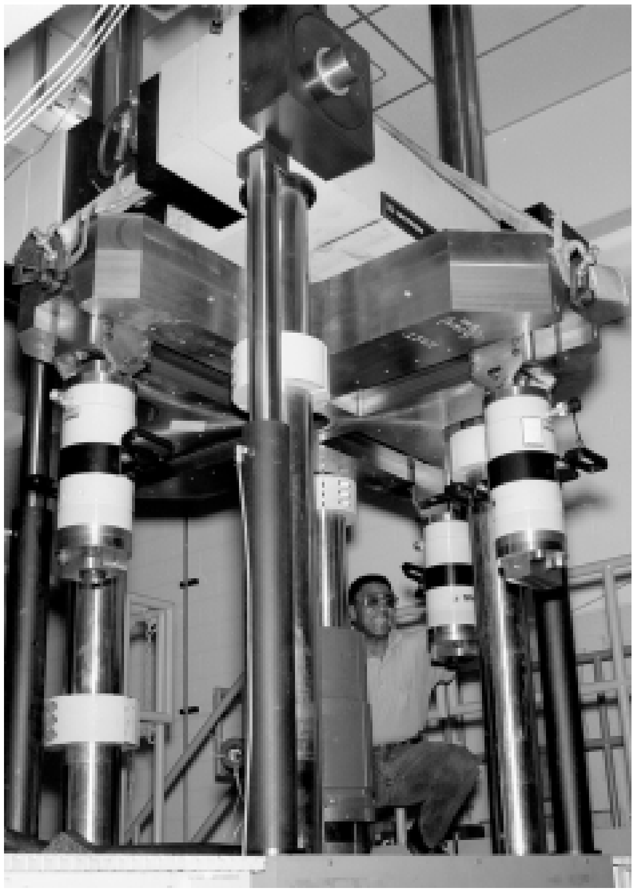

Fig. 3.6. Fracture Testing Laboratory (*top*) and specimens for testing (*right*).

ORNL 99-720 EFG

4

Fossil Energy Programs

Fossil fuels dominate the energy market of the United States and the world, accounting for 7000 Mtoe of the world's energy use of 9000 Mtoe per year. Consequently, improvements in the production and use of fossil fuels are of fundamental importance in energy R&D.

4.1 HISTORY

The ORNL Coal Technology Program was organized in 1974. It was succeeded by the ORNL Fossil Energy Program, which today integrates fossil energy–related work performed by ORNL and work performed by others with funding from ORNL.

In the mid-1970s, ORNL began fundamental studies of the structure of coal and investigated the carcinogenic properties of coal conversion products, the use of bacteria to remove nitrates and trace metals, oil synthesis, sulfur removal, fluidized-bed coal reactors, and the effects of strip mining.

ORNL also worked in the materials area with direct liquefaction pilot plants in Wilsonville, Alabama, and Fort Lewis, Washington, from 1975 through 1978. After the major liquefaction projects were assigned to the DOE Oak Ridge Operations Office (DOE-ORO) in 1979, ORNL's materials activities broadened to include materials testing and analysis at the H-Coal Pilot Plant and the Exxon Donor Solvent Pilot Plant; review of materials selections for the solvent refined coal (SRC) demonstration plant projects, SRC-I and SRC-II; and in-house R&D on problems in direct liquefaction technology.

In 1980, as a result of the unique breadth and strength of ORNL's materials capabilities, ORNL and DOE-ORO were given lead responsibility for DOE-FE materials activities carried out by the Fossil Energy AR&TD Materials Program. This program became the principal materials research program of the ORNL Fossil Energy Program, which conducted R&D on materials for fossil energy applications. The focus of this research was on the longer-term needs for materials with general applicability to the various fossil fuel technologies. ORNL's involvement in the materials area further increased in 1982, when ORNL and DOE-ORO assumed technical management responsibility for the Surface Gasification Materials Program.

Through a succession of solid achievements in the management of national fossil energy activities, the conduct of in-house R&D on priority fossil energy technology needs, and the integration of activities with strong in-house fundamental materials research, ORNL has gained national recognition as a leader in the fossil energy materials area.

Another major step in the development of the ORNL Fossil Energy Program occurred in 1976, when DOE-FE assigned to ORNL the responsibility for preparing all of its demonstration plant environmental impact statements (EISs) through the Fossil Energy Environmental Project. Sustained funding in this area from 1976 through 1981 resulted in pioneering, definitive work on characterization and disposal of coal conversion solid waste and in the preparation of an environmental monitoring handbook for demonstration plant subcontractors, a generic pipeline gas environmental assessment, and the EISs for six coal conversion demonstration plants. Three of the EISs (for SRC-I, SRC-II, and the Memphis Light, Gas, and Water gasification project) were taken to completion. In executing these activities, the ORNL Fossil Energy Program staff gained complete familiarity with national and state environmental regulations. The staff also developed a thorough understanding of the environmental impacts associated with various coal conversion technologies, the database underlying these assessments, the strengths and weaknesses of the assessment methodologies, and areas requiring further R&D to reduce uncertainties in environmental impact to acceptable levels.

Combustion research in the fluidized-bed combustion (FBC) area began in 1977 with program planning assistance to DOE-FE for a utility-oriented atmospheric FBC (AFBC) demonstration project. This work, the results of which were published in 1979, provided ORNL with a thorough understanding of the status of the AFBC technology development and priority R&D needs. Also in 1977, ORNL began work on an industrially oriented AFBC concept based on cogeneration. The concept, known as the atmospheric fluidized-bed coal combustor for cogeneration, received early recognition from industry. In 1979, ORNL began an examination of possible FBC cycle configurations, ranging from conventional AFBC systems to pressurized FBC (PFBC) systems with combustor pressures as high as 16 atm. A consistent theme in this work was the optimal use of the technological building blocks (combustor, turbine, etc.) that make up a given FBC cycle. The work led to two important conclusions: (1) unwarranted emphasis had been placed on the use of high turbine inlet temperatures, and (2) it was possible to devise new FBC cycles with thermal performance equivalent to that of known cycles that placed lower demands on advanced turbine performance. In addition, ORNL identified FBC cycles with performance superior to those previously recognized.

The Strategic Petroleum Reserve (SPR), established in 1975, supports a U.S. government policy of storing up to one billion barrels of crude oil and petroleum products to reduce U.S. vulnerability to the effects of disruptions in petroleum supplies. In 1987, ORNL began work to support DOE in the analysis of issues relating to the planning, management, and operation of the SPR.

ORNL has studied the value of expanding SPR, as well as the amount and timing of crude oil drawdowns during projected oil market disruptions. Three models that address these issues from different perspectives have been developed, applied, and documented. The Teisberg model, a stochastic dynamic programming model, computes “optimal” rates of SPR crude oil acquisition and drawdown. The Hogan-Leiby approach uses a dynamic model of the world oil market within a risk analysis framework. The DIS-Risk model is a probabilistic simulation model with a different market characterization; it follows the approach used in a 1990 DOE/Interagency study of SPR size, for which ORNL provided analytical support. ORNL also provided analytical support to DOE in its study of alternative financing mechanisms for the SPR and has examined the relative benefits and costs of different options for withdrawing and distributing SPR crude oil.

In the late 1980s, ORNL began research on bioconversion, investigating the use of microorganisms to convert organic materials, sewage, solid wastes, woody biomass, corn, and coal into fuels. Bioprocessing research continued in the early 1990s with the initiation of work on advanced bioreactor concepts and on the use of biological catalysts in organic media. In 1993, ORNL directed additional effort to the development of a new generation of gas-phase bioreactors, combining continuous operation, high cell densities, and efficient substrate mass transport.

4.2 OVERVIEW OF CURRENT PROGRAMS

ORNL’s activities in fossil energy R&D, performed primarily for DOE-OFE, focus on coal, clean coal technology, gas, petroleum, and support to the SPR. The main activities, which are conducted in several ORNL divisions, are materials R&D, EAS, bioprocessing research, combustion research, and fuel supply analysis and modeling. Recent program budgets are shown in Fig. 4.1.

The coal activities include materials R&D, EAS, bioprocessing of coal to produce liquid or gaseous fuels, and coal combustion research. ORNL’s work in gas technologies supports the Advanced Turbine Systems Program, primarily in the areas of materials and manufacturing. Activities contributing to petroleum technologies include the development of computational tools for seismic analysis and the use of bioconversion for removing impurities from heavy oils.

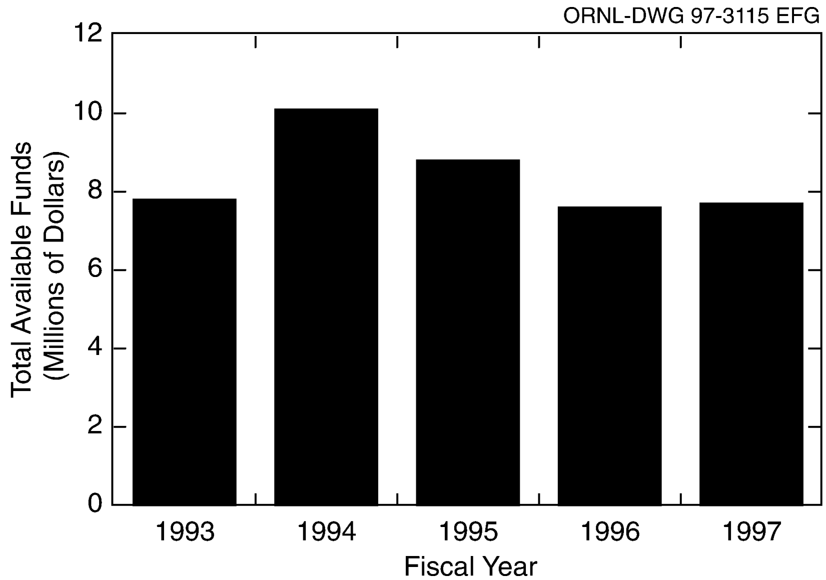

Fig. 4.1. Total funds (new BA) for the Fossil Energy Program, FY 1993–FY 1997.

A major part of the ORNL Fossil Energy Program is the technical management of all activities for the DOE-FE AR&TD Materials Program, which includes research at other DOE and government laboratories, at universities, and in industrial organizations. This research is aimed at providing a better understanding of the behavior of materials in fossil energy environments and at developing new materials that can provide substantial improvements in plant operations and reliability. The program addresses materials requirements for all fossil energy systems, including materials for coal preparation, coal liquefaction, coal gasification, heat engines and heat recovery, combustion systems, and fuels cells. DOE-ORO and ORNL have joint management responsibility for this national program.

4.3 MATERIALS R&D

The principal development efforts in fossil energy materials R&D are directed toward

- ceramic composites for high-temperature applications;
- new alloys with unique mechanical properties for advanced fossil energy systems;
- functional materials, such as ceramic and metal filters, inorganic membranes, and activated carbon materials; and
- corrosion research to understand the behavior of materials in coal-processing environments.

The program has the following goals:

- Develop fiber-reinforced ceramic composites and ceramic membranes for high-temperature and hostile environments.
- Fabricate carbon fiber composite molecular sieves and inorganic membranes for hydrogen separation from synthesis gas and for separation of CO_2 and H_2S from natural gas.

- Modify existing alloys to produce advanced austenitic alloys for use in FBC and pulverized-coal combustion power plants.
- Develop intermetallic alloys, primarily iron aluminides, for applications that require superior oxidation and sulfidation resistance and strength.
- Perform corrosion research on the formation and breakdown of protective oxide scales, particularly in sulfur-containing atmospheres.
- Develop and demonstrate the efficacy of porous materials technology as a low-cost fabrication process for the production of air electrodes for the tubular solid oxide fuel cell produced by Westinghouse Electric Corporation.
- Evaluate the potential performance of iron aluminide porous metal fillers in advanced PFBC and integrated gasification combined cycle (IGCC) environments.
- Develop, in coordination with Pall Corporation, porous sintered iron aluminide filters for removing hot particles from product streams in coal gasification systems.
- Investigate the treatment of petroleum, coal- and petroleum-derived products, and effluent streams for the removal of sulfur, nitrogen, and other contaminants.

The materials R&D program has been a very successful area for ORNL, with a number of notable accomplishments over the years.

- A modified silicon carbide fiber interface coating has been developed for Nicalon (silicon-carbon-oxygen) fiber/silicon carbide matrix composites. This coating allows the composites to survive for at least 1000 h in stressed oxidation at 950°C under a load of 175 MPa. Composites containing unprotected fibers or fibers coated with other interface materials typically fail much sooner (after several minutes to a few hours) and at much lower loads.
- Composite hot-gas filters (see Fig. 4.2) developed in collaboration with the 3M Company are in commercial use in the United States, Europe, and Asia. Evaluations of these filters in a variety of PFBC and gasifier systems, containing ten to several hundred filters, show good performance in most systems up to 750°C.
- An adsorption-based separation process, called electrical swing adsorption, shows promise for the separation of CO_2 and H_2S from CH_4. The process uses the unique properties of ORNL's carbon fiber composite molecular sieve material. Several patent applications have been filed, and numerous industrial interactions are in progress.
- In collaboration with researchers at Boston University, ORNL has developed mullite coatings applied via chemical vapor deposition (CVD) to protect SiC and Si_3N_4 materials from hot corrosion. Preliminary testing in a hot corrosion burner at

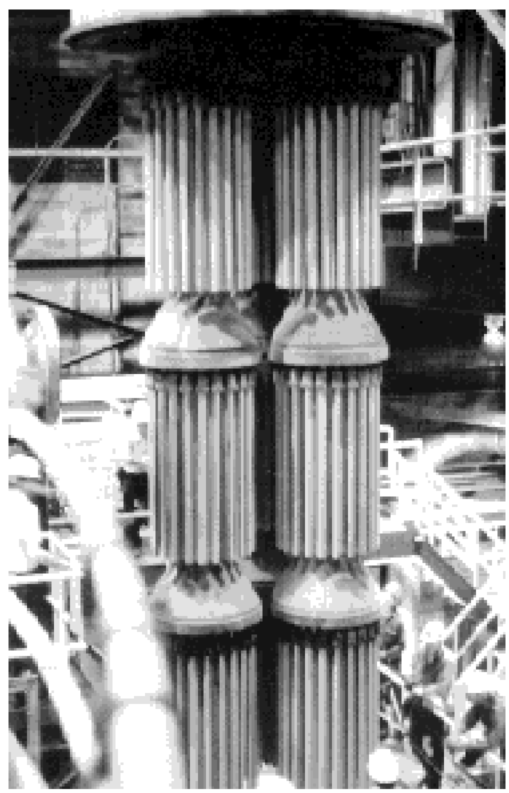

Fig. 4.2. Ceramic filters in a combined-cycle power plant. (Photograph courtesy of Westinghouse Electric Corporation.)

AlliedSignal Engines in Phoenix indicated that the CVD mullite coatings outperformed all previously investigated coatings.

- In a CRADA with Dow Corning, ORNL is assessing high-temperature particulate filter materials and systems for two applications in the production of dimethyldichlorosilane, a precursor for producing silicone-containing products.
- The creep strength of certain iron aluminide alloys has been significantly improved by controlling their microstructure with heat treatments. This strengthening is attributed to the pinning of dislocations by small zirconium-based precipitates and vacancy loops that form as a result of the rapid quenching.
- ORNL has developed an iron-sheathed, aluminum-core composite filler material for welding and cladding with iron aluminide alloys. The wire is commercially available in a range of compositions and can be used with either the gas metal arc or the gas tungsten arc process.
- Two-phase Cr_2Nb-Cr alloys for high-temperature use, fabricated by hot extrusion at 1480°C, showed excellent strength at 1200°C.
- An electron concentration and phase stability diagram for Cr_2Nb-based transition-metal Laves phases has been constructed and experimentally verified. This diagram is useful for design of Laves phase alloys with controlled crystal structures.
- ORNL has demonstrated a glass glazing technique for sealing a tubular alumina membrane to metal tubing. The seal will withstand thermal cycling to 600°C, permitting membranes to be sealed in a test system so that their separative performance can be measured at high temperature.
- A unique mixed gas test system has been developed to measure the separation efficiency of ceramic membranes with mixed gases at temperatures up to 600°C.
- ORNL-developed 9Cr-1MoV tubing has been subjected to 140,000 h of operation in the TVA Kingston Unit 5 superheater, where it replaced 321 stainless steel. Upon removal, the tubing was in excellent condition with virtually no change in its tensile strength or ductility.

Seven R&D 100 awards have been presented to ORNL for research accomplishments in fossil energy materials R&D.

The transfer of technology developed through this program is enhanced through interactions and joint research programs with more than 50 companies. An iron aluminide filter developed by ORNL and Pall Corporation is shown in Fig. 4.3. AMETEK Specialty Metals Division produced the powder used to fabricate the filters. Some examples of collaborative programs are listed in Table 4.1.

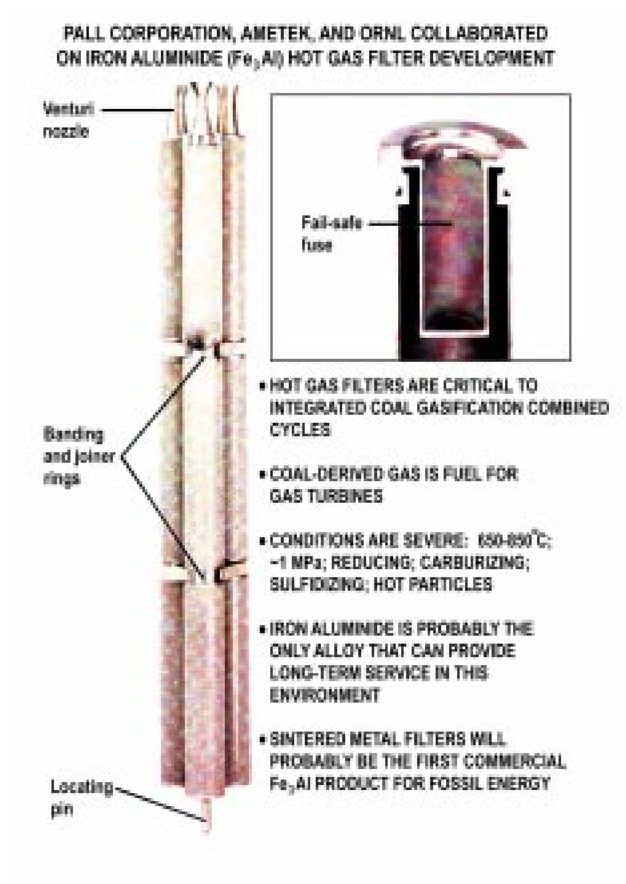

Fig. 4.3. Iron aluminide (Fe_3Al) hot gas filter developed by ORNL and Pall Corporation.

Table 4.1. Examples of fossil energy R&D interactions with industry

Company	Technical area
Pall Filters	Technical backup for application of iron aluminide filters in integrated gasification combined cycle (IGCC) plants. Product: Fe_3Al filters to be tested in the Wabash IGCC unit that could replace type 310 stainless steel, especially in sulfidizing environments
Pall Corp.	Technical support in processing, corrosion, and compositional modifications for development of iron aluminide hot gas filters for gasification plants and pressurized fluidized combustors
Solar Turbines	Development of metallic foil for use in recuperators, drawing on ORNL expertise in high-temperature corrosion processes
	Improved oxidation and creep resistance for stainless steels used in recuperators, with the goal of higher temperature capability and lifetime extension
Exxon Research & Engineering Co.	Thermochemical calculations of equilibrium concentrations of carbon and gaseous species at high temperatures and pressures
3M	Development of ceramic composite filters for hot gas cleanup in pressurized fluidized-bed combustion (PFBC) and IGCC systems
British Coal Corp.	Exposures of iron aluminides in product gas stream of a pressurized coal gasifier
EPRI	Research on protective properties of thin oxide scales and coatings

4.4 ENVIRONMENTAL ASSESSMENT SUPPORT

The goal of ORNL’s EAS activities is to provide environmental technical support to DOE’s Federal Energy Technology Center in the preparation of assessments required by the National Environmental Policy Act (NEPA) for site-specific projects, such as proof-of-concept–scale demonstrations of coal-fired technologies. Work in this area has included preparation of an EIS for the Healy Clean Coal Project in Alaska and preparation of a programmatic EIS (PEIS) to evaluate the environmental effects of widespread commercialization of clean coal technologies. For the PEIS, ORNL analyzed the impacts of each technology for the year 2010, including a no-action alternative, and predicted regional and national changes. Decision makers were provided with an easy-to-understand comparison of the potential of each technology to reduce emissions and solid waste. The PEIS also pinpointed regions that would benefit most from implementing these technologies.

4.5 BIOPROCESSING RESEARCH

Much of ORNL’s bioprocessing research is carried out in the Bioprocessing R&D Center, which conducts fundamental research in unique areas of bioprocess engineering and hybrids of chemical and biological processes and applies the technologies developed in the course of this research to the solution of energy-related problems (see Fig. 4.4). Goals in the bioprocessing research area are to

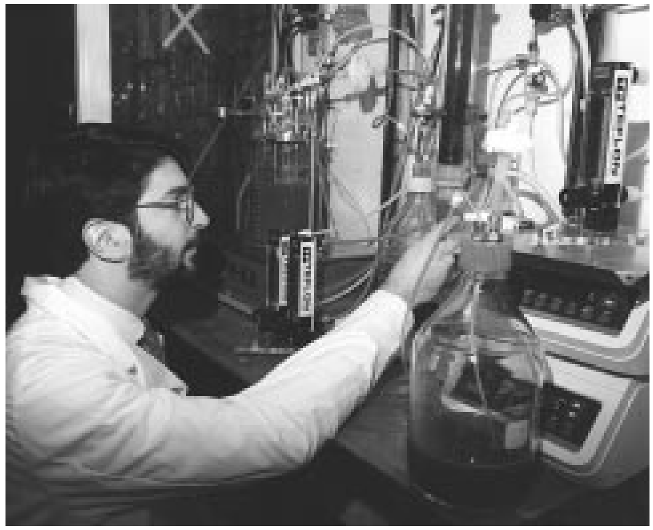

Fig. 4.4. Fundamental bioprocessing research for coal applications.

- investigate the treatment of petroleum, coal- and petroleum-derived products, and effluent streams for the removal of sulfur, nitrogen, and other contaminants;
- conduct research on the biological quality of soils containing hydrocarbons to evaluate measures for reducing ecological risk through bioremediation techniques;
- investigate innovative microbial and biochemical pathways for bioprocessing concepts for use in advanced bioreactor systems;
- continue research on the production of molecular hydrogen via photosynthetic water splitting; and
- participate in the Natural Gas and Oil Technology Partnership, supporting joint Laboratory-industry projects.

Important progress has been made in the following areas.

- Photosynthetic water splitting for hydrogen production. ORNL has demonstrated that the photobiological production of hydrogen can occur with an external 1-atm pressure of hydrogen. This encouraging result helps to define the thermodynamic limit of the photochemical machinery for photosynthesis and is a first step in the design of photobiological reactors.
- Demonstration of the ability to render enzymes soluble and active in organic media. This expanding role of enzymatic biocatalysts will enable the synthesis of new drugs and materials.
- Demonstration of biochemical processes for reclaiming elemental sulfur from flue-gas desulfurization systems, which will lead to cost savings from sale and recycling.
- Research on the biodesulfurization of oil.

In work with investigators from the Petroleum Environmental Research Forum, ORNL is developing faster methods for measuring petroleum contaminants in soils, using bioassays to help estimate ecological risks at petroleum industry sites, and investigating factors that regulate the bioavailability of petroleum contaminants in soils.

4.6 COAL COMBUSTION RESEARCH

The mission of ORNL’s coal combustion research is to provide critical analyses of existing technology options for U.S. industry and government and to develop new combustion technologies that are less polluting, more energy efficient, and less costly (see Fig. 4.5). Multidisciplinary teams of ORNL physicists, computer scientists, and mechanical, chemical, and electrical engineers are engaged in

- combustion systems analysis using nonlinear dynamics, chaos theory, and neural networks, coupled with measurements in practical environments;
- development of diagnostics and controls, including high-speed feedback controls;
- economic assessments of power plants, transportation systems, powering options, and fuel switching; and
- development of advanced combustion and fuel technologies, addressing internal combustion engines, gas turbines, FBC systems, alternative fuels, fuel additives, fuel characterization, mild gasification, and advanced power cycles.

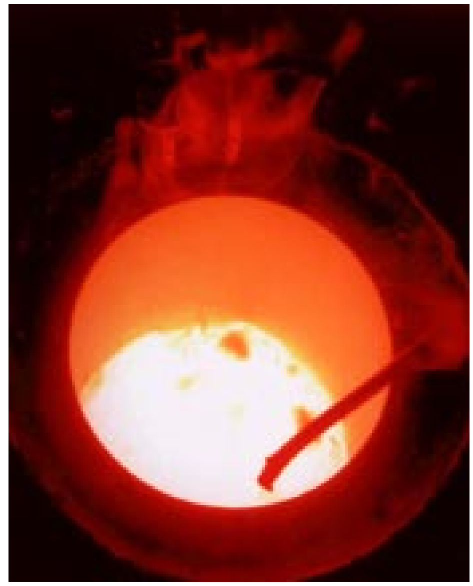

Fig. 4.5. Coal combustion. The performance of fossil energy conversion devices (e.g., FBC systems, pulsed combustors, steady combustors, internal combustion engines) is affected by deterministic chaos.

4.7 FUEL SUPPLY ANALYSIS AND MODELING

ORNL's fuel supply analysis and modeling activities help to maintain readiness for energy market disruptions. Program goals include

- providing assistance to the SPR in the development of models for planning SPR capacity and management and for analyzing the oil market; and
- developing and testing advanced computational tools for 3-D seismic analysis, using the model data set developed under the aegis of the U.S. Society of Exploration Geologists and the European Association of Exploration Geologists to enhance the value to the oil industry of the modeling project undertaken by these organizations.

ORNL researchers have analyzed, for the U.S. Navy, the effect of oil supply interruptions of the availability of military fuels during an emergency. The analysis considered the distribution of oil around the world and the ability of refineries to produce the needed fuels in an emergency. During a serious disruption, such as a war in an oil-producing region (see Fig. 4.6), government oil stockpiles may provide an essential buffer. ORNL maintains a set of computer models for evaluating alternative configurations for the SPR.

Fig. 4.6. War in an oil-producing region could disrupt oil supplies.

5

Fusion Energy Sciences Program

The development of practical fusion energy sources is a long-term research goal. Fusion, based upon deuterium fuel (1 part in 6500 of all hydrogen), is a potentially inexhaustible source of energy. As a complement to fission, fusion offers potential safety advantages resulting from low stored energy, minimal risk of proliferation, and substantially reduced radioactive wastes—no actinides are involved. There are two approaches to exploiting fusion: use either of magnetic fields or of inertial effects to confine a hot reacting gas, called a plasma. Plasma is the fourth and most common state of matter—the sun and stars are plasmas. ORNL is involved in magnetic fusion research. In this approach, a very hot plasma is confined by strong magnets and produces fusion reactions.

In addition to being the basis for fusion reactions, plasmas have many other applications, from lighting to materials processing. Consequently, the field of plasma science and technology has great importance beyond its value to fusion energy. ORNL is also involved in spin-offs from fusion research in such areas as semiconductor processing and the application of microwave and cryogenic pellet technologies to industrial needs.

5.1 HISTORY

ORNL has been a major player in the areas of magnetic fusion energy and plasma physics since 1957, when the Thermonuclear Experimental Division—now the Fusion Energy Division—was established. At that time the Direct Current Experiment (DCX) devices based on the use of magnetic mirrors was started.

The U.S. and ORNL programs changed substantially when, in 1968, a Russian tokamak facility confined a hot plasma at 10 million degrees. By the summer of 1971, the Oak Ridge Tokamak (ORMAK) was operating at ORNL. Along with the U.S. fusion program, ORNL expanded its efforts on theory, computing, atomic physics, diagnostics, neutral beam heating, development of gyrotrons and superconducting magnets, research on plasma-interactive and neutron-resistant materials, and fusion reactor studies.

In 1977, ORMAK was replaced by the Impurity Studies Experiment (ISX-A) tokamak, a joint effort with General Atomics in San Diego. With this facility, pioneering work continued on plasma-surface interactions, plasma transport, fueling with cryogenic pellets, and electron cyclotron heating (ECH). When it was replaced, in turn, by the ISX-B tokamak, work continued in the same areas with the addition of studies in magnetohydrodynamic (MHD) effects.

Work during the 1960s on the use of ECH in simple magnetic mirrors led to a toroidal mirror concept—the ELMO Bumpy Torus (EBT). Progress in the EBT program encouraged DOE to initiate the design of the larger EBT-P facility, with McDonnell Douglas and ORNL as partners, in 1979. However, before construction started, ORNL staff demonstrated that the EBT performance was poorer than previously believed. The program was canceled in 1986, having yielded fundamental information about relativistic electrons, electric fields, and radio-frequency (rf) heating.

The late 1970s was a period of great success for the ORNL plasma technology programs. Powerful neutral hydrogen beam injectors, built by ORNL, were used in 1979 at the Princeton Plasma Physics Laboratory (PPPL) to achieve record temperatures in the Princeton Large Torus tokamak—80 million degrees. In the ISX tokamaks, cryogenic pellet injection was established as a major fueling system for magnetic fusion devices.

Since then, ORNL's pellet fueling devices and designs have been installed on experiments at major fusion laboratories of the United States and the world.

In 1977 the superconducting magnet development program embarked on construction of the International Fusion Superconducting Magnet Test Facility as part of the Large Coil Task to test six 45–metric ton, 8-T toroidal coils—three from the United States, two from Europe, and one from Japan. The program, completed in 1987, was very successful, with all of the coils operating at their design value or above.

By the mid-1980s, however, the U.S. fusion budget was in decline, and the ORNL programs on ISX-B and in plasma-wall interactive materials, neutral beam heating and gyrotron development, and later superconducting coil development came to an end.

Meanwhile, despite budget decreases, other programs continued to produce results. The plasma technology program evolved to include the development of rf heating systems and continued the pellet development efforts. It also expanded to include spin-off applications based on ORNL fusion technologies. The atomic physics program contributed most of the world's data on ionization cross sections for fusion-relevant elements, while the diagnostic development program shrank. The materials irradiation program made major contributions to an understanding of the behavior of stainless steels and of irradiation effects on copper and ceramics.

The 1980s was a period of great inventiveness in the ORNL program. ORNL investigated an alternative to the tokamak, the stellarator, developing a variety of improved versions of this configuration. This work led to the construction of the Advanced Toroidal Facility (ATF), which began operation in 1987. Unfortunately, as a result of reductions in the U.S. fusion budget and a focusing of the national program on tokamaks in 1991, the ATF program was shut down after a few years, despite making some interesting physics contributions. However, a significant legacy from this program can be found in the numerous facilities across the world that are based on ORNL stellarator concepts.

A second ORNL development initiated in this period was the concept for a very low aspect ratio tokamak, the Spherical Torus (ST). This concept is being pursued with ORNL involvement in Europe, Russia, and the United States. ORNL involvement in the tokamak program was maintained through this effort and extensive collaborations that applied ORNL expertise in theory, modeling, diagnostics, and plasma technologies to experiments at other laboratories—notably at PPPL, General Atomics, Culham Laboratory in England, and the Commissariat à l'Energie Atomique facility in Cadarache, France.

5.2 OVERVIEW OF CURRENT PROGRAMS

The DOE-ER OFES sponsors the bulk of the ORNL fusion energy sciences and technology program; funding from JAERI supports materials irradiation research. Furthermore, 20% of the total budget for ORNL's Fusion Energy Division comes from other sponsors for spin-offs from the program. The recent fusion budgets are shown in Fig. 5.1.

A continuing strength of the ORNL program is the effective integration of fusion capabilities in theory, computer modeling, plasma experiments, plasma and nuclear technologies, materials, and engineering. This strength is reflected in the number of ORNL divisions involved in the research. The ORNL program is also one of the most collaborative in the world, involving 6 laboratories, 8 universities, and 13 foreign institutions.

In recent years, there have been substantial reductions in the U.S. magnetic fusion program and a major shift in emphasis away from an urgency to develop fusion as an energy source. These changes have had a profound effect on the scale and scope of the ORNL program. Of greatest significance has been the elimination of an in-house fusion plasma experimental program. This has led to a focus on experiments in other laboratories in the United States and abroad.

A second important driver for ORNL programs has been the emergence of ITER as a major world initiative. ORNL has been a substantial contributor to ITER. However, the United States has recently discontinued its participation in the ITER project.

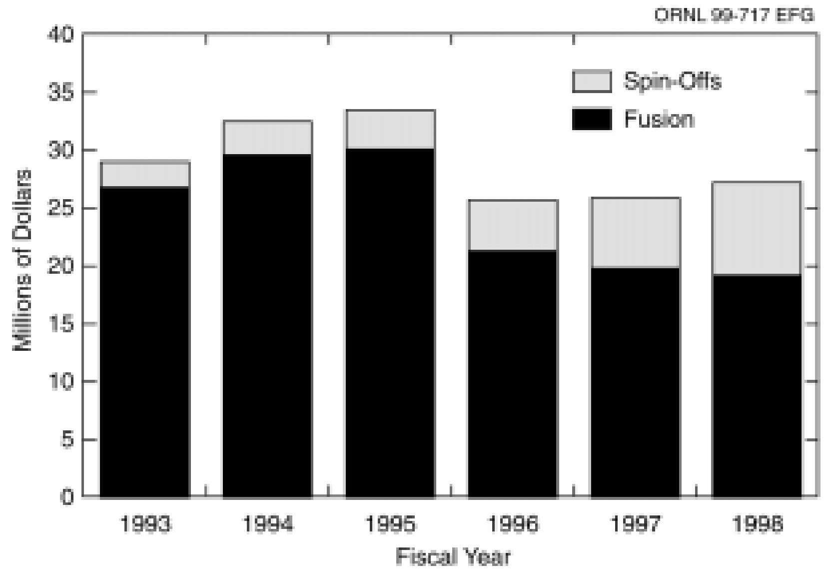

Fig. 5.1. ORNL fusion and fusion spin-off funding (new BA) has stabilized.

5.3 ATOMIC PHYSICS AND DIAGNOSTICS

The atomic physics and diagnostics program, undertaken in the ORNL Physics Division, has provided a large fraction of the world's experimental data on electron impact excitation and ionization cross sections of multiply charged ions of relevance to fusion research. In addition, this program provides low-energy electron capture cross-section data and electron-impact-induced molecular ion dissociation cross sections required for divertor and edge plasma modeling, as well as experimental data on electron emission and neutralization, particle reflection, molecular breakup, and sputtering occurring during interactions of low-energy, multicharged and molecular ions with surfaces. An important component of the program is the Controlled Fusion Atomic Data Center, which provides the interface between the program and the community by maintaining close links with the International Atomic Energy Agency (IAEA) and making available bibliographic and evaluated numerical data on the World Wide Web (see http://www-cfadc.phy.ornl.gov). The plasma diagnostics program currently focuses on (1) development of a far-infrared laser diagnostic for measuring the energy distribution of alpha particles generated in fusion plasmas and (2) development of a tangential viewing infrared interferometer/polarimeter system for electron density profile measurements on ITER.

5.4 THEORY

The theory program, a strong element of the ORNL plasma physics and fusion program for decades, has made important contributions in such areas as

- kinetic theory and the transport of heat and particles in a magnetic field;
- MHD theory of mirrors, EBTs, tokamaks, STs, and stellarators;

- the development of a number of improved confinement configurations for these devices;
- theory of microwave and rf heating and current drive systems; and
- computer codes for application in these areas (see Fig. 5.2).

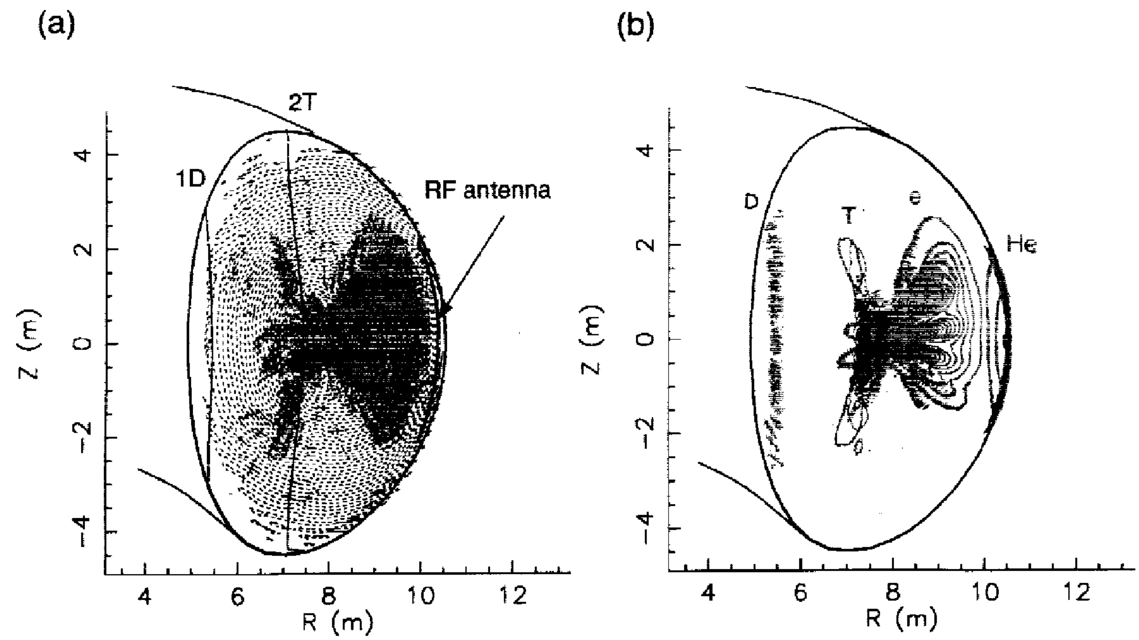

Fig. 5.2. Calculation of ion cyclotron resonance heating in ITER: (*a*) launched radio waves and (*b*) absorbed power.

Today, this program is focused on the continued development of understanding of fundamental plasma physics and a variety of applications. In particular, the program is well integrated into the experimental programs and contributes to some of the spin-off programs. Studies are under way on two proposed, complementary low-aspect-ratio stellarators—the National Compact Stellarator Experiment (NCSX), being conducted jointly by PPPL and ORNL at PPPL; and the Quasi-Omnigeneous Stellarator (QOS), a joint experiment by ORNL and the University of Texas at ORNL.

5.5 PLASMA EXPERIMENTS

The objective of the plasma confinement program is to advance the U.S. Fusion Program through the application of ORNL capabilities in

- edge physics and particle control,
- pellet fueling,
- rf heating and current drive,
- alternate concept development, and
- theory and modeling.

The following research areas are integrated in topical programs carried out in U.S. and international facilities.

- **Concept improvement.** The goal is improving magnetic confinement concepts through understanding and optimizing of tokamak confinement and stability and through exploration of alternate configurations through the following activities:
    1. Understand and optimize MHD stability and control in DIII-D (General Atomics).
    2. Investigate sustainment of advanced tokamak plasmas in Tore Supra (France).
    3. Explore the effects and performance of ultralow aspect ratio in the National Spherical Tokamak Experiment (NSTX) (joint ORNL/PPPL at PPPL).
    4. Utilize comparative transport studies in tokamaks and stellarators.
    5. Explore two complementary approaches to compact stellarators—NCSX and QOS.
    6. Study ion confinement in the Large Helical Device (LHD) in Japan.

- **Particle transport and control.** The goal is identifying and studying the underlying mechanisms responsible for particle transport in the core, scrape-off layer, and divertor and establishing a scientific basis for the effects of particle control and plasma-wall interactions on confinement through the following activities:
    1. Explore the effects of pellet fueling on density limits and investigate the underlying mechanisms on DIII-D, Tore Supra, and Wendelstein7-AS in Germany (W7-AS).
    2. Investigate the effects of internal transport barriers on the core confinement of hydrogenic particles, helium, and impurities in DIII-D and Tore Supra.
    3. Study the intrinsic impurity sources and transport in Tore Supra and DIII-D.
    4. Characterize the forces on helium, carbon, and neon impurities in the divertor under different flow conditions and determine the consequences on impurity entrainment.
    5. Study particle transport and control in stellarators—W7-AS and LHD.

- **Wave-plasma interactions.** The goal is studying and understanding wave-plasma interactions in order to optimize heating and current drive to control pressure and current profiles for improved confinement and to develop rf heating and current drive as an enabling technology through the following activities:
    1. Develop the scientific basis for the utilization of fast wave and mode conversion current drive for pressure and current profile control on DIII-D and Tore Supra.
    2. Investigate synergies between long-pulse fast wave and lower hybrid heating and current drive on Tore Supra.
    3. Study the effects of edge plasma–antenna interactions and optimize for plasma performance on Tore Supra.
    4. Develop reliable enabling technologies for rf heating, current drive, and profile control, including folded waveguides and long-pulse antennas.

    An example of an rf antenna, installed in the DIII-D tokamak, is shown in Fig. 5.3.

- **Spherical Torus (ST)**. The ST configuration is a very-low-aspect-ratio (typically ≤ 1.5) tokamak, which can support a high plasma pressure in relation to its magnetic field. Through ORNL efforts, this type of device has been adopted for research by a number of laboratories, notably Culham, the Ioffe Institute (Russia), and PPPL. Initial experiments at Culham in a small ST show relatively good confinement and encouraging prospects as a fusion device. ORNL is now partnered with PPPL in the NSTX, a 1-MA ST (see Fig. 5.4).

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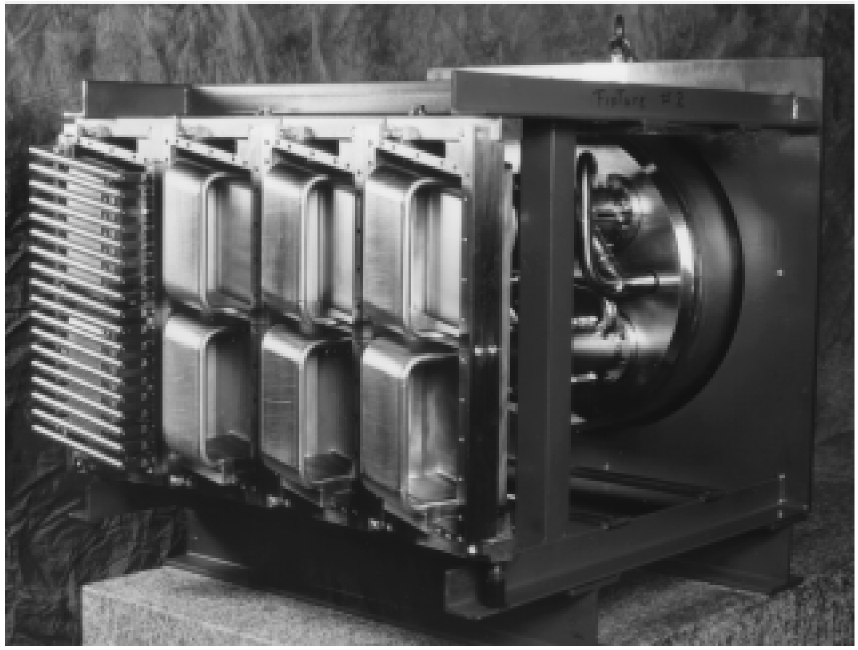

Fig. 5.3. ORNL-built rf antenna on the DIII-D tokamak at General Atomics in San Diego.

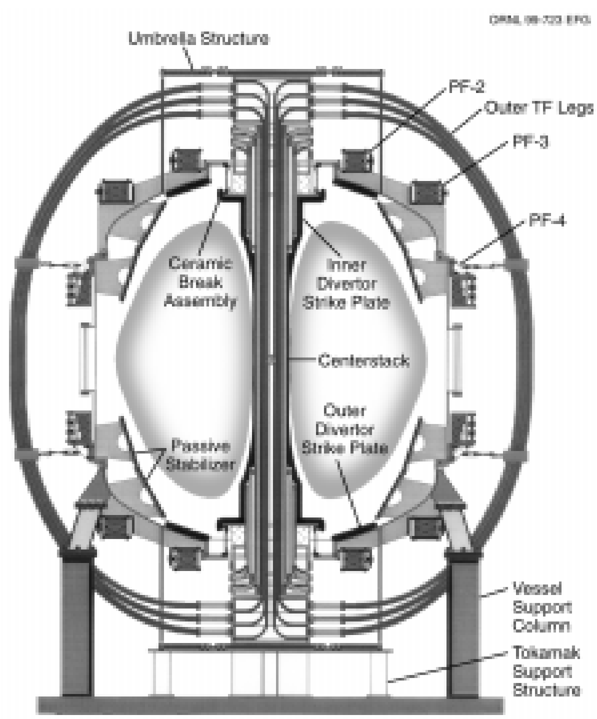

Fig. 5.4. Elevation view of the NSTX device under construction at PPPL.

- **Compact stellarators.** Two complementary possibilities for a compact, high-beta stellarator path to fusion energy are being examined: the quasi-axisymmetric NCSX, which uses a small current in external coils with a larger plasma-generated current to create the confining magnetic field; and the quasi-omnigeneous QOS, in which the relative current contributions are reversed. Figure 5.5 shows the plasma and coil shapes for the QOS configuration.

5.6 PLASMA TECHNOLOGIES

Plasma technologies have been a cornerstone of the ORNL fusion program since its inception, supporting the ability to undertake state-of-the-art plasma experiments at ORNL and other laboratories. Today the program concentrates in two major areas, RF heating and pellet fueling.

- **RF heating**. The RF heating program integrates the research and applied development capabilities of ORNL in the theory, computer modeling, design, and experimental areas to produce improved rf antennas and control systems for plasma heating and tokamak current drive. The Radio Frequency Test Facility is used to qualify the antennas. Substantial improvements in performance have been demonstrated, and the folded waveguide concept has been developed for compact, high-power-density applications. Equipment developed and made at ORNL has been used on numerous experiments—including ATF, DIII-D, the Tokamak Fusion Test Reactor at PPPL, Tore Supra, and the Joint European Torus (JET) at Culham.

- **Pellet fueling**. Much of the development of high-speed, cryogenic hydrogen pellet launchers has been pioneered at ORNL, including the theory and experimentation on pellet ablation in hot plasmas. Two main types of acceleration have been developed: gas guns that use high-pressure hydrogen to accelerate pellets to ~1500 m/s (single stage) and 4000 m/s (two stage), and centrifugal injectors that use a rotating arbor

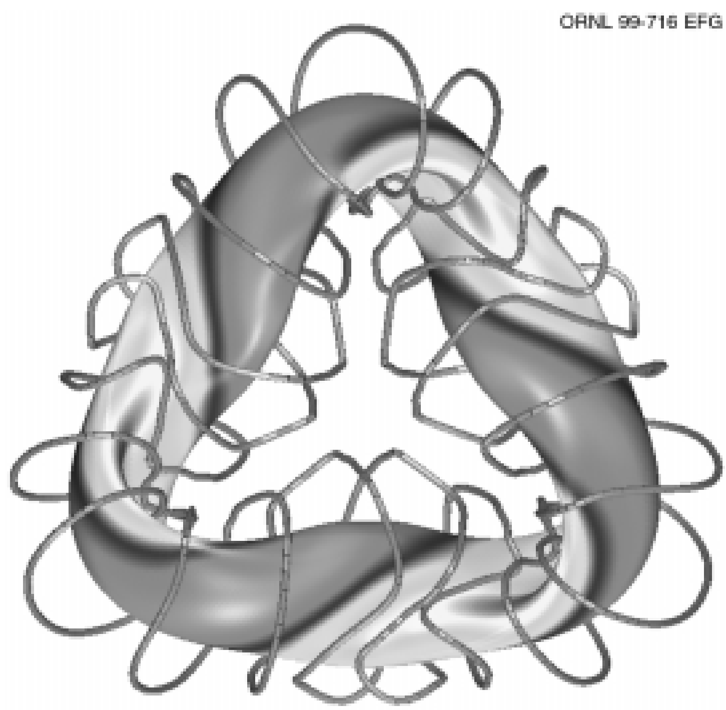

Fig. 5.5. The QOS configuration.

to accelerate pellets to speeds up to ~1 km/s. Both types of devices have demonstrated the capability for repetitive operation. Typical pellet sizes are in the range of 0.5 to 10 mm in diameter. ORNL injectors, or injectors based on ORNL designs, have been widely applied in the fusion laboratories of the United States and the world. The successes of the program include the demonstration of improved plasma performance on JET and the development of tritium pellet injectors in a collaboration with Los Alamos National Laboratory.

5.7 ITER

ITER is a multinational tokamak project undertaken under the aegis of the IAEA. Its goals are to produce and study thermonuclear plasmas at power levels up to 1500 MW, in both the driven and ignited states for durations of 1000 s or more, and to demonstrate fusion reactor technologies for extended periods, including steady state, with a 14-MeV neutron wall flux of 1 MW/m^2. The Engineering Design Activity (EDA) was completed in July 1998; a few-year transitional period is expected to precede a construction decision. The United States discontinued its participation in the ITER project in 1998. ORNL will continue to participate in future U.S. next-step design efforts.

5.8 ADVANCED MATERIALS FOR FUSION

ORNL has been involved in fusion materials R&D since the early 1970s. This program builds on the considerable experience derived from the Laboratory's fission programs of 1960–85 and from the continuing basic research in radiation effects supported by the DOE-ER Basic Energy Sciences Program.

One of the most critical challenges in the development of fusion as an energy source is to develop radiation-resistant structural materials that can withstand a high fluence of 14-MeV neutrons (typically 15 MW • $years/m^2$) that create unprecedented levels of displacement damage and transmutations. To realize the potential of fusion in terms of safety and minimal environmental impact, materials that have low neutron activation and relatively short decay half-lives must be developed. To maintain a range of options for design of thermally efficient breeding blankets and high-heat-flux components ORNL is pursuing the development of three reduced-activation materials: silicon carbide composites, vanadium alloys, and advanced martensitic steels. These three material systems are widely different in terms of physical and mechanical properties, fabrication methods, compatibility with chemical environments, and current levels of commercialization. However, much the same approach is used in developing all of these materials for fusion service; it involves tailoring the chemical composition and processing variables to develop a microstructure that has the required mechanical properties, radiation damage resistance, and chemical compatibility characteristics with coolants and breeding media over the temperatures, times, and radiation damage levels of application. Other important considerations include production and fabrication technology and welding and joining methods.

Substantial progress has been made in developing materials with the required properties and characteristics. Mechanisms of irradiation damage are being illuminated through a combination of theory, modeling, and experiment. ORNL researchers have identified the most limiting properties in each of the materials and are actively pursuing the development of compositions and structures that will exhibit improved performance. Figure 5.6 shows the improved resistance of an advanced low-activation martensitic steel to irradiation embrittlement as determined by the ductile-to-brittle transition temperature measured in a Charpy impact test. Figure 5.7 shows radiation damage in a commercially available composite and test results for a silicon carbide composite with improved strength developed for radiation damage resistance.

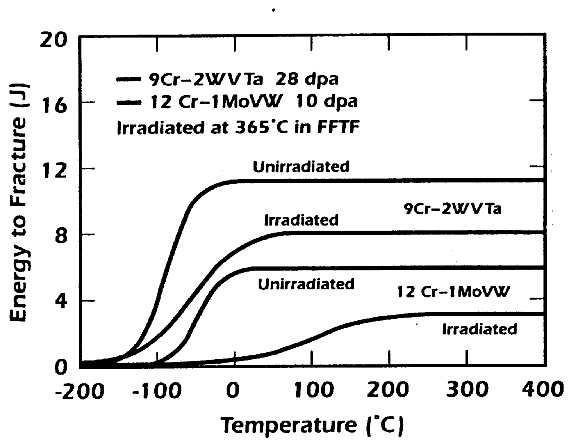

Fig. 5.6. Comparison of resistance to radiation embrittlement of low-activation martensitic steels. The 9Cr–2WVTa steel developed at ORNL is superior to commercial (9Cr–1Mo, HT-9) and other low-activation (9Cr–2WV, F82H) steels.

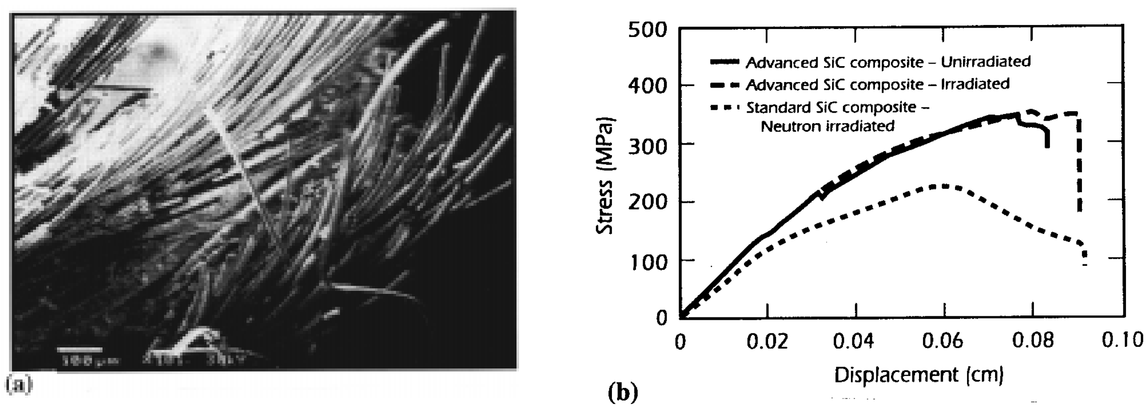

Fig. 5.7. Behavior of silicon carbide composites. (*a*) Radiation damage to a commercially available composite. Radiation causes the reinforcing fibers to shrink and pull out of the composite, reducing its strength. (*b*) Results from tests of standard and advanced composites, irradiated at 1000°C, 1 dpa in the High Flux Beam Reactor.

Other important activities within the fusion materials program include research on the effects of radiation on the dielectric properties of ceramic insulators and activities in support of the efforts to build a high-flux neutron source for fusion materials R&D, i.e., the International Fusion Materials Irradiation Facility.

5.9 SPIN-OFFS

Starting in the mid-1980s, the Fusion Energy Division branched out into programs that apply the technology and science developments of the fusion program to other areas. Today these programs supplement the fusion programs, allowing the division to retain critical levels of competency in a number of areas. The major activities are in the following areas:

- semiconductor processing using improved plasma sources;
- plasma processing for surface cleaning or deposition of coatings with special properties;

- microwave applications for materials processing and environmental cleanup;
- cryogenic pellet technology for material surface modification and cleaning (see Fig. 5.8), as well as for an advanced cold neutron moderator; and
- electrical applications of high-temperature superconductivity (transmission lines, transformers).

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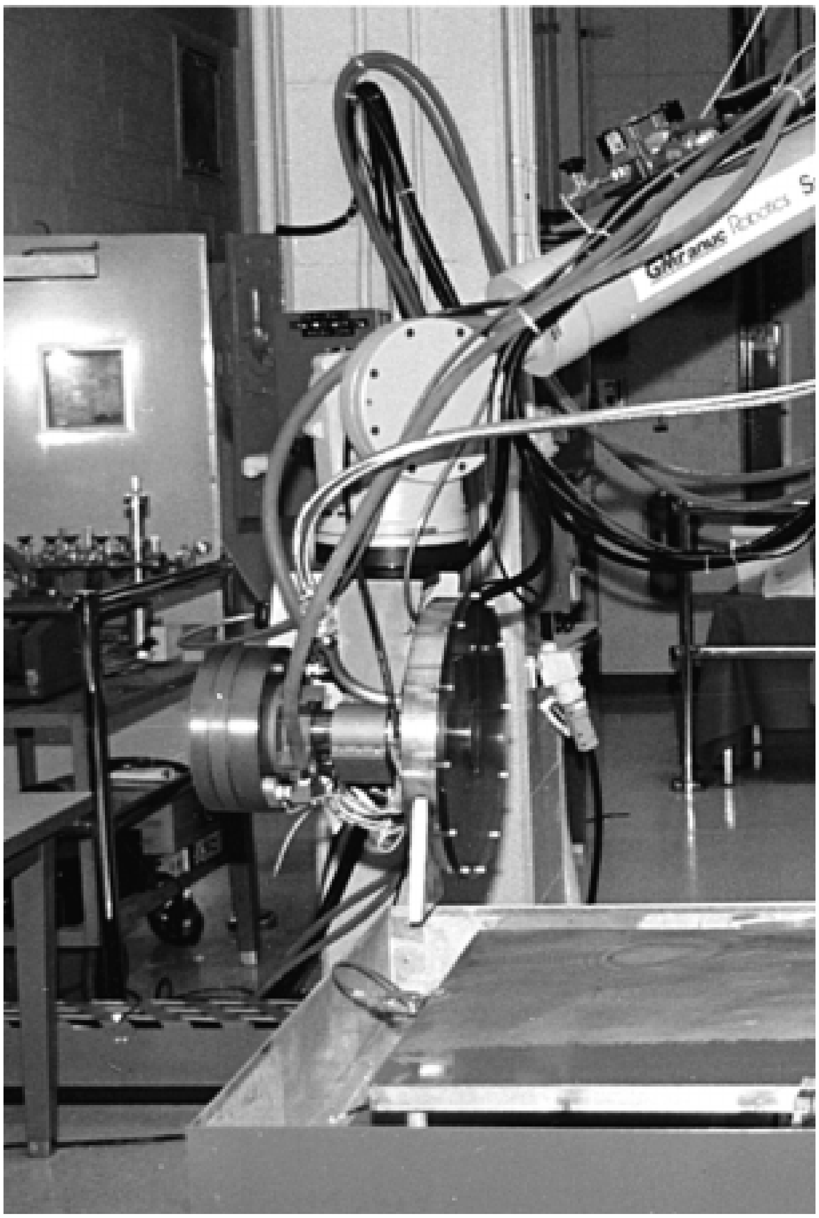

Fig. 5.8. A CO_2 cryoblaster device for solvent-free cleaning and paint stripping applications, using centrifugal accelerator technology developed in the Fusion Energy Program.

Acronyms and Abbreviations

AEC	Atomic Energy Commission
AFBC	atmospheric FBC
AHAM	Association of Home Appliance Manufacturers
AIM	Advanced Industrial Materials (program)
ANL	Argonne National Laboratory
AR&TD	Advanced Research and Technology (DOE-FE)
ASC	American Superconductor Corporation
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASIC	application-specific integrated circuit
ASP	Accident Sequence Precursor (program)
ATF	Advanced Toroidal Facility
BA	budget authority
BFDP	Bioenergy Feedstock Development Program
BSCCO	bismuth-strontium-calcium-copper oxide
BTC	Buildings Technology Center (ORNL)
BWR	boiling-water reactor
CABO	Council of American Building Officials
CADDET	Center for the Analysis and Dissemination of Demonstrated Energy Technologies
CANDU	Canadian deuterium uranium (reactor)
CFC	chlorofluorocarbon
CFCC	continuous fiber ceramic composite
CHS	Compact Helical System
CRADA	cooperative research and development agreement
CTA	Center for Transportation Analysis (ORNL)
CVD	chemical vapor deposition
D&D	decontamination and decommissioning
DCX	Direct Current Experiment
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOE-EE	Office of Energy Efficiency and Renewable Energy (DOE)
DOE-EM	Office of Environmental Management (DOE)
DOE-ER	Office of Energy Research (DOE)
DOE-FE	Assistant Secretary for Fossil Energy (DOE)
DOE-MD	Office of Fissile Materials Disposition (DOE)
DOE-NE	Office of Nuclear Energy, Science and Technology (DOE)
DOE-ORO	DOE Oak Ridge Operations Office
DOT	U.S. Department of Transportation
EAS	environmental analysis support
EBT	ELMO Bumpy Torus

ECH	electron cyclotron heating
EDA	engineering design activity
EERE	Energy Efficiency and Renewable Energy (ORNL program)
EIS	environmental impact statement
EMF	electromagnetic field
EMI/RFI	electromagnetic interference / radio-frequency interference
EPRI	Electric Power Research Institute
ERDA	Energy Research and Development Administration
ERIP	Energy-Related Inventions Program
FBC	fluidized-bed combustion
FBR	fluidized-bed bioreactor
FDA	Food and Drug Administration
GAX	generator absorber heat exchange
GCHP	ground-coupled heat pump
GREENTIE	Greenhouse Gas Technology Information Interchange
GRI	Gas Research Institute
HCFC	hydrochlorofluorocarbon
HFC	hydrofluorocarbon
HFIR	High Flux Isotope Reactor
HTS	high-temperature superconducting
I&C	instrumentation and control
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IGCC	integrated gasification combined cycle
INEEL	Idaho National Engineering and Environmental Laboratory
IOF	Industries of the Future
ISX-A	Impurity Studies Experiment
ITER	International Thermonuclear Experimental Reactor
ITS	intelligent transportation systems
JAERI	Japan Atomic Energy Research Institute
JET	Joint European Torus
LBNL	Lawrence Berkeley National Laboratory
LER	Licensee Event Report
LHD	Large Helical Device
LSCS	large-scale climate simulator
LWR	light-water reactor
MACS	mobile automated characterization system
MHD	magnetohydrodynamic
MOX	mixed-oxide
MPC&A	material protection, control, and accountability
Mtoe	megatons of oil equivalent
NASA	National Aeronautics and Space Administration
NCSX	National Compact Stellarator Experiment
NEAT	National Energy Audit Tool
NEPA	National Environmental Policy Act
NERI	Nuclear Energy Research Initiative
NIEHS	National Institute of Environmental Health Sciences
NIOSH	National Institute for Occupational Safety and Health

NRC	Nuclear Regulatory Commission
NREL	National Renewable Energy Laboratory
NSTX	National Spherical Tokamak Experiment
NUPEC	Nuclear Power Engineering Corporation
OFES	Office of Fusion Energy Sciences (DOE-ER)
OIT	Office of Industrial Technologies (DOE-EE)
ORACLE	Oak Ridge Automated Computer and Logical Engine
ORMAK	Oak Ridge Tokamak
ORNL	Oak Ridge National Laboratory
ORTRAN	Oak Ridge Transportation Technologies Center
OTT	Office of Transportation Technologies (DOE-EE)
PC	personal computer
PEIS	programmatic EIS
PFBC	pressurized FBC
PNGV	Partnership for a New Generation of Vehicles
PNNL	Pacific Northwest National Laboratory
PPL	Princeton Plasma Physics Laboratory
QOS	Quasi-Omnigeneous Stellarator
R&D	research and development (R&D)
RABiTS	rolling-assisted, biaxially textured substrates (trademarked process)
RAPID	National Electromagnetic Field Research and Public Information Dissemination (program)
RD&D	research, development, and demonstration
rf	radio frequency
RPV	reactor pressure vessels
RSI	resonant snubber inverter
SCSS	Sequence Coding Search System
SMARTH	small-aspect-ratio toroidal hybrid
SNL	Sandia National Laboratories
SPR	Strategic Petroleum Reserve
SRC	solvent refined coal
ST	Spherical Torus
3-D	three-dimensional
USAMP	U.S. Automotive Materials Partnership
USDA	U.S. Department of Agriculture
W7-AS	Wendelstein 7-AS
YBCO	yttrium-barium-copper oxide

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