OAK RIDGE NATIONAL LABORATORY

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60 YEARS OF GREAT SCIENCE

CONTENTS

ON THE COVER: Four current and former ORNL directors. From top left clockwise: ORNL Director Bill Madia, Alvin Weinberg, Herman Postma, and Alvin Trivelpiece. The directors gathered on the 100th anniversary of the birth of former ORNL Director and Nobel Laureate Eugene Wigner.

60 Years of Great Science 1943–2003

Among the most cherished artifacts of Oak Ridge National Laboratory is a small unassuming logbook with pages yellowed by time. The book was used by a group of researchers doing classified work in 1943 to record experiments at the X-10 Pile, a facility that later became known throughout the American scientific community as the Graphite Reactor. The book's most famous entry is dated November 4, 1943, with scrawled handwriting that reveals the author's excitement. The entry records a historic event of profound significance that had taken place in the hours just before dawn. In the hills of rural East Tennessee, the world's first powerful nuclear reactor had gone critical, ushering in the age of nuclear power and forever changing our assumptions about how we view science and its impact on our lives.

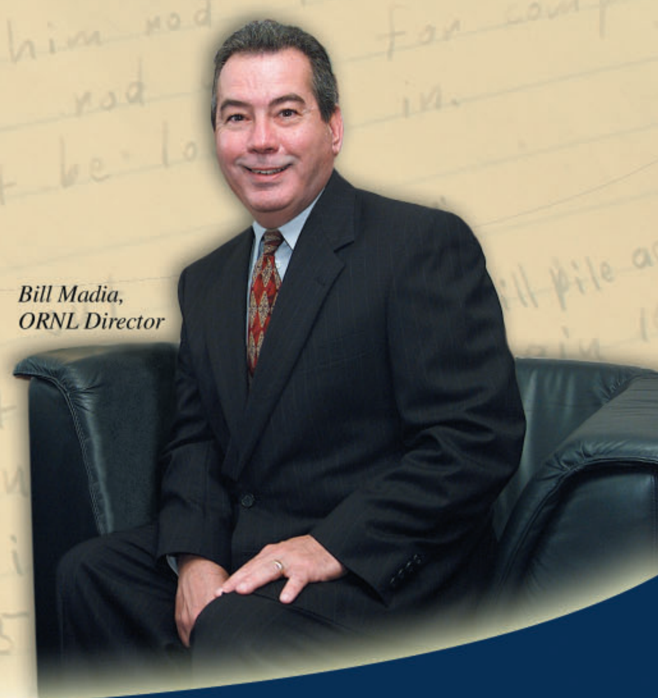
The extraordinary scientific breakthrough was the first in what was to be a long and distinguished list of contributions from the staff at ORNL. On the occasion of the Laboratory's 60th anniversary, we thought it appropriate for the *ORNL Review* to reflect on many of ORNL's contributions in science and technology that have improved people's lives. Our list is unavoidably an arbitrary one. Still, I believe the following pages capture both the scope of scientific research and the enormous influence of that research on a broad field of human endeavor. From nanophase materials research conducted at the atomic level, to the galactic scale of our experiments in astrophysics, ORNL for six decades has pushed the frontiers of science for the betterment of humankind.

The cover of the *Review's* anniversary edition pictures three lab directors who in many ways personify the evolution of ORNL's mission from a singular focus on developing nuclear weapons in 1943 to a broad and diverse center for world class scientific research in the 21st century. Alvin Weinberg, as research director and later as laboratory director, was among the first to understand that the laboratory must be a living organism, able to accommodate changes in America's scientific priorities. His leadership was critical in developing energy and environmental research competencies that strengthened ORNL's role in the nation's scientific community during the 1960s and 1970s.

Alvin Weinberg's vision was complemented by Herman Postma, who guided the laboratory through the transition from the Atomic Energy Commission to the new Department of Energy. Much of the laboratory's current suite of scientific capabilities, including an international reputation in advanced materials, can be traced to the leadership two decades ago of Herman Postma. These capabilities were enhanced further in the 1990s when Al Trivelpiece dreamed that ORNL could one day be home to the world's most powerful pulsed-neutron accelerator, the Spallation Neutron Source. Today atop Chestnut Ridge near the ORNL campus, the SNS has passed the halfway point in construction. When the SNS opens in 2006, ORNL will be the world's foremost center of neutron science research.

As we celebrate 60 years of great science and technology at ORNL, our challenge is to build on Alvin Weinberg's notion of a laboratory whose mission evolves and strengthens over time. To that end, we continue to build on ORNL's historic competencies in energy, life sciences, neutron sciences and advanced materials while adding new research missions in the areas of national security and high-performance computing. Equally important, we are literally rebuilding ORNL by undertaking a $300-million modernization program that will maintain our laboratory as one of the world's leading scientific research centers.

As we move into our new facilities, we will provide a place of distinction for that unassuming logbook that chronicled some of our earliest contributions. We do so knowing that this great event was only the first of many chapters in a story of success that will continue for years to come.



Bill Madia, ORNL Director

In December 1950, ORNL built its 2-megawatt Bulk Shielding Reactor by modifying its earlier Materials Testing Reactor mockup to create a "swimming pool" reactor. The reactor's enriched uranium core was submerged in water for both core cooling and neutron moderation.

NUCLEAR POWER AND RESEARCH REACTORS

From Manhattan Project to

More than 430 nuclear power reactors are operating in the world, and 103 nuclear power plants produce 20% of the electricity used in the United States. Most of these reactors are cooled by ordinary water. Water also is used to slow, or moderate, the neutrons emitted by fissioning uranium fuel so that reactions are sustained and heat is produced to make steam for power generation.

A strong proponent for the use of water as a reactor coolant was Eugene Wigner, who won a Nobel Prize for physics. Wigner was a mentor for Alvin Weinberg, who calls Wigner the founder of nuclear engineering as well as a great theoretical physicist. Both became ORNL directors and coauthored *The Physical Theory of Neutron Chain Reactors*. Wigner's reactor design was used largely by DuPont for water-cooled, graphite-moderated reactors built at Hanford, Washington; in 1945 these reactors produced plutonium for the atomic bomb that ended World War II. Wigner designed a water-cooled, water-moderated converter that enabled neutrons from fissioning plutonium to convert thorium to fissionable uranium-233, making him the grandfather of today's research reactors, naval reactors, and nuclear power plants.

Oak Ridge experiments by Art Snell in 1944 showed that 10 tons of ordinary uranium slugs would not explode and that chain reactions would not occur in a water-moderated natural uranium lattice. Additional experiments at the air-cooled Graphite Reactor led by Henry Newson and calculations by Weinberg suggested that to achieve sustained reactions in such a lattice, the uranium must be slightly enriched in fissionable uranium-235. In a 1944 letter, Weinberg suggested using high-pressure water as a coolant and moderator for a reactor to produce useful power; he also described the idea in a 1946 paper coauthored with Forrest Murray. Weinberg became a progenitor of the pressurized-water reactor (PWR), the basis of many nuclear power plants.

In the mid-1940s many power reactor concepts were born, with some evolving into technologies still considered valid. Because uranium was thought to be quite rare, some scientists conceived fast reactors that produce, or breed, more plutonium than they consume. In 1945 Wigner and Harry Soodak published the first design of a sodium-cooled breeder reactor.

In 1947 Farrington Daniels conceived the pebble-bed gas-cooled reactor in which helium rises through fissioning uranium oxide or carbide pebbles and cools them by carrying away heat for power production. The "Daniels' pile" was a crude version of the later high-temperature gas-cooled reactor developed further at ORNL.

Wigner also predicted that radiation damage to materials used to build reactors could impair their safe operation. To determine which materials fare best under irradiation, he conceived the Materials Testing Reactor (MTR), the first high-powered, enriched-uranium reactor cooled and moderated with water. For the MTR, ORNL researchers developed fuel elements with uranium oxide sandwiched between curved aluminum plates to prevent buckling, as well as a beryllium reflector to scatter neutrons back into the core.

While designing the MTR, ORNL researchers built a small mockup to test controls and hydraulic systems. In 1950, the experiment produced the first visible blue Cerenkov glow of a nuclear reaction underwater.

Because it is corrosion-resistant, zirconium was considered a good candidate for reactor fuel rods to contain uranium pellets. But some samples absorbed too many neutrons, suggesting an impurity. ORNL's

1939
Nuclear fission discovered

1942
Oak Ridge selected as site for World War II Manhattan Project

First sustained and controlled nuclear chain reaction in Chicago; Eugene Wigner present

1943
The $12-million Graphite Reactor, the world's first continuously operated reactor, goes critical after 9 months of construction

1944
Plutonium produced at Graphite Reactor, setting stage for Hanford reactors' production of plutonium for war-ending atomic bomb

Electricity Production

Herbert Pomerance discovered that hafnium, a common zirconium contaminant, absorbed many neutrons, and that pure zirconium soaked up very few. Oak Ridge researchers developed a separation process for producing pure zirconium, which was used in reactor fuel cladding for submarines and power plants.

Atomic Energy Commission officials, who had centered reactor development work at Argonne, realized that ORNL had much to contribute. The Laboratory was allowed to upgrade the mockup's shielding and cooling systems, increasing its power level to 10% of the MTR's. Labeled the "poor man's pile" by Wigner, the mockup was formally named the Low Intensity Test Reactor.

Experiments at the LITR established the feasibility of the boiling-water reactor, later a design prototype for commercial plants. ORNL researchers also developed principles of reactor control and protection systems that are used today.

Graduates of the Oak Ridge School of Reactor Technology (ORSORT), which was started by Wigner, designed a variety of reactors. One was the Aircraft Reactor for the ill-fated nuclear airplane project, whose aim was an aircraft that could fly indefinitely without refueling. The Bulk Shielding Reactor and Tower Shielding Facility were built to provide data on constructing lightweight radiation shielding for the aircraft. Another ORNL-developed reactor was built for display at the 1955 United Nations Conference on the Peaceful Uses of Atomic Energy. Yet another ORNL design was the Army Package Reactor, a transportable device built by a private contractor in 1957 for the Army Corps of Engineers to generate electric power at a remote base.

ORNL developed several homogeneous reactors that were fueled, cooled, and moderated by uranium-containing fluid, rather than the solid fuel and liquid coolant and moderator typical of most power plants today. A promising design was the molten-salt reactor, an outgrowth of the Aircraft Reactor project. Its fuel solution circulated continuously between the core and a processing plant that removed unwanted fissionable products. It was designed in the late 1960s to produce both electric power and new fuel, uranium-233. Today there is interest in Europe, Japan, and Russia in developing MSRs as actinide burners.

In the late 1950s there was international interest in gas-cooled reactors, and ORNL had a strong role in the U.S. commercial HTGR program. Responsibilities included developing an improved graphite moderator and developing and testing advanced coated-particle fuels that retain fission products at high temperatures. ORNL's experience in developing and testing spherical ceramic fuel has been sought to support development of the next-generation gas-turbine-modular-helium-cooled reactor and pebble-bed modular reactor.

Because of its researchers' extensive reactor experience and expertise, ORNL is the only national lab in Westinghouse Electric Company's international consortium to design the International Reactor Innovative and Secure power plant, a next-generation PWR. ORNL also is a co-leader of the Department of Energy's nuclear power programs.

ORSORT graduates also designed the many research reactors that have operated at ORNL (a half dozen in the 1960s). Among these were the Oak Ridge Research Reactor (1958-88) and the 37-year-old High Flux Isotope Reactor, still in operation for possibly another 30 years. In addition to producing isotopes for agricultural, industrial, and medical uses, the 85-megawatt HFIR is a valuable tool for materials testing and neutron-scattering research; it is one reason why ORNL will be the center of the neutron science universe at mid-decade. Thanks to neutrons, which make nuclear power possible, ORNL will soon become a world power in physical and biological materials research.

Discovery of Promethium

61
Pm

In 1914, one year before he was killed in action during World War I, Henry Moseley, a brilliant 26-year-old British physicist whose work influenced the final order of elements in the Periodic Table, demonstrated that element 61 should exist between the rare earths neodymium and samarium. In 1941-42 American chemists tried to create element 61 but could not prove they had produced it.

In 1945, chemists Jacob Marinsky and Larry Glendenin, working at the Graphite Reactor under the leadership of Charles Coryell, produced element 61. They did it both by uranium fission and by bombarding neodymium with neutrons from fissioning uranium in the reactor. Working in the nearby hot laboratory and chemistry building, they made the first chemical identification of two radioisotopes of element 61 by using ion-exchange chromatography.

Marinsky and Glendenin announced their chemical proof of the existence of element 61 at the 1947 American Chemical Society meeting. In 1948 when they were working at the Massachusetts Institute of Technology, they proposed the name "promethium" (Pm) for element 61 after Prometheus, the Titan in Greek mythology who stole fire from heaven for human benefit. The idea came from Coryell's wife Grace Mary. The name was accepted by the International Union of Chemistry in 1949.

Promethium is a radioactive beta-emitting metal not found in the earth's crust. It has been identified in the spectrum of a star in the Andromeda constellation.

Promethium-147 has been used in nuclear-powered batteries for instruments in guided missiles—one way to return fire to the heavens.

1945
Discovery at Graphite Reactor of element 61 (promethium)

First neutron scattering studies at a reactor (by Ernie Wollan and Cliff Shull; Shull won 1994 Nobel Prize for physics for his pioneering work at the Graphite Reactor)

1946
First shipment to a cancer hospital of a radioisotope from a reactor

Pressurized-water reactor conceived (later used for nuclear power and submarine propulsion)

Radiation detectors and dosimeters devised

NUCLEAR ISOTOPES

From Swords to Plowshares

During World War II, calutrons at the Oak Ridge Y-12 Plant were used to separate electromagnetically two uranium isotopes to produce bomb-grade material for the Manhattan Project. After the war, all but one of the calutron buildings were converted to other uses. The remaining facility was transferred to ORNL for the production of many isotopes for peaceful uses.

ORNL used the calutrons to produce hundreds of stable isotopes for numerous applications; many of these enriched isotopes were the starting materials for the preparation of radioisotopes. Some calutrons also were used to produce highly enriched uranium, plutonium, americium, and curium isotopes.

Radioactive medical isotopes produced from stable calutron-enriched isotopes include palladium-103 for treating prostate cancer; thallium-201 for heart imaging; rhenium-188 for treating cancer and restenosis; gallium-67 for imaging tumors; and strontium-89 for reducing metastatic bone pain. Non-medical products include nickel-63 for electronics and explosives detection and rubidium-87 for atomic clocks for geopositioning and cellular-phone systems. Since 1998 the calutrons have been maintained in a standby mode until needed.

For 56 years ORNL has produced radioisotopes using its reactors. Biochemist Waldo Cohn applied ion-exchange methods to the separation of fission products at the Graphite Reactor and organized the production and national distribution of its radioisotopes, including the first shipment from a reactor to a hospital.

Subsequent ORNL reactors have provided radioisotopes for use in agriculture, industry, and medicine. The High Flux Isotope Reactor is the principal supplier of several radioisotopes used in cancer treatment, nondestructive testing, and explosives detection. An important radioisotope produced at HFIR is californium-252, an excellent neutron source that has been used to find tiny cracks in aircraft parts. Clinical research on more than 5500 patients shows californium-252 has been extremely effective in treating cervical tumors and cancers of the head, neck, and oral cavity.

NUCLEAR MEDICINE

Diagnosing & Treating Disease

Transforming ORNL-produced radioisotopes into agents that can help restore human health has long been the goal of nuclear medicine researchers at ORNL. Led by Russ Knapp since the mid-1970s, they have developed a radioactive imaging agent for medical scanning diagnosis of heart disease. This agent, which has been tested in more than 350,000 patient studies worldwide, is commercially produced in Japan and Russia and used on numerous heart patients. The ORNL agent is a fatty acid labeled with radioactive iodine-123. It can be used to detect how much heart muscle is alive after a heart attack and to predict whether bypass surgery or balloon angioplasty will restore full blood flow.

In 1993 the ORNL group developed the tungsten-188/rhenium-188 isotope generator, tested the radioactive agents at ORNL, and established clinical trials in the United States and abroad. The trials showed that rhenium-188 (formed from the decay of tungsten-188) can reduce cancer-induced bone and liver pain and inflammation in arthritis patients. It also can prevent the buildup of smooth muscle cells in coronary arteries (restenosis) after balloon angioplasty, reducing the need to repeat the procedure.

Because ORNL's radioisotope delivery system offers low-cost therapy, it's being used to treat restenosis and cancer-induced pain in patients in developing countries (thanks to support from the International Atomic Energy Agency) as well as nations such as Germany and the United States.

A radioisotope generator developed by ORNL's Saed Mirzadeh and colleagues is providing a successful treatment for advanced leukemia patients. ORNL has a stockpile of uranium-233. The isotope decays to form actinium-225, which is shipped in ORNL generators to research sites around the world. At Memorial Sloan-Kettering Cancer Center, patients with acute myeloid leukemia are injected with antibodies labeled with bismuth-213, obtained from the decay of actinium-225. The bismuth isotope destroys the blood cells that make these patients dangerously ill.

Russ Knapp (bottom) led the development of the rhenium-188 generator in which tungsten-188 decays to rhenium-188, used to treat restenosis in heart patients and cancer-induced pain.

1947

Mice used to study radiation's genetic effects on mammals

Atomic Energy Commission established

1948

Union Carbide named government contractor in Oak Ridge

Fuel elements designed for use in research reactors

Materials Testing Reactor designed at ORNL and built in Idaho

1949

Purex process developed at ORNL; became worldwide method of recovering uranium and plutonium from spent reactor fuels

NUCLEAR FUEL

Developing New Processes

During World War II, Oak Ridge's Graphite Reactor was operated as a pilot plant to demonstrate plutonium production. ORNL researchers developed chemical processes to separate plutonium from spent uranium fuel and fission products. They designed and applied processes using precipitation to extract plutonium from spent fuel dissolved in nitric acid.

Subsequently, research by John Swartout and Frank Steahly had a profound impact on reprocessing. They favored the more efficient solvent-extraction technique being developed at ORNL. It used nitric acid and tri-butyl phosphate dissolved in an organic liquid to extract uranium and plutonium and separate them from fission products. This technique became the Purex (Plutonium/URanium EXtraction) process, still used worldwide to recover uranium and plutonium from spent fuel reactor fuels.

In the ensuing decades, ORNL teams headed by Floyd Culler, Frank Bruce, Raymond Wymer, William Unger, and others set the pace in designing and piloting nuclear fuel reprocessing plants using the Purex process. The designs became the basis for immense reprocessing plants built at Idaho Falls, Hanford, Savannah River, and elsewhere throughout the world.

During the late 1970s and 1980s ORNL advanced nuclear fuel reprocessing technology by developing more efficient equipment for dissolving spent fuels, controlling hazardous gaseous effluents, and performing solvent-extraction operations. Although ORNL's plans for recovering plutonium from the never-built Clinch River Breeder Reactor were canceled in the mid-1980s, many of its advanced techniques were employed in Europe and Japan.

ORNL-developed processes have been used worldwide to extract uranium from ores for electricity production. In the 1950s and 1960s a team led by Keith Brown developed methods for recovering uranium from ore. In the early 1980s Fred Hurst devised a method for extracting uranium from phosphoric acid. These techniques are the standard methods for recovering uranium for use in nuclear power plants.

Remote manipulation technology was initially developed at ORNL for nuclear fuel reprocessing.

International Software

SCALE is an easy-to-use computer software system for determining whether designs of nuclear facilities and transportation or storage packages meet nuclear safety standards. This ORNL-developed system is used worldwide to answer nuclear safety questions. Examples: Do storage casks containing spent nuclear fuel have enough shielding to protect employees from hazardous radiation levels? Will the cask design or arrangement of casks on a flatbed truck or railroad car prevent a criticality accident involving an uncontrolled release of energy and radiation?

In 1980 when the Standardized Computer Analyses for Licensing Evaluation code system was released, it was used to assess the safety of transporting nuclear material in casks. Since then, SCALE has been applied to questions about criticality safety and radiation shielding in a variety of nuclear facilities and containers for fissile and radioactive materials.

SCALE incorporates well-known computer codes, such as the KENO Monte Carlo code developed at ORNL in 1966 for criticality safety assessments. Experiments at ORNL's Critical Experiments Laboratory, led by Dixon Callihan and Joe Thomas, provided benchmark data against which the computer code calculations could be checked. Significant code enhancements and additional validation have continued.

SCALE was used to assure criticality safety in the recovery effort after fuel partially melted during the 1979 accident at the Three Mile Island nuclear power plant. SCALE is used on every continent except Antarctica. ORNL researchers conducted SCALE training for users in the United States, Europe, Japan, and Latin America. Users include the Department of Energy and Nuclear Regulatory Commission (both of which support SCALE development), as well as cask designers, fuel fabricators, reactor fuel vendors, and nuclear power plant utilities. SCALE 5, scheduled for release in 2003, will continue the tradition of providing state-of-the-art computational tools for nuclear-fuel-cycle safety analyses.

1950

Oak Ridge School of Reactor Technology established

Low Intensity Test Reactor first operated

1951

Startup of Bulk Shielding Reactor

Neutron's half-life measured

5-MW Van de Graaff accelerator installed

1952

ORNL's first heavy-ion cyclotron built

Based on irradiated mouse embryo studies, ORNL advises against x-raying possibly pregnant women

Homogeneous Reactor Experiment first run

In a nuclear safety test in the mid-1980s, bundles of non-nuclear fuel rods were heated until they melted to determine safe temperature limits.

NUCLEAR FUEL

New Designs for Nuclear Industry

In the late 1940s an ORNL team led by Eugene Wigner designed water-cooled fuel elements to ensure that the Materials Testing Reactor would produce a high enough concentration of neutrons to determine which materials would hold up best for future reactors. The team designed the fuel elements of uranium sandwiched between aluminum plates surrounded by beryllium, to reflect neutrons back into the core. Wigner's best-known innovation was to curve the plates so they would bow in only one direction under intense heat, preventing constriction of water coolant flow, which determined neutron intensity. This design was a model for cores of U.S. research reactors and submarines.

In 1958 the British, using an early gas-cooled design, produced commercial nuclear electricity. With increased interest in a high-temperature gas-cooled reactor (HTGR), ORNL researchers focused on making fuel that could perform at high temperatures in a reactor cooled by helium and moderated by graphite.

They formed hundreds of spherical particles of uranium dioxide or uranium carbide, coated them with carbon to retain fission products, and embedded the fuel beads in graphite structures. Using the Oak Ridge Research Reactor, Don Trauger's team proved this fuel was stable when irradiated, unlike the design in which uranium carbide particles were dispersed in graphite. The ORNL team's findings caused the Germans to switch to coated-particle fuel in their HTGR. Improved versions of this design were used in two commercial U.S. HTGRs and in test reactors in Germany, Japan, and China.

ORNL researchers are now helping to develop meltdown-proof fuel beads for use in advanced HTGR concepts.

NUCLEAR SAFETY

Understanding the Challenge

ORNL has influenced nuclear safety in numerous ways. It trained more than 900 engineers in reactor design and safe operation. The Laboratory published the journal *Nuclear Safety* for more than 30 years. Since the 1960s ORNL has had a major impact on nuclear criticality safety—using industrial controls to protect against potential consequences of an unintentional, uncontrolled chain reaction during uranium or plutonium processing, storage, or transport. ORNL researchers provided the basis for several criticality safety standards and administered the international group approving this guidance.

In the late 1960s ORNL researchers led by Grady Whitman began studying whether steel walls of reactor pressure vessels exposed to high temperatures and embrittling radiation could withstand the water pressures of reactor operation without cracking. Having conducted research for more than three decades on thermal shock, fracture mechanics, and radiation embrittlement, ORNL became the world leader in producing data that have provided a basis for licensing and operation of light-water-reactor (LWR) pressure vessels.

ORNL research showing that zirconium-alloy fuel cladding became brittle under simulated accident conditions led to new regulations limiting LWR power levels. These results, reported by ORNL experts during national safety hearings, led to tighter requirements to lower the probability that reactor cores would overheat if emergency cooling water were lost. ORNL fission-product-release studies also provided a basis for safety regulations.

When a loss-of-coolant accident occurred in 1979 at the Three Mile Island power plant, ORNL researchers assisted the Nuclear Regulatory Commission in ascertaining causes and consequences of the accident and discovered that less radioactive gas was released than expected. As a result of the accident, ORNL and NRC staff developed the Sequence Coding and Search System, which captures information on nuclear power plant operations for inclusion in a database. The system has been used for numerous safety studies, regulatory actions, and risk assessments.

ORNL researchers developed accident models for NRC that prompted improvements in advanced boiling-water-reactor designs. They also have helped establish regulatory guides for digital instrumentation and control systems in nuclear plants.

1953

Transportable reactor designed by ORNL for Army's use at remote sites

ORACLE, world's then most powerful computer, installed at ORNL

1954

ORNL ecology program started

ORNL's experimental aircraft reactor tested

Tower Shielding Facility first operated, to provide data for ill-fated U.S. nuclear airplane project

First detailed study of chemical reaction using colliding molecular beams of two different reactants

1955

NUCLEAR DESALINATION

Thirsting for Solutions

The United Nations estimates that the number of people without access to safe drinking water is 1.1 billion, or nearly one in six persons worldwide. One solution is to draw water from the ocean and remove its salt.

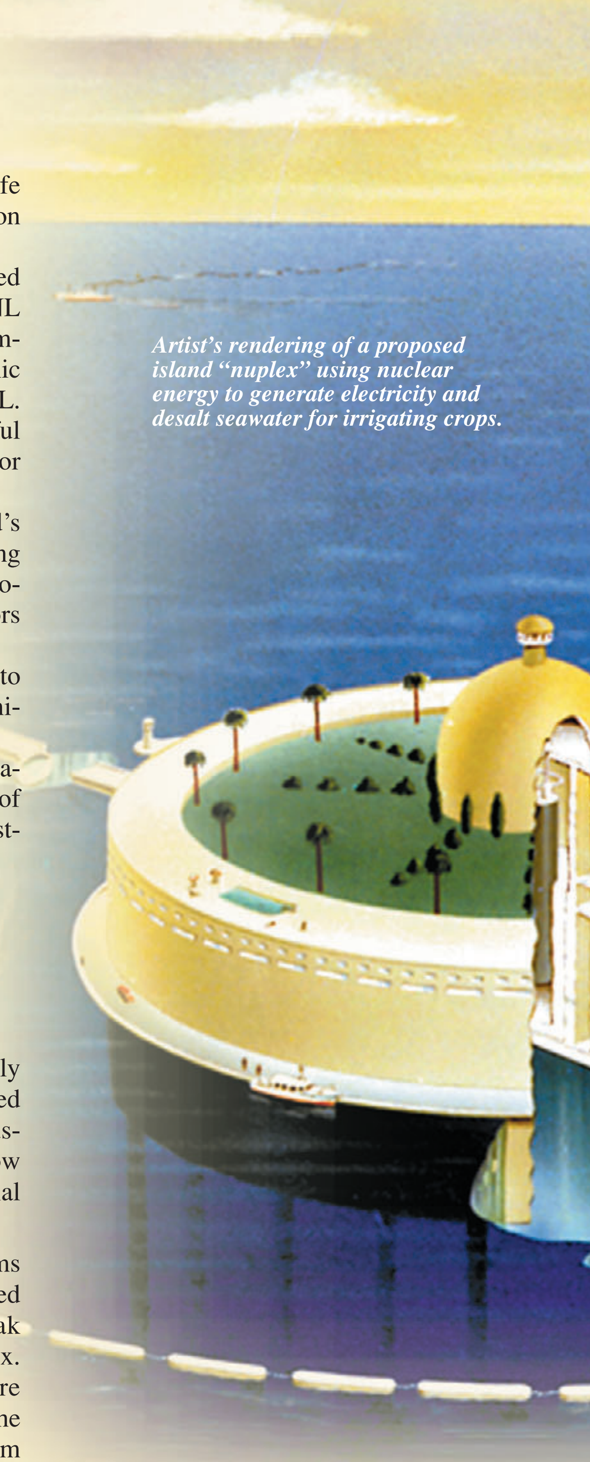
In 1963 ORNL's Philip Hammond promoted the idea that fresh water can be obtained cheaply by desalting seawater using excess heat from large nuclear power plants. ORNL Director Alvin Weinberg—then a member of President Kennedy's Science Advisory Committee—described this method of providing energy and making the "desert bloom" to Atomic Energy Commission and Interior Department officials and obtained project funding for ORNL.

Hammond's concept was featured at a 1964 United Nations Conference on Peaceful Uses of Atomic Energy in Geneva, was supported by President Johnson's 1965 "Water for Peace" program, and is endorsed by the International Atomic Energy Agency.

ORNL researchers contributed to desalination technology in two ways. Hammond's team improved distillation technology, to separate salt from seawater more efficiently using heat from nuclear plants. The group developed enhanced heat-transfer surfaces and processes for multi-stage flash distillation and designed aluminum vertical tube evaporators that were four times more efficient than contemporary models.

Kurt Kraus's team increased the efficiency of reverse osmosis (RO) and adapted it to desalination. In RO, pure water is produced by forcing salt-bearing water through a semi-permeable membrane that prevents salt passage.

RO is used in almost half of today's desalination plants. The heat source for desalination is oil or gas, except for a new plant in Kalpakkam, India, which is coupled to a pair of existing reactors. At least three other nations are developing desalination reactors, suggesting that nuclear desalination may become a major fresh water source.



Artist's rendering of a proposed island "nuplex" using nuclear energy to generate electricity and desalt seawater for irrigating crops.

NUCLEAR NONPROLIFERATION

Reducing the Nuclear Threat

After the Soviet Union was dissolved, its nations had nearly 1300 metric tons of weapons-usable nuclear material under varying degrees of safeguards and security. The U.S. feared that impoverished, unemployed weapons researchers might divert the material to terrorists or rogue nations. In response, the Department of Energy established nuclear nonproliferation programs that sponsor ORNL teams that have

- helped more than 80 Russian facilities secure weapons-usable nuclear materials, upgrade safeguards and security, and improve material accounting systems;
- helped the Russian Ministry of Defense improve weapons-systems security and worked with the U.S. Department of Defense to monitor the dismantlement of Russian weapons delivery systems;
- assisted Russian customs officials in detecting any nuclear materials being smuggled out of the country and provided them with radiation monitoring equipment and training;
- developed technology to verify that highly enriched uranium (HEU) from dismantled weapons has been blended down in Russian Federation facilities to produce low enriched uranium for use in commercial power plants;
- helped ensure in 1994 that 600 kilograms of HEU were loaded safely and shipped securely from Kazakhstan to the Oak Ridge Y-12 National Security Complex. Later, several hundred kilograms were transferred, with ORNL's help, from the Republic of Georgia to a United Kingdom processing facility. In 2002, an ORNL team worked with experts from DOE's National Nuclear Security Administration, the U.S. Department of State, and the International Atomic Energy Agency to safely remove 50 kg of HEU from a Yugoslavian reactor. The material was transported to Russia for conversion to reactor-grade fuel.

To reduce surplus weapons-grade plutonium from U.S. and Russian reactors, ORNL manages a multi-site effort to fabricate, irradiate, and test plutonium-based mixed-oxide (MOX) fuels for light-water reactors. ORNL manages and conducts research with Russia to develop the technology needed to fabricate MOX fuels for Russian reactors.

ORNL is creating meaningful jobs for former Soviet Union weapons researchers through the commercialization of indigenous technology and reindustrialization efforts.

ORNL's small "swimming-pool" reactor shown to President Eisenhower at UN conference

Alvin Weinberg named ORNL director, a position he held for 18 years

1956

Messenger RNA discovered; first bone marrow transplant demonstrated

Projections by National Academy of Sciences committee of genetic effects of radiation on humans, based on ORNL mouse data

1957

ORNL's first fusion research device (Direct-Current Experiment) built

Determination of permissible levels of radiation for medical uses and of radionuclides in the workplace influenced by ORNL leadership

ORNL's High Flux Isotope Reactor has been used for neutron-scattering studies since 1965. The reactor will have 15 new neutron-scattering instruments, and a cold neutron source will be added to slow neutrons, making them excellent probes for polymers and proteins.

NEUTRON SCATTERING

Instruments of Change

In 1994 Clifford Shull, who pioneered the use of neutron scattering for materials research at the Oak Ridge Graphite Reactor, shared the Nobel Prize for physics. Shull and his mentor, Ernest Wollan, used neutron scattering to determine where atoms are in a crystal. Neutron scattering has been used in reactors worldwide to probe the structure and dynamics of materials. The research has led to the development of high-strength plastics and the improved magnetic materials found in small motors, credit cards, computer disks, and compact discs.

In late 1945 Wollan, who had studied solids and gases using X-ray scattering, considered using neutrons from the Graphite Reactor for scattering studies. He produced a single-wavelength neutron beam by passing reactor neutrons through a crystal and used a spectrometer to measure the angles and energies at which neutrons are scattered by interacting with the nuclei of atoms in the target material. This information helped reveal material structure.

A year later, Shull and Wollan produced the first neutron diffraction pattern of a sodium chloride crystal and of polycrystalline manganese oxide (MnO). They also made the first neutron radiograph, determined how to correlate the intensities of scattered neutrons with the structure of the target material, and precisely located the positions of light atoms in sodium hydride and sodium deuteride.

In 1951 Shull showed the magnetic structure of the MnO crystal, which led to the discovery of antiferromagnetism (where some atoms of magnetic material point up and some point down). Because neutrons are tiny magnets, their interaction with atoms of magnetic material provides data important to the recording and computer industries.

In the late 1950s and early 1960s, neutron-scattering studies of magnetic structures and properties of rare earths were carried out by Ralph Moon, Wallace Koehler, Mike Wilkinson, and others at the Oak Ridge Research Reactor. Henri Levy, Selmer Peterson, Bill Busing, and George Brown pioneered single-crystal neutron-diffraction studies that revealed the structure of sugar and other crystals.

In 1965 the new High Flux Isotope Reactor (HFIR) began providing much higher intensities for neutron-scattering research, allowing studies of excited states of matter using triple-axis spectrometers. Wilkinson and Herb Mook used HFIR to scatter neutrons off helium-4 nuclei, to study the presence of Bose-Einstein condensation in the helium-4 when its atoms were chilled to near absolute zero.

Using a triple-axis spectrometer, Bob Nicklow and Harold Smith studied the superconducting crystal tantalum carbide and found evidence to support a theory of low-temperature superconductivity. In the 1970s Mook and his associates established the coexistence of superconductivity and magnetism in rare-earth rhodium borides.

Small-angle-neutron-scattering (SANS) studies began at HFIR, where Koehler established the National Center for Small-Angle Scattering Research. High-temperature superconducting oxides were discovered in 1986, so HFIR was used to help determine the structure of the new materials because neutrons could determine the position of light oxygen atoms better than X rays. Triple-axis measurements also elucidated the excited magnetic and lattice states, helping theorists explain high-temperature superconductivity.

Throughout the 1990s, SANS experiments led by George Wignall in collaboration with the University of North Carolina examined ways that polymers could be produced by using supercritical carbon dioxide as the organic solvent instead of traditionally used chlorofluorocarbons (believed to be depleting our protective ozone layer).

Measurements of residual stress also began at HFIR. One study focused on paper mill boilers clad with a steel alloy that can crack, leading to explosions. The measurements determined that use of a new steel alloy would prevent the problem.

In December 1999 ground was broken for the accelerator-based Spallation Neutron Source (SNS); among those present was Vice President Al Gore. The SNS, to be completed in 2006, will continue ORNL's tradition of world-class neutron-scattering studies.

1958

Startup of Oak Ridge Research Reactor

Project Salt Vault, the first national effort to site a high-level nuclear waste repository, started by ORNL

1959

Reactor shielding for the first U.S. nuclear-powered civilian ship evaluated by ORNL researchers

Maleness in mouse found to depend on presence of Y chromosome

SEMICONDUCTORS

Shaping the Digital Future

Over the past four decades ORNL researchers provided key information and technologies that sparked the growth and improved the economics of the semiconductor industry.

In 1962 Ordean Oen and Mark Robinson, while conducting theoretical research on radiation damage in crystalline materials, ran computer simulations that revealed the ion channeling effect—the long-range motion of atoms parallel to long rows of atoms in the solid. This work and energetic ion-channeling experiments by Thomas Noggle, Bill Appleton, Charles Moak, Sheldon Datz, Herb Krause, and others enabled understanding of channeling phenomena, helping industry produce ion-implanted semiconductor materials with the right properties.

In the 1960s, using the Bulk Shielding Reactor, John Cleland and other ORNL scientists devised a neutron transmutation doping (NTD) method for uniformly distributing phosphorus ions in silicon. More than 100 tons of NTD silicon are produced worldwide each year for use in electronic components.

By combining accelerator-based ion-implantation doping and laser annealing, Rosa Young, C.W. White, and Greg Clarke introduced boron ions into the near surface of a silicon crystal and incorporated them into electrically active sites, while removing all displacement damage in the silicon lattice. This work provided the foundation for the development of rapid thermal annealing, a process widely used in the semiconductor industry.

In 1998 Ken Tobin and associates built two award-winning software tools that help companies rapidly identify manufacturing problems that cause semiconductor wafer defects, thus reducing defect generation, increasing product yield, and cutting costs. These tools have been licensed to Applied Materials, IBM, Motorola, Texas Instruments, and 20 other companies.

ORNL's award-winning direct-to-digital holography process transferred to nLine rapidly finds small defects in deep-lying contacts and trenches in wafers. Tony Moore and associates invented a sensor-based system to control radiofrequency power that produces plasmas for etching wafer circuit patterns. Use of ORNL's system has saved the industry millions of dollars.

SUPERCONDUCTORS

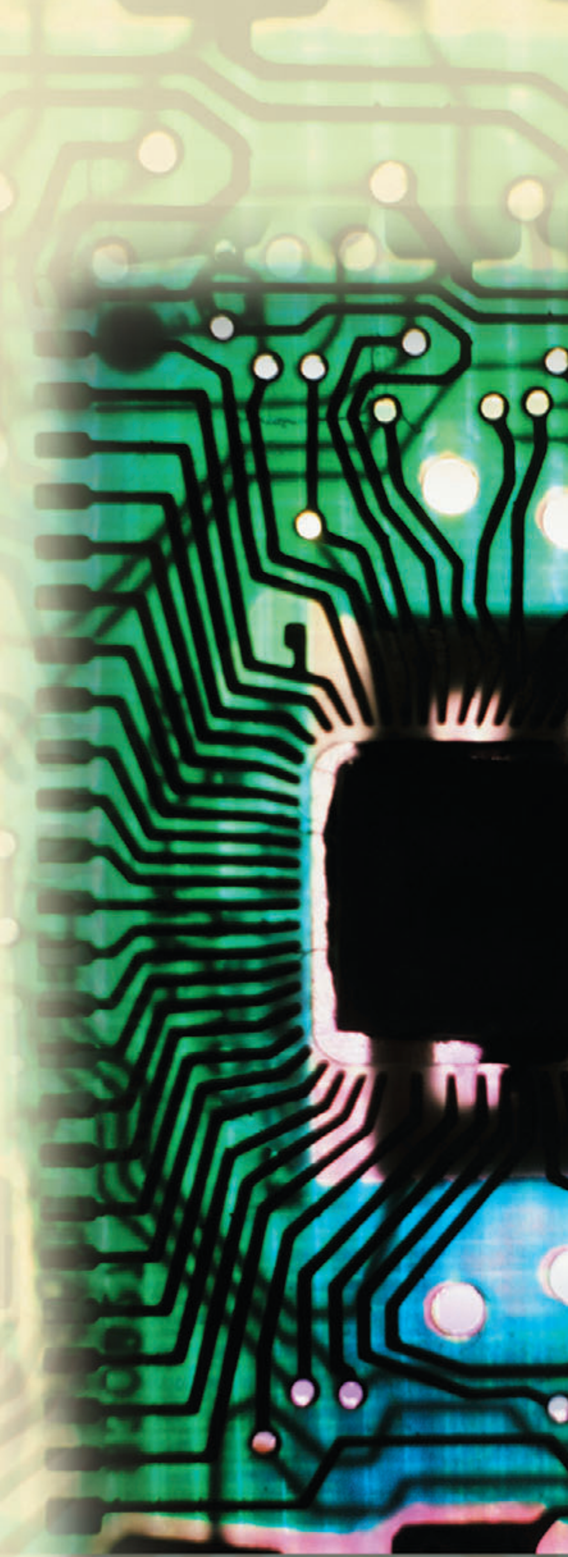
Experiencing the Power

The power grid of the future will be more efficient than the present one, thanks to high-temperature superconducting (HTS) wires and cables. HTS wires—being developed by ORNL researchers in collaboration with industrial partners to exploit a phenomenon discovered in 1986—offer much less resistance to the flow of electricity than do copper lines. Devices with such wires will take less space, cost less to operate, and use less energy than equivalent technologies. Superconducting cables in the U.S. power grid will conduct five times as much current as a copper cable of the same size. Because an HTS cable loses little energy as heat, it will cut electrical transmission losses in half, from 8% to 4%.

Using ORNL's rolling assisted, biaxially textured substrates (RABiTS™) technology, developed in 1995, American Superconductor has produced unprecedented 10-meter lengths of nickel-tungsten tapes on which a superconductive oxide and buffer layers have been deposited in alignment with the alloy texture. These tapes carry 100 amperes per centimeter of width, exceeding a Department of Energy goal for 2003. 3M and three other companies seek to commercialize the award-winning ORNL technology. RABiTS™ wires should be available commercially later in this decade for underground transmission cables, motors, transformers, and magnets.

ORNL researchers helped Southwire develop an HTS cable 30 meters long for the company's facility in Carrollton, Georgia. The cable—made of bismuth-strontium-calcium-copper oxide first-generation wires chilled by liquid nitrogen—has operated more than 16,000 hours. RABITS™ wires will be used in second-generation Southwire cables.

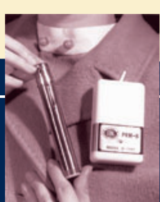
ORNL researchers also have developed an innovative cryogenic system to chill HTS wires in a superconducting transformer built by Waukesha Electric Systems and IGC-Superpower. Waukesha's transformer, which uses no flammable oil as do conventional transformers, is to be laboratory tested in 2003.



ORNL's work helped industry produce semiconductor chips for computers economically.

1960

Pocket screamer devised for use as personnel radiation monitor

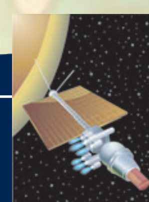


Program started to measure genetic effects of chemicals on mice

ORTEC and Tennelec founded by ORNL employees

1961

Development begun on radioisotope heat sources to power space satellites



Neutron transmutation doping method developed at ORNL reactor; later used for making electronic components

An ion-implanted hip joint

ION-IMPLANTED MATERIALS

Real Artificial Joints

The remarkable discovery of ion channeling by purely theoretical means at ORNL ultimately led to accelerator-based programs to introduce ions into materials. Ion implantation was found to improve the surfaces of many materials, including alloys used to make artificial hips and knees. Research was performed by ORNL's Jim Williams in collaboration with Ray Buchanan, then at the University of Alabama and now at the University of Tennessee. They discovered in 1980 that implanting the titanium alloy used in artificial joints with nitrogen ions hardens the alloy and greatly improves its resistance to wear and corrosion.

Ion implantation was found to improve both the titanium and cobalt-chrome alloys used to make surgically implantable artificial joints, but different mechanisms are involved. The technique hardens the titanium alloy's surface so that it cannot be scratched by the alloy's own oxide coating (which reduces surface chemical reactivity). For the cobalt-chrome alloy, ion implantation improves its wettability so that the artificial joint slides more easily and makes the surface hardness more uniform. Thus, the alloy interacts better with its mating polymer component, extending its life. In the early 1990s the Food and Drug Administration issued guidance requiring that all newly submitted titanium orthopedic devices be ion implanted.

Ion implantation of orthopedic materials was first applied commercially by Spire Corporation and then by Implant Sciences Corporation. Combined sales of several hundred thousand devices per year amount to about $10 million annually to the orthopedics manufacturers for wholesale surface treatments. Williams estimates that cumulative sales for the treatments are well over $100 million. The more important benefit, however, lies in the improved lives and comfort levels for millions of Americans who have ion-implanted artificial hips, knees, and other joints.

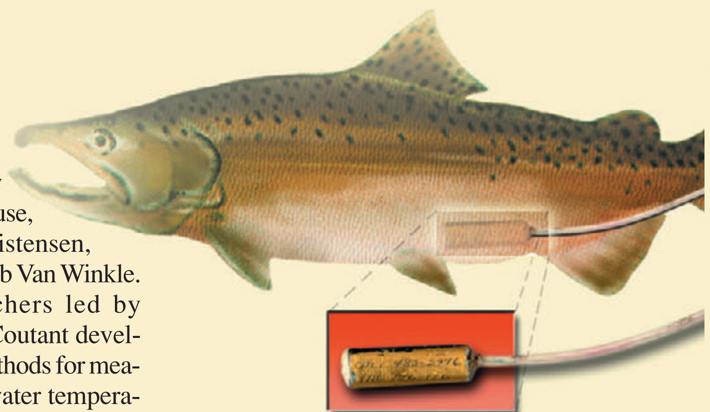
ENVIRONMENTAL IMPACT ANALYSES

Searching for the Balance

Before federally funded or approved installations can be constructed, the effects of the projects must be scrutinized. Their costs and benefits must be weighed in environmental impact statements (EIS), which have been prepared for nuclear power plants since 1971. Researchers from ORNL and three other national laboratories became involved in a crash project to draft EIS's for 90 operating nuclear power plants, as well as those under construction or on the drawing boards. Also in the 1970s, ORNL was involved in decisions about whether cooling towers should be built for proposed power plants to protect the Hudson River's striped bass.

During that decade and after, many questions arose. Will fish populations decline if fish pass through power plant cooling systems or are exposed to heated water discharged by nuclear facilities? How much radioactivity are workers and the public exposed to during normal operation of nuclear plants? What are the environmental and socioeconomic impacts of geothermal, solar, fossil, synthetic-fuel, biomass-conversion, and hydropower projects? To address these and other questions, the EIS team headed by ORNL's Ed Struxness, Bill Fulkerson, Tom Row, and Johnnie Cannon conducted considerable research.

To assess impacts on fish of passing through intake screens, ORNL researchers developed computer models under the leadership of Larry Barnthouse, Sig Christensen, and Webb Van Winkle. Researchers led by Chuck Coutant developed methods for measuring water temperature preferences of fish and motivated the development of power plant engineering controls to minimize damage to nearby fish populations.



ORNL engineers developed an electronic tag that can be surgically implanted in a fish. This tag, which emits ultrasonic signals, is being used to observe the behavior of salmon near hydroelectric dams—information that will facilitate the fish's safe upstream and downstream passage.

ORNL researchers have been national leaders in developing fish protection devices for hydropower plants, examining socioeconomic and cultural impacts of power plant construction and operation, and predicting risks and benefits of operations ranging from research facilities in Antarctica to the permanent high-level nuclear waste repository approved by Congress for Nevada's Yucca Mountain.

1962

Health Physics Research Reactor completed

Ion channeling discovered with aid of computer modeling

Civil defense research program started

Forest stand tagged with cesium-137; analyses showed hazards of fallout from nuclear weapons testing

1963

Radiation Shielding Information Center established at ORNL

Oak Ridge Isochronous Cyclotron first operated

ENVIRONMENTAL QUALITY

Planting Scientific Seeds

What are the effects of radioactive and toxic substances from industrial facilities on the plants and animals that make up an ecosystem? How do ecosystems interact with the earth's atmosphere? ORNL has helped answer these and other questions for more than half a century, creating new fields of ecological study.

In the 1950s ORNL researchers pioneered the use of radionuclides as tracers for the natural movement of elements in ecosystems, including forest nutrients and pollutants. Work by Stan Auerbach, Dan Nelson, Jerry Olson, and others led to the development of the field of radioecology.

Olson, Bob O'Neill, and others pioneered the development of computer models to understand ecosystem structure and function and the movement of elements, nutrients, and pollutants in forest ecosystems, spawning systems ecology.

In 1958 ORNL scientists established a major study of the Clinch River—first regularly sampled in 1947 because it was near ORNL—along with numerous federal and state agencies. This was the first multiagency effort to evaluate potential long-term hazards of radionuclide releases from a major nuclear facility.

Using a Ford Foundation grant in the early 1960s, ORNL researchers developed advanced mathematical and computer approaches to understanding changes in terrestrial ecosystems. They tagged a forest stand with cesium-137—a pioneering large-scale use of a radioactive waste material—to provide data for new computer models, which showed the ill effects of long-term contamination of landscapes by radioactive fallout from atmospheric weapons testing.

Because of its contributions, in 1967 ORNL was selected and funded by the National Science Foundation to lead a major U.S. ecosystem research program under the International Biological Program. This multimillion-dollar effort involving several hundred scientists and graduate students worldwide produced valuable information on the role of ecosystems in the global carbon cycle.

In the same year, the Walker Branch Watershed research facility was first used to study ecosystem processes in water and on land and then atmospheric deposition of pollutants. In 1975, Steve Lindberg determined that 40 to 70% of sulfuric and nitric acids deposited on forests arrive as dry particulates rather than in rain.

ORNL research then began on the biological effects of chemicals produced by converting coal to liquid and gaseous "synfuels." In 1980 cricket eggs exposed to synthetic fuel chemicals were found to produce insects with an extra eye or head. Owing to these studies, Barbara Walton, Glenn Suter, and Larry Barnthouse helped develop the field of ecological risk assessment and an ecological risk assessment framework later adopted by the U.S. Environmental Protection Agency.

By the 1980s ORNL was an established leader in the development and use of computer models of ecosystems, including "individual-based models" of Michael Huston, Don DeAngelis, and Mac Post that predicted ecological and evolutionary changes in forests and fish populations. During the 1990s O'Neill, Virginia Dale, and others contributed to the development of the field of landscape ecology (e.g., studies of effects of fires and volcanic eruptions).

By 1990 ORNL's Sandy McLaughlin, Dale Johnson, Lindberg, and others completed 10 years of research support to the National Acid Precipitation Assessment Program. This work led to restrictions on industrial emissions of sulfur and nitrogen oxides.

In 1994 ORNL established the world's largest global change experiment in a forest. It demonstrated the effects of both drought and unusually wet conditions potentially resulting from climate change.

In 1998 ORNL began operating the Free Air Carbon Dioxide Enrichment facility, to evaluate the effects of increased atmospheric carbon dioxide on a sweetgum plantation. Early findings showed that the plantation's trees grow faster than those in a normal atmosphere.

ORNL mercury research led by Ralph Turner resulted in a faster, less costly removal of soil mercury from Oak Ridge land contaminated by a mid-century hydrogen bomb project. Conclusions of studies by Lindberg and others on atmospheric mercury were used by EPA in its report to Congress, resulting in federal recommendations for controls of mercury emissions from combustion sources.

Standing in a hydraulic lift, Rich Norby collects leaves in ORNL's sweetgum forest being used to test effects of an atmosphere enriched in carbon dioxide.

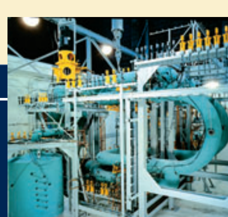
1964

ORNL concept of nuclear desalination featured at UN conference

ORNL becomes first national lab to hire social scientists (initially for civil defense research)

1965

Startup of High Flux Isotope Reactor (HFIR) and Molten Salt Reactor (MSR)

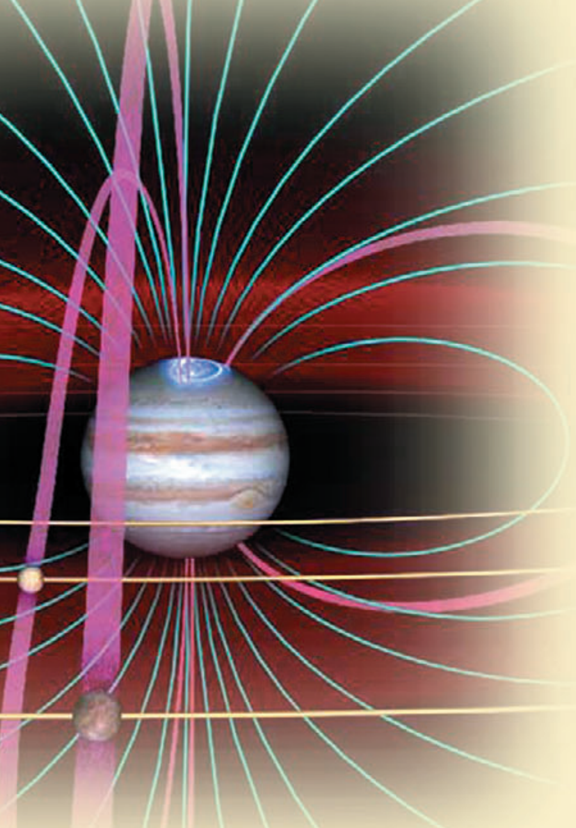


ORNL-UT graduate program in biomedical science established

Heavy-Section Steel Technology program for reactor safety studies begun

1966

Graphite Reactor named a National Historic Landmark



The vast magnetosphere of charged particles whirling around Jupiter, normally invisible, can be seen here, thanks to a new type of imaging instrument aboard NASA's Cassini spacecraft (which has ORNL materials aboard).

SPACE EXPLORATION

Science for the Final Frontier

On August 20, 2002, the National Aeronautics and Space Administration celebrated the 25th anniversary of the Voyager 2 space probe's odyssey through our solar system—perhaps humanity's greatest feat of space exploration. Voyager 2 sent to Earth spectacular photographs of the planetary terrains, rings, and moons of Jupiter, Saturn, Uranus, and Neptune. Voyager 2, now well over 6 billion miles away from the sun, is carrying materials made at ORNL.

In 1975, ORNL researchers led by C. T. Liu developed an iridium alloy needed to clad spheres of plutonium-238 oxide fuel in the Voyager 1 and 2 spacecraft, which were launched in 1977. The radioactive fuel is used to supply electrical power to the space probes' experiments and communication equipment. The iridium-alloy cladding would prevent the fuel from escaping into the environment in the unlikely event that the spacecraft would accidentally re-enter Earth's atmosphere, undergo its searing heat, and strike Earth's surface.

Pure iridium has a high melting point and excellent resistance to oxidation at elevated temperatures but is too weak and brittle to withstand maximum impact. ORNL researchers discovered that adding just the right levels of alloying agents (e.g., thorium) imparted the extra ductility that would enable the iridium alloy to withstand the impact forces of maximum credible accidents.

Another ORNL material aboard Voyagers 1 and 2 is thermal insulation composed of bonded mattes of carbon fiber, needed to maintain the fuel cladding in a preferred temperature range. The two ORNL materials, which are still being produced, also are aboard NASA's Galileo, in orbit around Jupiter, and Cassini, a spacecraft headed for orbit around Saturn in July 2004.

ORNL researchers also helped design radiation shielding for moon-bound astronauts, scoops for collecting moon rocks, and boxes to hold them on Earth. The next project is to design a power conversion system for a possible nuclear reactor on a Mars-bound spacecraft.

GRAPHITE AND CARBON PRODUCTS

From Missiles to NASCAR

The name Graphite Reactor acknowledges graphite's desirable properties. This form of crystallized carbon was chosen as the moderator for both Oak Ridge's first reactor and the Hanford plutonium-production reactors. Graphite not only slows neutrons from uranium fission enough for plutonium to form but also grows stronger at high temperatures and resists radiation damage.

In the 1940s Eugene Wigner correctly predicted that neutron irradiation of graphite would cause it to swell. Concern about "Wigner disease" helped spur the growth of ORNL materials research.

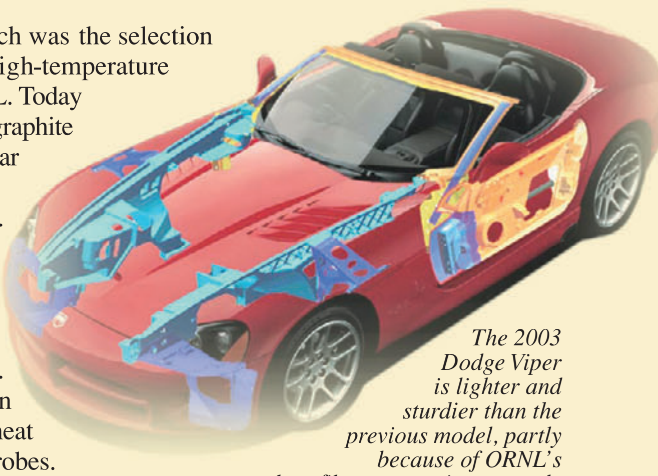
By controlling the orientation of graphite's crystalline grains, ORNL's Walt Eatherly, Ray Kennedy, and Fred Jeffers developed the award-winning GraphNOL, which was commercialized in the 1980s. This graphite, which resists radiation damage and withstands extreme thermal shock and stress, has been used in missile nose cones.

One motivation for this research was the selection of graphite as the moderator for high-temperature gas-cooled reactors designed at ORNL. Today Laboratory researchers are assessing graphite properties and standards for the Nuclear Regulatory Commission as part of the advanced gas-cooled-reactor program.

In the 1960s, Oak Ridge researchers led by John Googin developed the first method to produce carbon foams, which have been used as high-temperature furnace insulation. Carbon-bonded carbon-fiber insulation was developed at ORNL for use in heat sources aboard satellites and space probes.

In the 1990s Ted Besmann and others developed carbon-composite bipolar plates to make lighter, longer lasting auto fuel cells. The technology was licensed to Porvair, Inc., which is installing a pilot unit to produce plates for a major fuel-cell developer.

Tim Burchell and James Klett developed a process that was commercialized for making carbon-carbon brake discs that give airplanes better stopping power. In 1998 Klett produced graphite foam that transfers heat unusually well. This licensed technology has uses for vehicles, electronics, and homeland security.

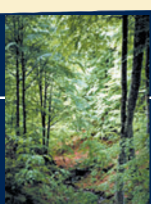


The 2003 Dodge Viper is lighter and sturdier than the previous model, partly because of ORNL's carbon-fiber-composite research. (Courtesy of the Chrysler Group)

KENO Monte Carlo code developed for assessments of nuclear criticality safety

1967

Walker Branch Watershed research facility opens for ecosystem studies



ORNL selected to lead U.S. ecosystem research under International Biological Program

Viruses separated in high-speed ORNL centrifuges

Simulation code developed for assessments of protective ability of radiation shields

1968

Second MSR operated using uranium-233 (first reactor to use this fuel)

ADVANCED MATERIALS

Alloys for Industry

Material synthesis. The first ORNL-developed alloy to be commercialized was Hastelloy-N, first sold by International Nickel Company and now marketed by Haynes International. This nickel-molybdenum-copper-iron alloy was developed by Hank Inouye and others to contain the fuel used in the ORNL-developed molten-salt reactor. The alloy resists aging, embrittlement, and corrosion from exposure to hot fluoride salts.

Another commercialized alloy, modified chrome-moly steel, was developed by ORNL's Vinod Sikka and others in collaboration with Combustion Engineering for the nation's breeder reactor program. For 20 years the alloy has been produced by companies in France, Germany, Japan, and the United States for a total of more than $400 million in sales.

This alloy, which has excellent high-temperature mechanical properties, doesn't easily corrode or deform under normal operating conditions. Made mostly of iron, it is 9% by weight chromium and 1% by weight molybdenum, with a few trace elements added. It is used in utility boilers that produce electricity and in oil refinery furnaces that make unleaded gasoline.

Another alloy developed for the breeder project was an austenitic stainless steel that does not swell and become embrittled when exposed to high temperatures and fast neutrons (as explained by ORNL's Jim Weir). Jim Stiegler, Everett Bloom, and Arthur Rowcliffe developed a low-swelling stainless-steel alloy by doping it with silicon and titanium, using microstructural control technology. The alloy has been used for fuel cladding in breeder reactors in Japan and France.

ORNL's C. T. Liu and others developed modified nickel aluminide alloys that are now used to replace Bethlehem Steel's steel rolls (for moving steel plates into a furnace) and to make trays for Delphi Automotive Systems for heating and hardening surfaces of automotive ball bearings, gears, and valves.

Welding. ORNL, which has an international reputation in materials joining, has produced computer models that have helped U.S. industry solve problems in welding stainless-steel and nickel-aluminide alloys. ORNL researchers developed a test to evaluate weld-cracking susceptibility and brazing techniques that have been used nationwide. Laboratory models are guiding industrial welding repairs of nickel-based-superalloy, single-crystal turbine blades to be used in power-producing, land-based gas turbines. To help secure sensitive nuclear technologies, researchers led by Stan David and John Vitek are working with former weapons researchers in the Ukraine to develop repair-welding techniques for turbine engine components.

Material characterization. The design of low-swelling stainless steels at ORNL was enabled by parallel developments in analytical electron microscopy and transmission electron microscopy. AEM and TEM, as well as the three-dimensional atom-probe-field ion microscopy refined and used at ORNL, made possible a thorough understanding of microstructure and the composition of microscopic precipitates that form in steel during its manufacture. ORNL metallurgists changed steel composition to engineer its microstructure and obtain desired properties.

Since the 1960s ORNL researchers have developed optics to significantly improve the brightness and intensity of X rays for analyzing materials structure. Cullie Sparks' graphite monochrometer crystals are used worldwide for X rays and neutrons. In the 1980s Sparks and Gene Ice invented an X-ray-focusing method using curved perfect crystals for studies at synchrotron sources. Their precision crystal-bending methods that focus 20 times more radiation than alternative optics are now used in the world's most sophisticated X-ray facilities. In 2001 Ice and Ben Larson developed an X-ray microscope that enables studies of crystal grain structure with submicron resolution in three dimensions.

Z-contrast imaging of crystals, developed at ORNL by Steve Pennycook and others in the 1990s, allows scientists to use a scanning transmission electron microscope to see columns of atoms in materials ranging from superconductors to automobile catalysts. This technique achieved the highest-resolution image of a crystal ever produced. It is now available on commercially produced microscopes and is used worldwide.

Computer models of arc welding have been built at ORNL.

Centrifugal fast analyzer invented for medical diagnoses

Ultrapure vaccines produced using ORNL-developed zonal centrifuges

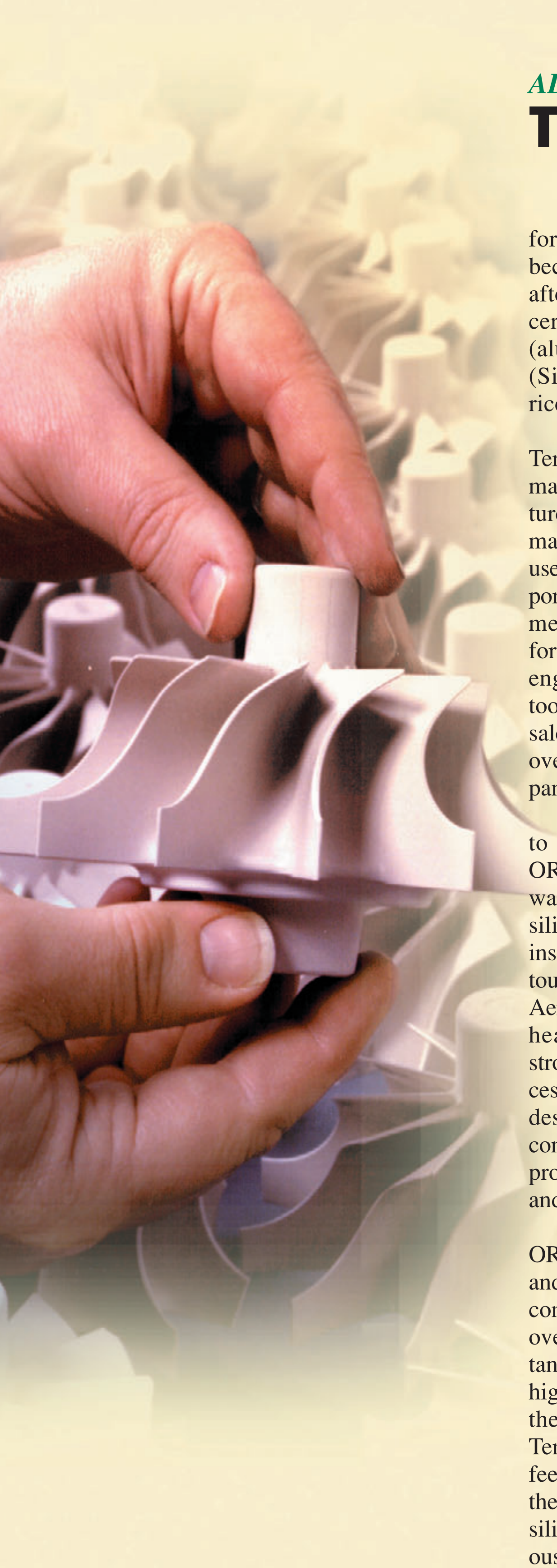
Stainless-steel alloy designed to better resist neutron-induced swelling

1969

Neutron cross-section measurements first made using new Oak Ridge Electron Linear Accelerator

ORNL becomes leader in geographic information systems combined with remote sensing

Apollo 11 moon rock scoop designed



Ceramic materials developed for gas turbine rotors are used in aircraft and diesel engine parts.

ADVANCED MATERIALS

Tools, Turbines, & Diesel Engines

Many innovations do not make it from the lab to the factory for 10 to 15 years, but one ORNL ceramic became a commercial product three years after it was discovered. This hall-of-fame ceramic is a composite of aluminum oxide (alumina) and microscopic silicon carbide (SiC) whiskers made from the common rice hull.

In 1981-82 ORNL's George Wei, Terry Tiegs, and Paul Becher discovered this material, which has high strength and fracture toughness. By 1985 the technology for making the patented composite was being used by Advanced Composite Materials Corporation and Greenleaf Corporation for commercial cutting tools. SiC-whisker-reinforced alumina cutting tools can machine jet engine components ten times faster than tools made of competing materials. Annual sales of these tools in the United States are over $20 million. Sandvik, a Swedish company, sells the cutting tools worldwide.

SiC whiskers were eventually found to be a health hazard if inhaled, but the ORNL concept of whisker reinforcement was key to the development of improved silicon nitrides in which seed crystals grow inside the material as it sinters, making it tougher. Research at ORNL and the National Aeronautics and Space Administration, with heavy industry investment, spawned a strong, fracture-resistant silicon nitride, processes to produce this ceramic, and advanced designs for turbines using silicon nitride components. The result was a significant improvement in the performance, emissions, and durability of small gas turbines.

Under the leadership of Ray Johnson, ORNL researchers Vic Tennery, Matt Ferber, and Ken Liu tested and characterized silicon nitride samples from different suppliers over several years to determine their resistance to fast fracture, fatigue, and creep at high temperatures. For this work, they used the sophisticated equipment at the High Temperature Materials Laboratory. ORNL's feedback to ceramic manufacturers helped them dramatically improve the properties of silicon nitride so it would not fail under various conditions.

This tougher silicon nitride—originally developed for the Department of Energy's industry program to design advanced gas turbines to power cars—is being used in commercial components aboard aircraft and in diesel trucks. Honeywell found that silicon nitride components survive airport dust and grit better than metal parts in auxiliary power units (APUs) that generate electricity for air conditioning, electronics, and certain nonessential services on airplanes parked at the gate. Since 1992, APUs with silicon nitride parts have been flying on Boeing and Airbus aircraft.

Since 1996, Honeywell and Kyocera have fabricated durable silicon nitride oil seals that more effectively prevent leakages from fuel pumps in small business jets. These seals were installed in 7000 jet engines that have more than 6 million accumulated flight hours.

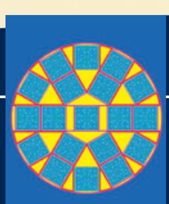
Silicon nitride parts are being incorporated into next-generation, high-efficiency, low-emission microturbines, as well as larger gas turbines, for stationary power generation. Current metal microturbines operate at efficiencies of about 25%; the incorporation of ceramics allowing hotter operation should raise that efficiency to 35 or 40%. Honeywell is making prototype ceramic wheels for a microturbine manufacturer, using the gelcasting process developed by ORNL's Mark Janney and Omats Omatete for fabricating large, complex-shaped components.

Improved silicon nitride also is being used to help reduce exhaust emissions from large diesel engines in highway trucks. To meet Environmental Protection Agency standards, diesel fuel-injection systems must be run at high pressures to reduce emissions. Because cam-roller followers are part of the mechanical chain that creates high fuel pressures, they must withstand high stresses. Silicon nitride produced by Ceradyne has been used to make cam roller-followers for Detroit Diesel Corporation. Kyocera has sold more than 3 million of the parts for diesel trucks.

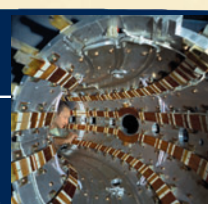
Another ceramic that ORNL helped improve is transformation-toughened zirconia (TTZ), made by CoorsTEC and sold to Cummins Engine Company for diesel trucks. Cummins has experienced virtually no problems with the millions of TTZ plungers it makes for its high-pressure fuel injectors.

1970

SCALE code developed to help ensure safe storage and transportation of spent nuclear fuel



ORMAK–the Lab's first doughnut-shaped (tokamak) fusion research machine–operated for plasma physics experiments



1971

Aquatic Ecology Laboratory built; data on fishes' water temperature preferences obtained for environmental impact statements

The likely shape of a deformed uranium-234 nucleus determined in accelerator studies

1972

Energy conservation research program launched

BIOLOGICAL SYSTEMS

Cleaning with Bacteria

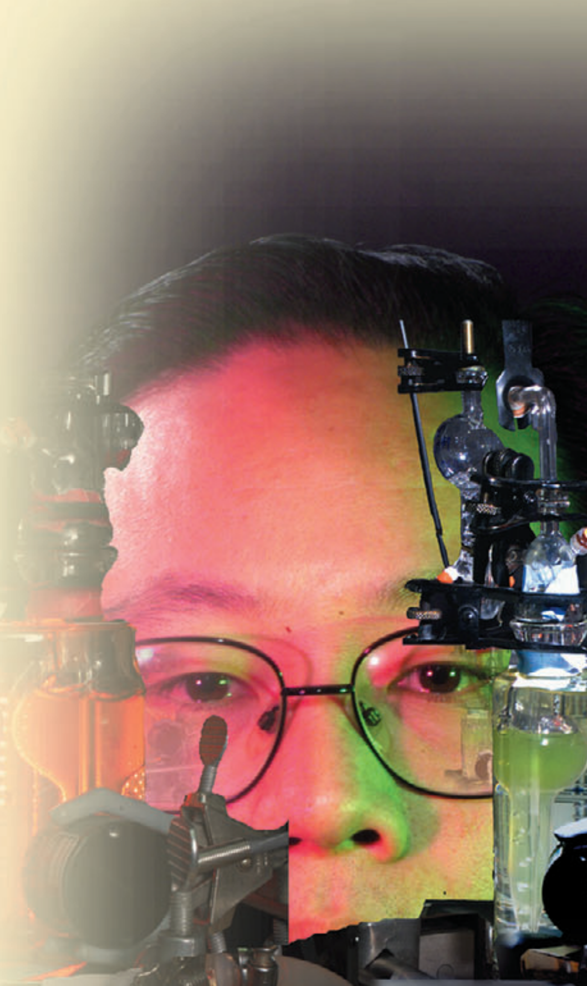
An early example of biotechnology at ORNL was the 1972 demonstration by Chet Francis that garden soil bacteria in bioreactors could remove nitrates and trace metals from industrial waste effluents. ORNL built a pilot bioreactor to treat nitrate wastes at the uranium enrichment plant in Portsmouth, Ohio. The Oak Ridge Y-12 National Security Complex used Francis' design for a full-scale plant to treat nitric acid wastes. Bioremediation has continued at these sites using recombinant and natural bacteria to treat wastes underground.

In 1997 lysimeter experiments, ORNL used a genetically engineered microorganism to detect soil contaminants; its controlled release into the environment at a Department of Energy site was the first to be approved by government agencies.

In the 1960s Howard Adler and associates were studying the effects of radiation on *Escherichia coli*. Some radiation-damaged bacteria died except, mysteriously, when they were grown in the presence of other bacteria. The eventual explanation was an enzyme-containing membrane fraction from those other bacteria, which removed oxygen from the media, allowing the damaged *E. coli* bacteria to recover.

Adler and Jim Copeland developed a technique for extracting and freezing these membrane fragments and using them to remove oxygen from liquid media that support the growth of anaerobic bacteria (which die in oxygen). Their technique is useful for early detection of diseases caused by anaerobic bacteria, such as gangrene and tetanus, as well as production of chemicals like butanol. In 1987 they formed Oxyrase, a company that continues to sell diagnostic media to hospital pathology and research labs in North and South America, Asia, and Europe.

ORNL and other DOE national laboratories, working with Applied CarboChemicals (ACC), developed a fermentation process using a novel microorganism that converts corn sugar to succinic acid, needed in the manufacture of de-icers, food additives, solvents, and ultimately plastics. ORNL's Nhuan Nghiem and Brian Davison developed the fermentation process in a bioreactor. ACC recently demonstrated this soon-to-be commercialized process with a 100,000-liter fermentation.—*Brian Davison*



Finding the Light

Several ORNL biologists interested in studying green plant cells and radiation focused on photosynthesis. In this process, plants synthesize carbohydrates (tissues) from airborne carbon dioxide and water, using light as an energy source.

William Arnold and Robert Emerson identified the photosynthetic unit in pioneering studies that led to Arnold's 1966 discovery of delayed light, an internationally recognized fundamental discovery in photosynthesis. (Arnold also is known for coining the term "nuclear fission," used universally to describe the process of splitting atomic nuclei.) Roderick Clayton provided evidence for the electronic nature of the first step of photosynthesis.

In the 1970s and 1980s Robert Pearlstein developed theoretical models that described the migration of light energy in the chlorophyll antenna lattice of green plants and bacteria. Later in the 1980s Elias Greenbaum and his ORNL colleagues Perry Eubanks, Jim Thompson, Mark Reeves, and Ginger Tevault used photosynthesis in spinach and later algae to split water molecules to produce oxygen and the energy-rich gas, hydrogen. In 1985 Greenbaum demonstrated direct electrical contact of photosynthetic electrons with platinum metal nanoparticles; this work was featured on the cover of *Science* magazine. In 1995, Greenbaum, working in collaboration with Ida Lee and James Lee, discovered the diode properties of isolated Photosystem I reaction centers. In 2000, the continuation of this work led to the first measurement of photovoltages of isolated photosynthetic reaction centers.

In 2002 Greenbaum and his associates at ORNL and the University of Southern California investigated the use of photosynthetic reaction centers for restoring sight to the legally blind. ORNL has had only a handful of photosynthesis researchers, but they all have made noteworthy contributions to this field.

James Lee helped show that hydrogen can be produced photosynthetically by algae in illuminated water.

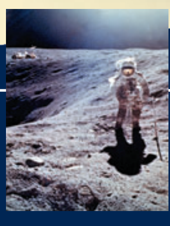
Mouse embryos frozen, thawed, and implanted in surrogate mothers who gave birth to healthy mouse pups

Garden soil bacteria in bioreactors found to remove nitrates and trace metals from industrial waste

Discovery of giant quadrupole resonance; wide study of these giant vibrational modes of nuclei resulted

1973

Composition of moon rocks analyzed



Ultrasonic fish tag devised to measure and transmit fish's water temperature preferences

BIOLOGICAL SYSTEMS

Glimpses of Life's Fabric

ORNL's biological research program was established to determine the nature and effects of radiation on living cells. These studies were motivated by concerns about health effects of radiation from reactors, atomic weapons testing, and radioactive elements that enter the body.

Alexander Hollaender, a world authority in radiation biology, came to Oak Ridge in 1946 to lead studies on the effects of radiation on microorganisms, fruit flies, plants, and later mice. He built a broad program that once gave ORNL the largest biological laboratory in the world. Twenty researchers who have worked in the biological sciences at ORNL have been elected to the National Academy of Sciences.

Under Hollaender, Bill and Liane Russell started a large-scale mouse-genetics project in 1947. They began to build up special mouse strains for study of the effects on offspring born to parents exposed to radiation. The mouse-genetics program eventually would accommodate a steady-state census of 250,000 mice.

The Russells also initiated a project to study radiation effects on development. In 1950, Liane Russell reported that specific types of birth defects resulted from radiation exposure during "critical periods" in embryonic development. In 1952, the Russells jointly informed the medical community that the stage of prenatal development at which radiation is introduced strongly influences the amount and type of damage to the human embryo and fetus. They made specific recommendations on avoiding risks to unsuspected human pregnancies from diagnostic X rays that were adopted worldwide.

Gene Oakberg's studies of mouse development have helped biologists worldwide interpret the genetic effects of mutagens. ORNL's radiation-mutagenesis studies had generated so many findings by 1956 that a National Academy of Sciences committee used these mouse data to formulate projections for the genetic effects of radiation in humans. National and international bodies continued to rely on ORNL data on the effects of biological and physical variables on mutation rates in recommending limits for human radiation exposures.

Also in 1956, Takashi Makinodan used high radiation doses to suppress mouse immune systems by destroying certain blood cells and then performed the world's first successful transplants of bone marrow (from rats into mice). That same year Elliott Volkin and Larry Astrachan discovered messenger RNA, which "reads" DNA's genetic code and becomes a template for mass-producing proteins. Nine years earlier, Volkin and Waldo Cohn observed that RNA (ribonucleic acid) has the same general structure as DNA (deoxyribonucleic acid), a discovery that had a fundamental impact on molecular biology, virology, and genetics.

In 1958 Bill Russell and colleagues demonstrated that spreading a given radiation dose over days or weeks produced fewer mutations in mice than administering the same amount of radiation within minutes. This provided the first evidence that DNA damage that would result in mutations can be repaired. The finding also had implications for permissible exposure levels.

In 1959 Liane Russell and colleagues found that maleness in the mouse depends on the presence of the Y chromosome and is unrelated to the number of X chromosomes. A year later she showed that only one of the two X chromosomes of a mammalian female is active.

In the mid-1960s, ORNL biologists began measuring the genetic effects of chemicals, using several methods that had been developed for research on radiation effects. The National Cancer Institute supported ORNL investigations of the complex biochemical events leading to cancer growth in mice exposed to radiation or chemicals. Arthur Upton (who later became NCI director), John Storer, and others conducted experiments to determine whether lung cancer tumors in mice form as a result of exposure to pesticides, sulfur dioxide, city smog, or cigarette smoke, both singly and together.

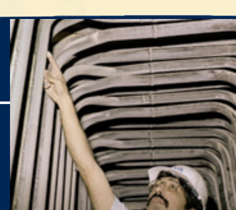
In 1967, Oscar Miller and Barbara Beatty placed frog eggs under a high-resolution experimental microscope built at ORNL and photographed genes in the act of making RNA. The journal *Cell Biology* named the resulting paper a landmark publication.

In 1972 ORNL's Peter Mazur and Stanley Leibo (with England's David Whittingham) froze, thawed, and implanted mouse embryos in surrogate mothers that gave birth to healthy mouse pups. The technique, featured on the cover of *Science* magazine, was adopted by the cattle industry for multiplying

1974

Herman Postma appointed ORNL director, a position he held for 14 years

Chrome-moly steel developed; used in electric utility boilers and oil refinery furnaces worldwide

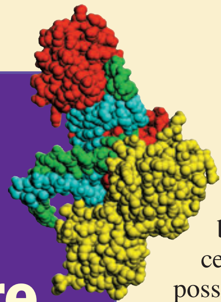


1975

AEC abolished; replaced with Energy Research and Development Administration (ERDA) and Nuclear Regulatory Commission (NRC)

Computer models of ecosystems developed, making ORNL leader in systems ecology

Tough iridium alloy developed to encapsulate nuclear fuel in space probes



COMPUTATIONAL BIOLOGY

Finding Genes, Predicting Protein Structure

ORNL's computational biology researchers played an important role in the Human Genome Project. In 2001, special issues of *Science* and *Nature* that included the draft of the human genome made reference to ORNL's bioinformatics research. ORNL's Frank Larimer, Jay Snoddy, and Ed Uberbacher are listed as co-authors on the lead paper of the *Nature* issue. The GRAIL gene-finding tool, developed by Uberbacher and Richard Mural, was used for the work, and it is mentioned on *Science*'s human genome program timeline.

Ying Xu and Dong Xu developed the Protein Structure Prediction and Evaluation Computer Toolkit (PROSPECT), computational tools for predicting three-dimensional structures of proteins from their amino acid sequences. Knowledge of these specific three-dimensional structures is vital to disease research and drug discovery. PROSPECT can determine a protein's geometry in a few hours, rather than the months required by traditional experiments. PROSPECT has been ranked among the world's best protein-structure prediction tools.

the reproductive potential of prize cattle. The embryo cryopreservation technique, used in Oak Ridge and at the Jackson Laboratory in Bar Harbor, Maine, allows the affordable maintenance of genetic lines of mice and provides a method for obtaining virus-free lines of mice with known genetic traits.

In 1979, Willie Lijinsky showed in rats that nitrites from food preservatives react with amines from food and drugs to form cancer-causing nitrosamines during digestion in the stomach. Walderico Generoso discovered that the genetic makeup of the unexposed female mouse is critically important for determining the amount of genetic damage passed to offspring by males exposed to certain chemicals. Bill Russell discovered that ethylnitrosourea (ENU) is the most effective chemical for inducing mutations in mice. Subsequently, it was found that this chemical generates primarily "point" mutations (DNA base substitutions rather than deletions), and ENU is now in widespread use as the gold-standard reagent for the discovery and cloning of genes associated with human diseases.

In 1986 Generoso discovered that exposure of newly fertilized mouse embryos within the mother to certain chemicals increases the possibility of specific late-fetal birth defects. This work upset teratology dogma that exposure only during the formation and development of organs poses a significant risk.

By the 1990s, numerous studies led by Liane Russell on the nature and frequency of chemically induced mutations concluded that germ-cell-stage exposure to a mutagen is more important than the mutagen itself in determining the nature of a heritable mutation. Thus, it was possible to find suitable chemicals and exposure protocols for making certain classes of mutations "to order."

In 1992 Scott Bultman, Ed Michaud, and Rick Woychik identified and cloned the mouse agouti gene, which causes altered fur color, obesity, diabetes, and cancer in mice and has a human counterpart. In 1993 Gene Rinchik helped identify the human and mouse pink-eyed dilution gene that enables normal pigmentation in mammals. In 1994, using mice, Woychik and his associates generated an insertional mutation exhibiting polycystic kidney disease and identified the gene responsible.

In 1995 Cymbeline Culiat and Rinchik demonstrated that deficiency of a neurotransmitter receptor leads to cleft palate in mice, resulting in tests by human geneticists. Gerald Bunick produced the seeds of DNA-protein crystals that were grown in space aboard the space shuttle and an orbiting space station.

In 1998 Audrey Stevens was elected to the National Academy of Sciences for her successes in identifying numerous proteins involved in RNA metabolism. In 2001 Dabney Johnson, Culiat, and Rinchik proved they had developed mouse models for the acute and the chronic forms of the human disease hereditary tyrosinemia, enabling laboratory tests that might lead to therapies.

Today ORNL biologists are looking forward to conducting research at the new Mouse House, scheduled to open in July 2003, to further advance the field of mammalian genetics.

1976

Program started to improve production of liquid and gaseous fuels from coal and determine their biological effects

Pilot ANFLOW bioreactor installed at Oak Ridge municipal sewage treatment plant

1977

Department of Energy created

1978

President Jimmy Carter visits ORNL

Mike Ramsey pioneered the development of the "lab on a chip" for rapid, inexpensive biological and chemical analyses.

BIOMEDICAL TECHNOLOGIES

Detecting & Preventing Disease

Over the past five decades, ORNL researchers have devised large instruments, compact analyzers, and small chips to diagnose or prevent human diseases and disorders.

In 1950 an ORNL team led by physicist P. R. Bell invented an improved scintillation spectrometer that measured the number and intensity of light flashes arising from phosphors in proportion to the radiation striking these crystals. Multichannel analyzers electronically recorded these flashes, enabling rapid analysis of beta and gamma radiation energies.

In 1956 Bell's team found ways to incorporate electronic computers in medical scanners to more precisely highlight tumors that had taken up radioisotopes, making intrusive surgery unnecessary for cancer detection. Commercial versions of these ORNL-developed imaging machines were used at major medical centers throughout the world to locate cancerous tumors, leading to treatments that extended patients' lives.

In 1961, with funding from the Atomic Energy Commission (AEC) and the National Institutes of Health, an ORNL team led by Norman Anderson found a medical application for centrifuge technology used to produce enriched uranium for nuclear reactor fuel. The researchers demonstrated that rapidly spinning centrifuges, which separate substances into molecular constituents according to size and density, could purify vaccines, removing foreign proteins that can cause side effects in immunized patients. By 1967, commercial zonal centrifuges based on the ORNL invention produced safer vaccines for millions of people.

Guided by Anderson, Charles Scott and other ORNL researchers devised portable centrifugal fast analyzers in the late 1960s and 1970s that were used in medical clinics across the nation. Whirling at high speeds, these analyzers assayed components of blood, urine, and other body fluids in minutes, recording the data for medical diagnoses.

The best known of these machines was the Laboratory's GeMSAEC, funded jointly by the NIH's General Medical Sciences Division and AEC. Using a rotor that spun 15 transparent tubes past a light beam, GeMSAEC displayed the results on an oscilloscope and fed the data into a computer, completing 15 medical analyses in the time it previously took for one. Medical analyzers based on this invention were used in many U.S. clinics.

In the 1970s and 1980s ORNL's Carl Burtis invented a portable blood rotor, which employed the newest technology to improve upon the GeMSAEC concept. This compact analyzer used a variety of reagents that react with blood constituents in the presence of a light beam. It was designed to provide clinicians and veterinarians with rapid and simultaneous measurements of blood constituents in both humans and animals. The technology was licensed in 1992 to Abaxis Corporation, which still manufactures point-of-care blood analyzers based on the technology.

A nonsurgical laser technique for determining whether esophageal tumors are benign or cancerous was developed in the 1990s by ORNL's Tuan Vo Dinh and Bergein Overholt and Masoud Panjehpour, both of the Thompson Cancer Survival Center in Knoxville.

This optical biopsy sensor—which uses an endoscope, optical fibers, laser light, and algorithm to gather and compare fluorescence patterns in the esophagus (which differ for normal and malignant tissue)—has been tested in 1000 samples from 200 Thompson patients. In 98% of the tests the results of the optical and surgical biopsies agreed. ORNL has licensed the optical biopsy technique to Oak Ridge Instant Cancer Test of Nashville.

Vo-Dinh, Alan Wintenberg, and others devised an advanced multifunctional biochip system that someday could diagnose a range of diseases quickly in a doctor's office. This technology has been licensed to HealthSpex of Oak Ridge.

Improved versions of the "lab on a chip" devised by ORNL's Mike Ramsey in the early 1990s are being commercialized by Caliper Technologies. The matchbox-size chips contain several channels—thinner than human hair—that connect reservoirs, all of which are carved into miniature glass plates, using microfabrication technologies. Chips are available for analyses of DNA, RNA, proteins, and cells. Caliper also is marketing devices for high-throughput experimentation directed at drug discovery. Caliper posted 2001 sales of nearly $30 million, a 59% increase over the previous year.

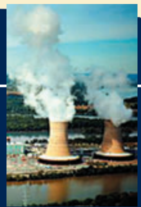
Pellet injection method for refueling fusion energy research devices developed

1979

ORNL's neutral-beam injectors help Princeton Plasma Physics Lab reach record fusion plasma temperatures

Ethylnitrosourea found to be the most effective chemical for inducing mutations in mice

ORNL assists NRC in identifying causes and consequences of Three Mile Island nuclear power plant accident



In rat study, nitrites in food preservatives found to react with food and drug amines, forming cancer-causing nitrosamines

INTELLIGENT MACHINES

Reducing Risk with Robots

Mechanical manipulators have long been employed in hot cells to protect users from radioactive materials. Beginning in the late 1970s, ORNL researchers devised remotely controlled dexterous servomanipulators whose work could be viewed on television. Such "teleoperation" techniques enabled work in radioactive zones too hazardous for people. This technology, which extended earlier concepts developed at Argonne National Laboratory, was the start of ORNL's robotics activities. Since then, remote manipulation technology has been applied to nuclear fuel reprocessing, military-field-munitions handling, accelerators, fusion reactors, and environmental cleanup projects (e.g., remotely controlled plasma arc cutting of metal structures to dismantle contaminated equipment) at Department of Energy waste sites nationwide.

In 1980 ORNL's John White and Howard Harvey founded REMOTEC, an Oak Ridge company (now owned by Northrup Grumman) that is the world leader in mobile robot systems. More than 700 REMOTEC robots are in use in 45 nations by military organizations, law enforcement agencies, nuclear facilities, and research laboratories. In 1986 ORNL's Lee Martin and Paul Satterlee founded Telerobotics International, which later morphed into iPIX, an imaging software and services provider whose customers work in security, observation, real estate, online auctions, and digital content development.

In 1984 Satterlee, Martin, and Joe Herndon received ORNL's first R&D 100 award in robotics for a digitally controlled servomanipulator. (R&D 100 awards are given annually by *R&D* magazine for the 100 best innovations of the year. ORNL has won more of these awards than any other DOE lab.) This control system became the basis for Central Research Laboratories' control product line. In 1993 François Pin and Stephen Killough received ORNL's second robotics R&D 100 award for their invention of an omnidirectional holonomic platform. This innovation became the basis for several robotic platforms for DOE and the Department of Defense, as well as for a commercial omnidirectional wheelchair.

In the 1990s ORNL robotics researchers contributed to remediation of DOE waste containers. Engineers devised remotely controlled robots with "common sense" that mapped the waste-filled silos at DOE's facility at Fernald, Ohio; this effort helped DOE complete the project on schedule and saved the agency millions of dollars.

Dirk Van Hoosen and Barry Burks led the development of the radioactive tank cleaning system that successfully emptied ORNL's underground gunite tanks, which stored liquid radioactive wastes from ORNL's early reactor operations. This system avoided $120 million in costs to DOE, and lessons learned are guiding cleanup plans for other DOE sites.

In the late 1990s Lynne Parker developed ALLIANCE, software that enables robots to be "trained" to carry out tasks as a team, to reduce the chance of mission failure. Her innovative work in cooperative robotics may provide Caterpillar and the U.S. military with autonomous, robust, decision-making machines.

Pin is leading a major project for the U.S. Army to create "exoskeletons" powered by small fuel cells to enable soldiers to run faster and farther while carrying heavier loads. His group recently developed a small lightweight fuel cell for an effort that could amplify the strength, endurance, and speed of humans. In addition to helping soldiers, such an exoskeleton could improve worker safety and productivity in the construction, mining, and manufacturing industries and make rescue operations safer and faster.

ORNL staff designed robotics devices (right) for safe removal of radioactive sludge from underground storage tanks; Nageswara Rao (shown below) demonstrates that his connectivity-through-time protocol enables robots to communicate with each other in performing a job.

1980

Holifield Heavy Ion Research Facility opens as nuclear physics user facility

HFIR becomes user facility when National Center for Small-Angle Scattering Research opens

National Environmental Research Park (12,400 acres) opens

New ion-implantation accelerator techniques found to improve materials' surface properties

Longer-lasting artificial joints made after ORNL implants titanium alloy with nitrogen ions

Using a phantom, Jim Bogard tests dosimeter responses to radiation from nearby sources.

HEALTH PHYSICS AND RADIATION DOSIMETRY

Helping Set Guidelines for Radiation Protection

In December 1942 when the first controlled chain reaction was achieved in Chicago, some physicists measured radiation levels in the workplace. As the Manhattan Project began, "health physics" methods were needed to measure radiation emitted by manmade radionuclides and control radioactive contamination of the workplace.

In the 1940s Oak Ridge health physicists Karl Morgan, Herbert Parker, Ernest Wollan, and others developed instrumentation for measuring radiation to help protect worker health. With Elda Anderson, Myron Fair, and Doc Emerson, Morgan spearheaded the formation of the national Health Physics Society and became its first president. Morgan and Jim Turner wrote the first textbook on health physics.

In Oak Ridge, programs of theoretical and applied research were carried out to foster the development of health physics instruments and dosimeters for monitoring radiation levels and worker exposures. In the mid-1950s ORNL health physicists developed neutron dosimetry techniques and portable personnel monitors for alpha and gamma radiation that have since been used worldwide.

Before the Manhattan Project, radiation protection was largely concerned with controlling medical uses of radiation, principally X-ray machines. Also, radionuclides for medical and industrial use were largely limited to members of the naturally occurring uranium series, such as radium-226. The development of fission reactors (e.g., the Oak Ridge Graphite Reactor) resulted in the generation of a variety of new radionuclides with important applications in research, industry, and medicine. Guidance was needed to ensure the beneficial uses of these radioisotopes, while protecting those who used them. Under Morgan's direction, the first formal report on permissible concentrations of radionuclides in the workplace was issued in 1959 as Publication 2 of the International Commission on Radiological Protection (ICRP).

The calculations underlying that report were carried out by ORNL's dosimetry research group, headed by Walter Snyder, with the able assistance of Mary Rose Ford. This group helped establish ORNL as an international center for dose calculations. At the time, workers were the focus of radiation protection. To establish guidance that would achieve international consensus, it was necessary to agree on typical characteristics of a radiation worker. Under Snyder's leadership, Mary Jane Cook and others assembled ICRP Publication 23, a massive collection of anatomical and physiological data that defined ICRP's "Reference Man," a model that has served as an international standard for decades.

Using this information, Snyder and coworkers formulated a 3D model of the body, incorporating Monte Carlo methods for modeling radiation transport, to calculate radiation dose. The resulting model was developed with the Medical Internal Radiation Dose (MIRD) Committee of the Society of Nuclear Medicine and is referred to worldwide as the "MIRD Phantom."

Since the late 1970s ORNL's dosimetry research has been guided by Keith Eckerman, a member of ICRP's committee on dose limits and chairman of its dose calculations group. Recognizing the growing need to address intakes of radionuclides by the public (e.g., by inhalation, ingestion, or injection), Eckerman refocused ORNL's dosimetry research toward developing age- and gender-specific dose estimates. As a first step, Eckerman and Mark Cristy extended the radiation transport models and mathematical phantoms from a reference adult male to children and adult females.

Next came a long-term project to identify and model changes with age in the biological behavior ("biokinetics") of radionuclides. This required the introduction of biologically realistic models that incorporate physiological changes common during human maturation. The effort, led by Rich Leggett, provided not only the needed models for children but also yielded improvements in predictions of the fate of radionuclides in adults. These physiologically based models, which form the core of ICRP's recent publications on doses to the public, also have replaced ICRP's traditional biokinetic models for the radiation worker. The information collected during this work provided a valuable starting point for a new ICRP publication on anatomical and physiological characteristics of a "Reference Family," soon to replace "Reference Man."

Computer models built to predict power plant impacts on Hudson River fish

ORNL researchers start REMOTEC, world leader in making robots for hazardous duties

1981

Whisker-toughened, fracture-resistant ceramic developed; used in commercial cutting tools

1982

Standards and designs developed to increase efficiency of refrigerators and heat pumps

Insulation standards developed; later adopted by federal agencies

RADIATION SHIELDING

Putting Safety First

In the 1930s Eugene Wigner devised a formula indicating that some materials are more effective than others in absorbing, or slowing down, neutron radiation. This work established the basis for radiation-shielding studies.

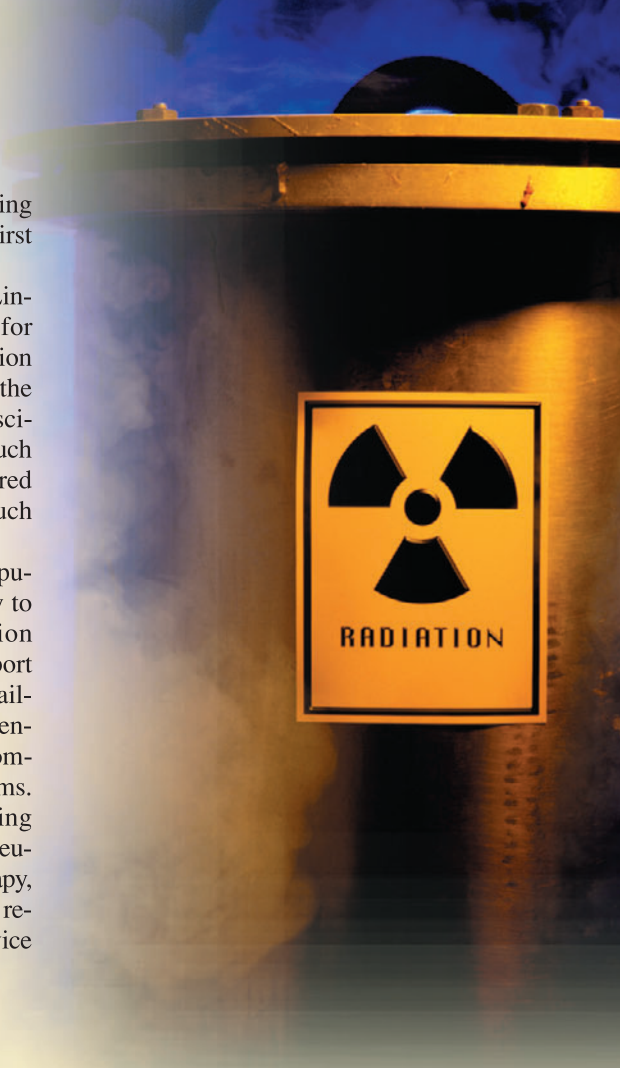
By 1951, under Everitt Blizard's guidance, ORNL became a world leader in performing calculations to determine the thicknesses and configurations of lead, steel, and concrete shielding necessary to protect people and equipment from exposure to hazardous radiation levels. For the later-aborted nuclear aircraft project, ORNL researchers worked to identify lightweight shielding materials that would protect the crew of an airplane powered by a small nuclear reactor from radiation. To provide data for this effort, the ORNL Bulk Shielding Reactor and Tower Shielding Facility were built in the 1950s.

In 1958 ORNL researchers developed a neutron transport code and photon transport code to predict which shielding configurations best protect humans from neutrons and gamma rays. In 1959 they evaluated the effectiveness of reactor shielding proposed for the *Savannah*, the nation's first and only nuclear-powered civilian ship.

In 1966 the Oak Ridge Electron Linear Accelerator began providing data for shielding-code developers on how radiation interacts with individual atoms within the shield material. The accelerator helps scientists answer questions such as "How much neutron radiation is captured by or scattered off the atom's nucleus?" and "How much causes the atom to fission?"

In 1967 ORNL developed a computational simulation code still used today to evaluate the effectiveness of radiation shielding. In 1986 the Oak Ridge Transport model was released; this first openly available radiation transport simulation code enables the solution of extremely large, complex, three-dimensional shielding problems.

ORNL shielding research is being applied to the design of the Spallation Neutron Source's target, medical radiation therapy, and homeland security projects. ORNL researchers also respond to requests for advice on difficult shielding issues.



Containers for radioactive material are designed to protect those working nearby from hazardous radiation.

INFORMATION CENTERS

Sharing Scientific Data

Forty years ago, then ORNL Director Alvin Weinberg headed a presidential panel to study the problem of handling rapidly growing amounts of data. The panel recommended the creation of specialized information centers to review, analyze, condense, and interpret scientific literature for the scientific community.

In response to the Weinberg report, *Science, Government, and Information*, the Radiation Shielding Information Center was established in 1963. In 1996 it morphed into the Radiation Safety Information Computational Center to reflect the scope of technical coverage and keep up with changing computational technology. For scientists and educators in 73 countries, the center has collected, tested, packaged, and disseminated 1600 computational tools used in radiation shielding, transport, and protection.

Since its founding in 1963, the Controlled Fusion Atomic Data Center has made available atomic, molecular, and particle-solid collision data of interest to fusion energy and plasma research. The center has provided valuable data from ORNL's electron-cyclotron-resonance ion source to national fusion research centers at ORNL, Princeton Plasma Physics Laboratory, and General Atomics and has participated in the International Atomic Energy Agency's Data Center Network.

Since the early 1960s, numerous other ORNL information centers have come and gone. They have covered ecological sciences, health and environmental effects of toxic chemicals, nuclear data, nuclear safety, and remedial action programs.

The Carbon Dioxide Information Analysis Center (CDIAC), established in 1982 at ORNL, is the Department of Energy's primary center for global-change data. CDIAC's accurate, impartial data are used by a diverse group of clients. The center's greatest moment of international impact came in the run-up to the 1997 Kyoto conference, when countries negotiated reductions in greenhouse gas emissions. CDIAC provided its unique database of country-by-country, year-by-year emissions of carbon dioxide from fossil-fuel combustion to representatives of many countries, as well as to the news media and a variety of nongovernmental organizations.

Modified nickel aluminide alloys developed; used in commercial production of steel & auto parts

Superconducting electromagnets successfully tested by fusion energy researchers at Large Coil Test Facility

Carbon Dioxide Information Analysis Center established; world-renowned repository of global-change data

1983

Martin Marietta becomes ORNL managing contractor, succeeding Union Carbide

1984

Experiments started to produce hydrogen from water using photosynthesis in spinach and algae

Ed Vineyard checks the instrumentation in a highly efficient refrigerator model. Vineyard's team redesigned a refrigerator to reduce its energy use by 50%.

ENERGY EFFICIENCY

Cooling More with Less

In the past three decades, ORNL has spearheaded the development of refrigeration systems that use less energy and pose less of a threat to the environment. The motivations have been the rise in energy prices since the 1970s because of unstable supplies of imported oil for fuel; the recent goal to reduce the need for coal-fired power plants and thus cut climate-altering carbon dioxide emissions; and the mandate to replace conventional refrigerants containing chlorofluorocarbons, to preserve the stratospheric ozone layer protecting us.

ORNL engineers have worked with major appliance manufacturers to improve the energy efficiency of refrigeration equipment and to investigate ozone-friendly alternative refrigerants. In collaboration with Arthur D. Little, Amana, Maytag, General Electric, Sub-Zero, Sanyo, DuPont, Frigidaire, and Whirlpool, ORNL researchers designed more-efficient refrigerators, compressors, and supermarket refrigeration systems. In the early 1980s, they built a computer model still used to design energy-efficient refrigerators. In the late 1990s, relying on computer analyses and input from appliance manufacturers, researchers led by Ed Vineyard altered the design of the refrigerator-freezer to reduce energy use by 50% to one kilowatt-hour per day.

A team at ORNL's Buildings Technology Center worked with DuPont to identify ozone-safe refrigerant blends and suggest system changes that allow new blends to increase energy efficiency. Partly as a result of ORNL's refrigerant tests and computer modeling, chlorine-free HFC-134a is commonly used in new refrigeration systems.

ORNL researchers led by Van Baxter influenced the design of supermarket refrigeration units, which now have improved microprocessors and their own compressors (rather than potentially leaky lines to a central compressor). These changes cut supermarket energy consumption by 30% and annual electricity costs by $4 billion.

ORNL's refrigeration work was recently cited by the Department of Energy as the second-highest-rated accomplishment among 100 DOE-developed technologies that have most improved consumers' lives.

Heating More with Less

The earth stores almost half the energy it receives from the sun—at least 500 times more energy than humankind needs each year. By exploiting this impressive energy storage capability, geothermal heat pumps (GHPs) warm and cool buildings and provide hot water. Using a system of underground pipes containing an environmentally friendly heat-exchange fluid, a GHP transfers heat from the warmer earth to a building in the winter and moves heat from a building in the summer for discharge into the cooler ground.

An Environmental Protection Agency study recently showed that the GHP is the most energy efficient, environmentally benign, and cost-effective space-conditioning system available. Despite their potential, GHPs were still regarded as "new" in 1990, and their delivery infrastructure was still in its infancy. Careful research and technical assistance provided by ORNL's Buildings Technology Center cleared the way for widespread acceptance and implementation of GHPs in federal facilities and helped usher GHPs into the mainstream of the U.S. heating and cooling industry.

Since the late 1970s, ORNL's Patrick Hughes has researched, field-tested, and improved the engineering of GHP systems. During the mid-1980s, Van Baxter, Vince Mei, and others at ORNL helped upgrade component technologies for GHP systems. Hughes and John Shonder documented the energy- and cost-saving benefits of GHPs in an evaluation of a 4000-home GHP retrofit at the U.S. Army's Fort Polk Joint Readiness Training Center near Leesville, Louisiana. The study found that electricity use was reduced by 33% in the retrofitted homes, and summer peak electricity demand was cut by 43%.

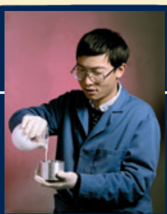
In 1998 the Federal Energy Management Program launched a program, supported by Hughes and Shonder's team, to make GHPs available to federal agencies. Since then, the annual federal investment in GHPs continues to grow, reaching $76 million in 2001.

1985

Fatty acid labeled with iodine-123 developed for medical scanning diagnosis of heart disease

UT-ORNL establishes Science Alliance

Gelcasting developed; now used commercially to form ceramic parts for microturbines

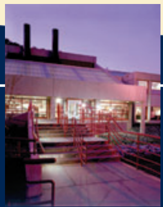


1986

ORNL determines when Chernobyl nuclear plant accident occurred, and why it released so much radioactivity

1987

High Temperature Materials Laboratory opens as user facility for industrial researchers seeking to build energy-efficient engines



ENERGY EFFICIENCY

Building for the Future

After the Arab oil embargo of 1974 when gas stations had long lines and energy prices climbed, ORNL was asked to serve as the federal government's program manager for energy conservation research. ORNL's residential conservation program, headed by Roger Carlsmith, addressed the problem of reducing home use of oil, gas, and electricity (20% of which was produced by oil-fired plants). Because heating and cooling account for 50 to 70% of the energy used in the average American home, energy use and bills can be reduced significantly by adding insulation to cut unwanted heat flow through walls. ORNL researchers studied ways to improve home insulation and calculated the energy saved by adding insulation to homes and businesses.

The Laboratory became the federal government's prime resource for developing thermal insulation standards, later adopted by the Department of Energy's predecessor, by the Department of Commerce, and by building trade associations. These standards helped reduce U.S. energy use.

ORNL researchers worked on tightening mobile home design. Relying on data from an instrumented mobile home, researchers led by John Moyers and John Wilson proposed tighter insulation and storm window standards to reduce energy use. The standards were adopted by the American National Standards Institute and the Department of Housing and Urban Development, and the manufactured housing industry began producing mobile homes with much greater energy efficiency.

In 1988, as a result of testimony by ORNL researchers at the International Energy Conservation Code hearings in Charleston, South Carolina, ORNL researchers helped place standards concerning below-grade insulation and thermal mass credits into the building code used throughout the nation. The recommended insulation thicknesses (R-values) on most bags of insulation sold today stem from ORNL studies.

In the 1980s ORNL staff drafted and published *The Insulation Fact Sheet*, saving Owens Corning from investing $2 million in compiling such a needed publication. The document provides consumers with objective recommendations on the use of insulation in residences and is the second most widely used DOE publication.

In 1995 ORNL researchers found the cause of significant heat losses from low-density, loose-fill insulation in attics in cold climates and identified insulation strategies to reduce the losses. Using these findings, the state of Minnesota incorporated insulation standards in its building code.

ORNL researchers Mike Gettings and Terry Sharp developed a computer program that helps low-income homeowners reduce energy use and costs through DOE's Weatherization Assistance Program (WAP). By entering data on a house's walls, doors, attic, insulation, lighting, and heating and cooling systems into a computer with ORNL's National Energy Audit (NEAT) software, a WAP representative can determine if the house needs attic and water-heater insulation, a furnace tuneup, and energy-saving compact fluorescent light bulbs. WAP can install all of these at no cost. Some 800 copies of the computer program have been distributed since 1995, and ORNL training on NEAT use has been provided to representatives of at least 43 states.

Researchers working at DOE's first buildings user facility—the Buildings Technology Center—wrote a series of handbooks for builders on foundation design and moisture control to increase energy efficiency. These were predecessors to handbooks now available through the Energy and Environmental Building Association to guide construction of energy-efficient houses.

ORNL researchers led by Jeff Christian established the whole-wall-rating labeling procedure that has been tested on more than 225 wall systems to determine which hold in heat most effectively. ORNL was the first to use Habitat for Humanity homes as research houses, first for testing walls and then for testing heating, ventilation, and air-conditioning systems. These houses will be used to show that homes with structurally insulated panels, energy-efficient appliances (e.g., the ORNL-developed heat pump water heater), and solar photovoltaic collectors consume no more electricity than they generate, making them zero energy buildings. This work could influence standards for future affordable, energy-efficient houses.

This Habitat for Humanity house being built near ORNL will produce as much energy as it uses, making it a zero energy building. ORNL was the first organization to use Habitat for Humanity houses to test energy-efficient building concepts.

Lasers used to make high-temperature superconducting materials

All ORNL reactors shut down in response to DOe's concerns about Lab's reactor safety management

1988

Advanced Toroidal Facility starts up for fusion energy research using a stellarator

Alvin Trivelpiece named director of ORNL, a position he held for 12 years

1989

First draft of "generic environmental impact statement" for NRC to renew nuclear power plant operating licenses

CHEMISTRY AND MASS SPECTROMETRY

Making a Mark

Oak Ridge chemists pioneered methods of separating plutonium and other fission products from the spent uranium fuel at the Graphite Reactor, achieving the Laboratory's mission in the effort to end World War II.

In the 1940s ORNL chemists were the first to conduct reactor-based neutron activation analyses. A famous use of these capabilities was the 1991 analysis of hair and nail samples from President Zachary Taylor's grave that refuted a historian's theory that he died from arsenic poisoning.

In 1947 ORNL chemists measured ion-exchange properties of almost all the elements, producing a body of information invaluable for developing both analytical and industrial separations of numerous metals.

In 1954 Sheldon Datz and Ellison Taylor pioneered molecular beam chemistry in which two beams of molecules are crossed, avoiding the complications of accounting for collisions with atoms in container walls and enabling better understanding of the dynamic interchange of atoms during chemical reactions. This crossed-beam scattering technique was further developed by two recipients of the 1986 Nobel Prize for chemistry.

Carroll Johnson and Mike Burnett developed a revolutionary computer program for the visualization of molecular structure data determined by X-ray crystallography. The program, released in 1965, facilitated the generation of stereoscopic images of molecules for presentations and publications.

In the 1980s ORNL groups led by Bob Mesmer and Mike Simonson obtained detailed data and developed predictive models for high-temperature aqueous solutions. These have been incorporated into process models widely used in the steam generator and geothermal energy industries.

In the 1990s Bruce Moyer's group extended early ORNL-developed solvent extraction methods to the invention of a new process for separating cesium from nuclear wastes. The technology is being adopted for processing high-level waste at the Department of Energy's Savannah River Site.

Starting in the late 1950s, ORNL's Gus Cameron, Joel Carter, Warner Christie, David Smith, and Ray Walker pioneered thermal ionization mass spectrometry methods for the precise isotopic quantification of very small amounts of nuclear materials. These techniques of sorting particles of uranium, plutonium, and other elements according to their mass-to-charge ratios have been further developed at ORNL and other laboratories for applications ranging from nuclear safeguards to life sciences.

During the 1980s and 1990s, ORNL researchers Scott McLuckey, Gary Glish, Doug Goeringer, Gary Van Berkel, Kevin Hart, and Marc Wise made a number of fundamental discoveries in quadrupole ion-trap mass spectrometry. This instrument stores ions within an oscillating electric field that are ejected from the trap into a detector according to their mass-to-charge ratios. The work led to the development of the direct-sampling ion trap mass spectrometer, accepted in 2002 by the Environmental Protection Agency for on-site characterization of waste sites. This instrument also is the heart of the chemical biological mass spectrometer, developed by a team led by Wayne Griest for the U.S. Army for real-time detection of chemical and biological threat agents.

In 1985 ORNL was the first DOE lab to use Fourier transform ion cyclotron resonance, another mass spectrometer that combines electrostatic and magnetic fields to trap ions. Bob Hettich and Michelle Buchanan developed techniques for applying this instrument's mass-resolving power to analysis of DNA and proteins, linking these analytical tools to the life sciences.

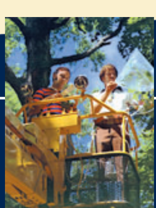
During the 1990s, by improving secondary ion mass spectrometers, Peter Todd imaged and analyzed target molecules in whole tissues, including neurotransmitters in brain tissue. McLuckey, Van Berkel, and Glish were the first to couple the electrospray ionization technique with the ion trap mass spectrometer, enabling the identification of proteins.

Bill Partridge and others developed the spatially resolved capillary inlet mass spectrometer measurement strategy to characterize reactions within after-treatment devices used to remove pollutants from diesel engine exhaust gases. This technology is being adopted by government, academic, and industrial research labs, including those of Cummins, Ford, and Engelhard.

ORNL's chemistry activities continue to support DOE's missions of promoting energy production and efficiency and protecting people and the environment in and around energy production units.

1990

ORNL's acid rain research leads to curbs on industrial sulfur and nitrogen oxide emissions



Existence of quarks inside neutron confirmed

Z-contrast electron microscope images columns of atoms

Computer code helps military better deploy personnel and equipment to war zones

1991

Neutron activation analysis at HFIR refutes theory a U.S. president died of arsenic poisoning

Software written to solve problems by linking widely dispersed PCs

NUCLEAR PHYSICS AND ASTROPHYSICS

From Atoms to Exploding Stars

Nuclear physics research at ORNL took off in the late 1940s, largely because of the nuclear aircraft project's need for information about the behavior and effects of reactor-borne neutrons on shielding materials. In 1948 Arthur Snell initiated research using an upgraded 3-megavolt Van de Graaff accelerator, a high-voltage direct-current machine that produced a neutron stream by bombarding lithium with protons. In 1951 a 5-MV Van de Graaff accelerator was installed, the world's highest-energy machine of its kind.

At the Oak Ridge Y-12 Plant, Robert Livingston and his team built cyclotrons using discarded electromagnets from isotope-separating calutrons. The cyclotrons also obtained support from the aircraft project because they could be used for radiation damage research.

In 1951 Snell and Frances Pleasonton measured the half-life of the neutron, providing first experimental proof that a neutron decays into a proton, electron, and electron antineutrino. The next year Alex Zucker used ORNL's first heavy-ion cyclotron beam to lay to rest a nightmarish concern that a hydrogen bomb explosion could ignite the atmosphere.

Performing the first experiment on the Oak Ridge Research Reactor in 1958, Cleland, Johnson, Snell, and Pleasonton observed directions of neutron and electron emission in the decay of helium-6, confirming the electron-neutrino theory of nuclear beta decay, a key piece of today's Standard Model of particle physics.

In the 1960s at the ORR, Philip Miller, James Baird, and William Dress, in a collaboration with Harvard University's Norman Ramsey, set an upper limit for the electric dipole moment of the neutron, a sensitive way to test invariance of the laws of physics under time reversal. John Gibbons, Richard Macklin, and colleagues used the 3-MV Van de Graaff to confirm that atomic elements arose from nucleosynthesis in stars; Cal Tech's Willy Fowler won the Nobel Prize for the theory and credited the key influence of these data. Ray Satchler and colleagues developed computer codes to analyze nuclear scattering and reactions, and Joe McGrory and colleagues developed codes describing the nuclear shell model. All of these were used worldwide.

In 1964 the Oak Ridge Isochronous Cyclotron (ORIC) became one of the first cyclotrons to operate using the principle of strong focusing now commonplace in accelerator design. In 1971 the likely shape of a deformed uranium-234 nucleus was found using ORIC. In 1972 at ORIC, the giant quadrupole resonance was found by a team led by Fred Bertrand, sparking increased study of these vibrational modes of nuclei. Another team led by Curt Bemis found that the uranium-238 nucleus has a hexadecapole deformation resembling a rugby ball.

In 1980 the Holifield Heavy Ion Research Facility (HHIRF) began operation for nuclear physics studies and as a user facility. The 25-MV tandem accelerator, which was coupled to the ORIC, has the world's highest direct-current voltage. In 1995 using HHIRF, Cyrus Baktash discovered superdeformation extended to nuclei lighter than mass 100. In 1997 HHIRF morphed into the Holifield Radioactive Ion Beam Facility (HRIBF), to provide for nuclear structure and astrophysics research the first beams of ions that do not exist naturally on earth. Witek Nazarewicz and others predicted numerous new phenomena, such as steady loss of shell effects for nuclei far from stability, now a cornerstone of research using radioactive beams. In 2000 Jorge Gomez del Campo and Jim Beene led a group that discovered a new form of radioactivity—simultaneous emission of two protons from a decaying atomic nucleus.

Measurements at HRIBF and the Oak Ridge Electron Linear Accelerator help improve simulations of nova, supernova, and red giant stars. Michael Smith, Jeff Blackmon, Dan Bardayan, and others improved predictions of the abundances of 87 different isotopes in stellar explosions.

In 2001 Tony Mezzacappa formed a national collaboration to simulate core-collapse supernovae to pin down the supernova explosion mechanism. An ORNL group led by Glenn Young and Frank Plasil developed detectors for DOE's Relativistic Heavy Ion Collider at Brookhaven National Laboratory, to study the quark-gluon plasma, mimicking the beginning of the universe. In 2002 at HRIBF, a beam of tin-132 was produced for the first time, allowing "doubly magic" short-lived nuclei to be probed.

The likely shape of a deformed uranium-234 nucleus was determined in 1971 by ORNL physicists.

1992

President George Bush visits ORNL

Rhenium-188 isotope generator invented; used worldwide to treat cancer and heart patients

Mouse agouti gene identified and cloned; mutated gene found to cause obesity, diabetes, cancer

Thin-film lithium micro-battery invented

GRAIL developed for recognizing genes in DNA sequences on computer

1993

Optical biopsy technique devised to find cancerous tumors in esophagus without surgery

UT-ORNL ranks top 500 super-computers

ORNL's Intel Paragon machine was the fastest supercomputer in the world in 1995.

HIGH-PERFORMANCE COMPUTING

Pushing the Limits

For 50 years ORNL has been a leader in advancing supercomputing. In 1954 an ORNL group led by Alston Householder partnered with Argonne National Laboratory to create a computer with the fastest speed and largest data storage capacity of any computer in the world. Called the Oak Ridge Automatic Computer and Logical Engine (ORACLE), this machine helped scientists solve problems in nuclear physics, radiation effects, and the development of shielding for the ill-fated nuclear aircraft project.

In the 1980s ORNL researchers made computational breakthroughs using a new "parallel computer," which harnessed several thousand processors working together to solve scientific problems. In 1995 ORNL obtained the Intel Paragon XP/S 150, a parallel supercomputer linking 3000 processors that was the fastest in the world at the time. It helped scientists predict climate change and develop groundwater movement models. Five years later, ORNL became the first Department of Energy laboratory to have a one-teraflop computer—that is, a machine capable of a trillion calculations per second. ORNL continued its progress with the purchase of an IBM system dubbed "Cheetah," the 8th fastest computer in the world at the time and now the 16th fastest machine.

In 2002 ORNL established an ultra-high-speed, real-time connection that enables the research community to tap supercomputing resources previously unavailable for general use. This feat was accomplished by bridging the gap between DOE's Esnet and Internet2.

Also in 2002 ORNL and Cray forged a partnership under the guidance of DOE and with the cooperation of other national labs. This collaboration is expected to result in supercomputers that will exceed the capabilities of Japan's 40-teraflop Earth Simulator, currently the world's fastest computer. The partnership, which will provide resources enabling unprecedented solutions to scientific problems, will advance ORNL to the forefront in supercomputing for the new millennium.

SOFTWARE SIMULATIONS

Models for Scientific Discovery

ORNL has had significant influence worldwide on the software and algorithms used for scientific discovery. In the late 1980s, Parallel Virtual Machine (PVM) software was developed at ORNL. PVM, which had more than 400,000 users in the mid-1990s, became a worldwide de facto standard for clustering computers into a virtual supercomputer.

In the mid-1990s, the Message Passing Interface (MPI) effort was begun by Jack Dongarra, who has joint appointments at ORNL and the University of Tennessee. MPI is the dominant programming paradigm used by scientific codes around the world. Dongarra also led the development of LAPACK and BLAS to solve linear algebra problems by high-performance computers. LAPACK and its parallel version ScaLAPACK are now used on all supercomputers around the world.

In the late 1990s ORNL, other national labs, and IBM developed an award-winning, ultrafast data storage system, known as the High Performance Storage System, which is used today on supercomputers across the nation. At the same time, ORNL researchers developed electronic notebook software that allows large scientific research teams to collaborate more efficiently. This software now has thousands of users in research, industry, medicine, and academia.

In 2002 a national software effort led by ORNL called OSCAR (Open Source Cluster Application Resources) became the most used cluster-computing management software in the world. It has 50,000 users.

With the help of software and simulation codes partly developed at ORNL, Laboratory researchers have used supercomputers for three-dimensional modeling of fusion plasmas and exploding stars; finding genes and predicting future climate as industrial emissions change; and simulating car crashes to aid the design of lighter, more efficient cars that better protect car-crash victims. ORNL's computer modeling of giant magnetoresistance already has influenced Seagate and IBM, leading to faster desktop computers and smaller, smarter digital cameras.

1994

"Lab on a chip" invented; now used commercially for protein analyses & drug discovery experiments

Mass spectrometry techniques devised for detecting pollutants, explosives, proteins

Codes prepared to run models of future climate on new parallel supercomputers

ALLIANCE software developed to make team of robots work cooperatively

1995

Startup of Intel Paragon XP/S 150, then the world's fastest supercomputer

RABiTS™ method devised for making high-temperature superconducting wires

GEOGRAPHIC INFORMATION SYSTEMS

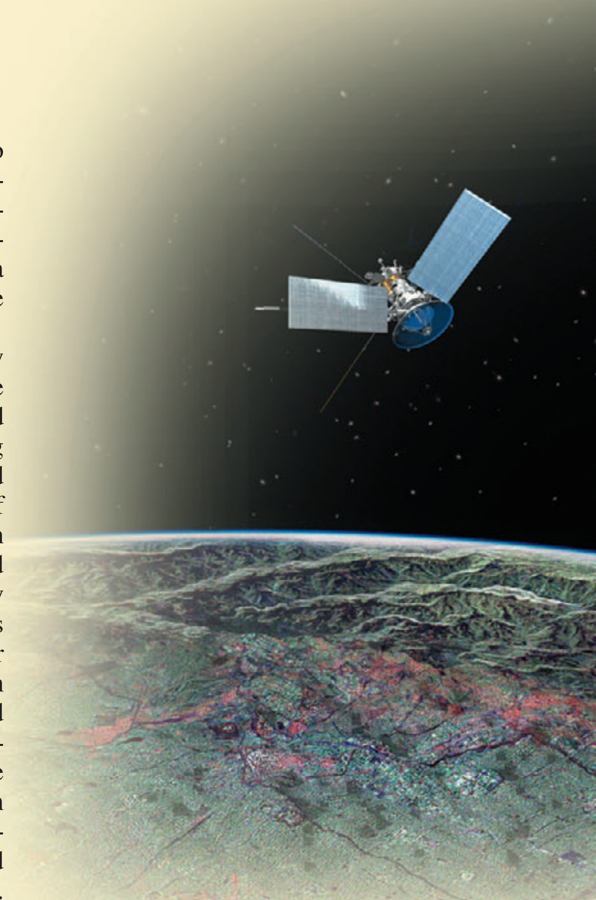
Tracking the Globe

Geographic information science was pioneered at ORNL in 1969, more than a decade before the commercial geographic information system (GIS) industry blossomed. A GIS is a computer system that can assemble, store, manipulate, and display geographic information, including images collected by satellites and aircraft. ORNL has used GIS to integrate multidisciplinary research projects addressing issues of local to global scale.

In the mid-1980s, ORNL researchers performed studies for the U.S. Army Toxic and Hazardous Materials Agency to help it decide the safest way to dispose of nerve gas weapons stored in Alabama, Arkansas, Kentucky, Oregon, and Utah. Researchers used GIS methodologies to examine truck and rail routes between sites and evaluate the safety of transporting the weapons to a central incinerator. The Army adopted ORNL's recommendation to build an incinerator at each site to avoid the potential dangers of transporting material to one site.

In the late 1980s, the National Oceanic and Atmospheric Administration's National Marine Fisheries Services funded studies to relate coastal fish population declines to increased urbanization and agricultural alteration of coastal landscapes. ORNL researchers led the technical effort that resulted in a standardized database of land cover change for all U.S. coastal areas.

A key to dealing successfully with any disaster is to accurately estimate the daytime and nighttime population of the affected area. Combining GIS and remote sensing technologies, an ORNL team developed Landscan, the most accurate and detailed of global population databases, to help decision makers. LandScan enables ORNL's Hazard Prediction and Assessment Capability (HPAC) software to help emergency planners "see" where and how much of a chemical or biological agent will disperse and also which populations need protection. HPAC is used by some 2000 employees with U.S. and foreign governments and military branches in the North Atlantic Treaty Organization and with state and local emergency planning and response units. LandScan is used by the United Nations and government agencies worldwide.



GIS researchers use satellite images.

TRANSPORTATION LOGISTICS

Finding the Shortest Path

What is the fastest way to transport troops and needed equipment from American bases to foreign bases for possible military action? Thanks to special software developed for the Air Force by ORNL and University of Tennessee researchers, U.S. military troops and equipment have been airlifted to potential war zones more quickly than before.

The Air Mobility Command (AMC) Deployment Analysis System (ADANS) is a series of aircraft-scheduling algorithms and tools that enabled the AMC to deploy troops and equipment to the Persian Gulf in 1990 and 1991 more rapidly and more efficiently. The system was developed by ORNL and UT researchers led by Mike Hilliard and Charlie Davis.

Since 1990, ADANS has been used for all U.S. deployments, including those to Somalia, Haiti, Rwanda, Bosnia, Kosovo, Afghanistan, and Iraq. ORNL researchers have enhanced and supported the operation of the system, which has been renamed CAMPS (Consolidated Air Mobility Planning System). They are modifying scheduling algorithms to work with a new database management system.

What is the fastest and safest way to transfer spent nuclear fuel from U.S. power plants in the East to a permanent waste repository planned for the West? The Transportation Routing Analysis Geographic Information System (TRAGIS), developed by ORNL researchers Paul Johnson and Richard Michelhaugh, can determine the fastest highway, railroad, or waterway routes from starting point to destination. TRAGIS provides information on population distribution and densities. It picks routes that conform with government regulations (e.g., trucks carrying radioactive waste must go around, not through, cities), and it calculates alternative routes if a preferred route is blocked.

Users of TRAGIS include the U.S. Energy, Defense, and Transportation departments and the Nuclear Regulatory Commission.

A C-17 cargo aircraft in flight toward a war zone

Ultrafast system for storing and retrieving supercomputer data developed

ORNL's DNA-protein crystals grown in space aboard Columbia space shuttle

Signal analysis system developed for Navy to detect passing submarines

1996

Discovery of graphite foam that transfers heat unusually well

Popular refrigerator model altered to cut its energy use in half

Heartbeat detector devised to spot terrorists, prisoners hiding in vehicles

Searchable electronic notebook helps collaborators run experiments remotely over Internet

Janet Cushman examines species of fast-growing switchgrass that, like the hybrid poplar, is a potential energy source.

BIOMASS ENERGY

A New World for Wood

Thanks to a Department of Energy program managed by ORNL for 20 years, industry has a more efficient source of pulp fiber and wood for making paper, construction materials, and furniture. The original purpose of DOE's Bioenergy Feedstock Development Program was to develop sustainable farm-grown crops that could be converted to fuel. However, as a result of ORNL's collaborations with U.S. Department of Agriculture Forest Service and Agricultural Research stations, many universities, and several forest products companies, fast-growing trees and grasses were selected and developed that could be used for wood products, as well as energy. Poplar trees and switchgrass emerged as model crops.

The DOE program participants developed a technology of growing genetically superior hardwood trees that can be harvested every 6 to 12 years. The U.S. forest products industry has adopted this technology, especially in the Pacific Northwest and South, and, more recently, in the North Central region. Nationwide, approximately 120,000 acres are being used to grow short-rotation woody crops consisting mostly of poplars or poplar hybrids. The estimated value of the annual harvest for pulp fiber is about $50 million.—*Lynn Wright*

FUSION ENERGY

Seeking the Ultimate Source

Scientists from Russia and Japan to Europe and the United States have long sought to develop fusion as an abundant, safe, and environmentally friendly source of electric power. To reach this ambitious goal, they must overcome problems in a range of scientific and engineering disciplines. ORNL is known in the international fusion community as a laboratory that has made strong contributions in virtually every discipline of fusion science and engineering and that has the skills to maintain a central role in developing fusion energy.

Need to heat and fuel a plasma? ORNL researchers developed the physics and technology of bullet-like solid hydrogen pellets, high-frequency microwave tubes hundreds of times more powerful than a home microwave oven, and particle beams and radiofrequency heating systems with megawatts of power to heat fusion plasmas many millions of degrees.

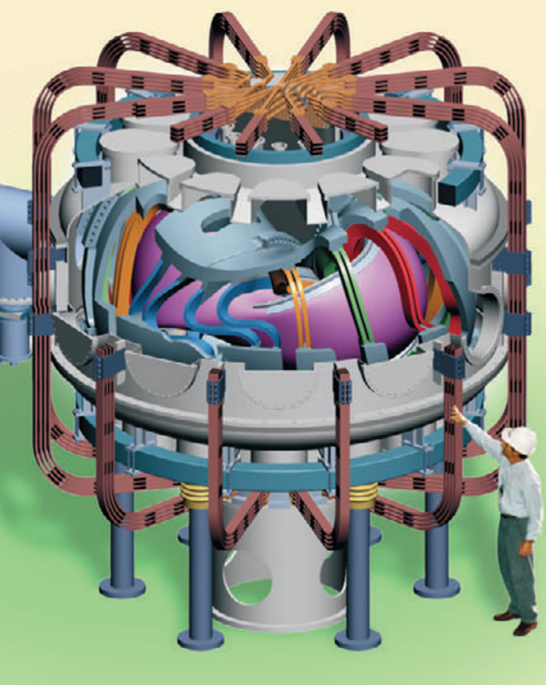
Need a better magnetic confinement system? ORNL researchers have developed improved magnetic "bottles" that are being tested in facilities in Madrid, Oxford, Moscow, and Princeton, and in new facilities under way in Princeton and Oak Ridge (i.e., the Quasi-Poloidal Stellarator, an approach to developing a smaller, less costly fusion device). These new facilities have been developed using ORNL's state-of-the-art computers.

Need longer lasting, more reliable materials? New materials that meet the needs of engineering test reactors have been developed at ORNL. Thanks to ORNL's unique irradiation and microcharacterization facilities, researchers are obtaining a fundamental understanding of how materials respond to radiation, enabling the creation of better materials.

Here are some selected highlights in ORNL's fusion energy career. To produce as much energy by sustained fusion reactions as is introduced into the fusion device (energy breakeven), certain conditions must be met. They are a sufficiently high fusion plasma temperature and density for a long enough time—the so-called Lawson criterion.

In 1978 ORNL's high-power neutral beam injection plasma heating system, developed under the leadership of Hal Haselton, enabled a tokamak at the Princeton Plasma Physics Laboratory (PPPL) to achieve a record plasma temperature. The Lawson criterion was first exceeded in 1983 in a landmark experiment on the Alcator-C tokamak at MIT using a fueling technique pioneered by Stan Milora and others at ORNL in which "bullets" of frozen hydrogen were fired into the plasma chamber from a gas gun. In 1986, a record Lawson parameter was set on PPPL's Tokamak Fusion Test Reactor in experiments performed by Milora and PPPL's G. L. Schmidt using a machine-gun-like fuel injector developed by ORNL.

In short, ORNL is known for applying its broad capabilities to advancing magnetic fusion to meet the goal of producing practical power.—*Lee Berry*

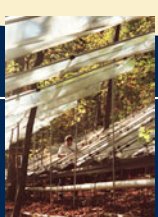


ORNL researchers have designed the compact Quasi-Poloidal Stellarator, a fusion research device that will be built at ORNL this decade.

1997

- Device developed to verify conversion of Russian weapons-grade uranium to reactor-grade fuel
- Initial design of mass spectrometer to help Army detect chem-bio threats

- First approved release of genetically engineered microbe
- VITALE devised to enhance signals from damaged videotapes, helping police solve crimes
- World's largest watershed experiment shows effects of droughts and heavy rainfall on forests



1998

- MicroCAT scanner invented; maps internal changes in mutated mice

TECHNOLOGY TRANSFER

From Benchtop to Marketplace

For more than four decades many of the technologies developed at ORNL have been transformed into practical goods and services that serve as the basis for the creation of new companies. Now institutionalized as a part of the Laboratory, ORNL's technology transfer program and the economic growth it generates are "downstream" by-products of basic scientific research. Indeed, since April 2000 30 new companies, including many in the Oak Ridge region, have been created with technologies licensed at ORNL.

A representative example of ORNL's technology transfer is found in the area of detectors, sensors, and scanners. In 1960 ORNL's John Neiler, Jack Gibbons, Hal Schmitt, and Phil Miller founded ORTEC. This spin-off firm built and sold detectors of charged particles (alpha particles, fission fragments) based on silicon surface barrier detection technology developed at the Laboratory. ORTEC, now part of AMETEK, has been a world leader in commercial radiation detection instrumentation. The creation of ORTEC and Tennelec—an Oak Ridge company founded in 1960 by Edward Fairstein to make signal amplifiers for ORTEC detectors and now owned by Canberra—marked the first significant examples of technology transfer from ORNL.

In the mid-1970s ORNL researchers developed a technique to analyze noise in reactors. General Electric marketed the technique, which could measure stability in boiling-water reactors.

Position-sensitive detectors that measure the angle and energy at which particles bounce off a target were devised for physics and neutron-scattering experiments. Such detectors, invented by Cas Borkowski and Manfred Kopp, were commercialized.

ORNL physicists and electronics experts have played a major role in developing detectors and electronic components to search for evidence that the beginning of the universe (quark-gluon plasma) has been mimicked at the Department of Energy's Brookhaven National Laboratory. The PHENIX detector development work provided the springboard for ORNL to develop a significant capability in creating low-power, mixed-signal integrated circuits. Several small start-up companies in detection and measurement markets have taken advantage of this capability through licensing agreements and collaborations.

Like bicycle tires, nuclear power plants have check valves, devices that allow gas or liquid to flow in only one direction. In the 1980s Howard Haynes, Don Casada, and Dave Eissenberg devised magnetic technologies that nonintrusively monitor the motion of check-valve internal parts, permitting identification of valves that are degraded or operating in an abnormal way that could lead to premature failure. Framatome ANP licensed the ORNL technology, which is the basis of a system sold to diagnose problems in power plant check valves.

Framatome ANP also licensed Haynes and Eissenberg's innovation for breaking down electrical signals from motors and generators into such fine detail that even small changes in the condition of a machine can be detected. Framatome ANP has sold more than 50 signal analysis systems for improving equipment safety and reliability and predicting equipment lifetime to customers including Boeing, Eli Lilly, General Motors, NASA, and electric utilities.

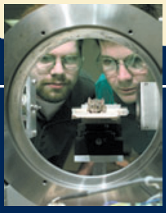
In the 1990s ORNL engineers led by Randall Wetherington developed the world's most advanced underwater acoustic measurement system. The U.S. Navy is using this technology to determine whether its next-generation submarines will operate at a level of quietness required to escape detection by enemy subs.

Michael Paulus and Shaun Gleason developed the MicroCAT scanner, an X-ray computed tomography system for mapping internal defects and organ changes in experimental mice. Their company, ImTek, has sold 17 scanners to universities and private firms for cancer, genetics, and drug discovery research.

Thomas Thundat showed that microcantilevers—miniature diving boards similar to probes in atomic force microscopes—could be used to detect environmental pollutants, explosives, and chemical signals for disease. This ORNL technology has been licensed to Graviton, for chemical and biochemical sensors soon to be marketed; Sense Technologies, for detecting unexploded ordnance at airports; and Sarcon, for infrared imaging.

The commercial success of these and dozens of other ORNL technologies underscore the belief that scientific discovery can bring a variety of benefits to the public we serve.

When a microcantilever is coated with a substance that adsorbs a particular molecule, it will bend more and its natural rate of vibration will change, altering the angle of deflection of incoming laser light.



Outdoor FACE experiment shows sweetgum trees grow faster in enriched CO_2 atmosphere

ORNL techniques help semiconductor firms find problems causing defects in computer chips

1999

Vice President Gore speaks at Spallation Neutron Source groundbreaking

Alloy studies lead to retrofitted or new boilers in paper industry, making it safer

Multifunctional biochip devised to rapidly detect diseases in humans

UT-ORNL PARTNERSHIP

Growing a Joint Research Agenda

Beginning with degree programs in 1943, ORNL has had a special relationship with the University of Tennessee. Since UT became a managing contractor of the Laboratory in April 2000, the two institutions have expanded a variety of programs that enrich and strengthen the research agenda of both ORNL and the university.

UT's first major Oak Ridge outreach activity was the formation of the Oak Ridge Institute of Nuclear Studies. In 1948 the UT Physics Department's William Pollard and Kenneth Hertel established ORINS, which later became Oak Ridge Associated Universities, a consortium of more than 80 universities that provides training and research opportunities in Oak Ridge for faculty and students throughout the nation.

As adjunct faculty, ORNL staff members have long taught science and engineering courses at UT, while university faculty have served as consultants and research participants at the Laboratory. Many ORNL scientists and engineers attended the UT Resident Graduate Program in Oak Ridge, which offered evening courses to those pursuing advanced degrees.

The first formal joint programs between the institutions were two UT graduate schools located at ORNL. One was the UT Graduate Program in Ecology. The other was the UT-Oak Ridge Graduate School of Biomedical Sciences, later called the UT-Oak Ridge Graduate School of Genome Science and Technology and moved to UT's Knoxville campus. More than 300 program graduates conduct biological research at universities, institutes, and businesses.

"The partnership between UT and ORNL holds unlimited potential for the research agendas of both institutions."

—Lee Riedinger

UT-ORNL Research Relationships
- 10 distinguished scientists; 6 searches/pending offers
- 23 joint faculty
- 96 graduate students
- 81 postdoctoral researchers
- UT investments in partnerships: $3.0M/yr
- UT-Battelle subcontracts to UT, FY2002: $7.47M
- Publications with joint authorship: 100/year

UT-ORNL Research Facilities
- Joint Institute for Biological Science
- Joint Institute for Computational Sciences
- Joint Institute for Neutron Science
- Joint Institute for Heavy Ion Research
- National Transportation Research Center

In 1984 the relationship matured further with the creation of the Science Alliance, a UT Center of Excellence sponsored by the Tennessee Higher Education Commission. The alliance, whose directors included Lee Riedinger (now deputy director of science and technology at ORNL), has been the primary vehicle through which the state of Tennessee promotes research and educational collaborations between UT and ORNL.

The UT-ORNL partnership's cornerstone is the Distinguished Scientist Program, through which esteemed researchers are appointed to joint positions. Ten current Distinguished Scientists have brought excellent research groups and external funding that enrich the local science community. Former Distinguished Scientist Jerry Mahan was elected to the National Academy of Sciences. The partnership also includes a joint faculty program for participants at all academic levels. Joint faculty number about 20 and can be based at ORNL or UT.

The Science Alliance administers the Joint Institute for Heavy Ion Research and the Joint Institute for Energy and Environment. UT also is a partner in the Joint Institute for Computational Sciences, Joint Institute for Neutron Science, and Joint Institute for Biological Sciences at ORNL. In 2002 Governor Don Sundquist joined UT President John Shumaker and ORNL Director Bill Madia at a ground breaking ceremony for the ORNL building that will house the Joint Institute for Computational Science and the Oak Ridge Center for Advanced Studies. State leaders have committed funding support for the other two institutes.

A unique area of collaboration involves transportation research projects of national interest at the National Transportation Research Center in Knox County, managed by UT and ORNL. With UT taking the lead, ORNL and several medical organizations formed the Tennessee Mouse Genome Consortium, funded to create new strains of mutant mice for studies of neurological disorders.

The scope of research relationships between UT and ORNL continues to grow. ORNL partners with UT in the Center for Genomics and Bioinformatics, Tennessee Advanced Materials Laboratory, Center for Environmental Biotechnology, Center for Structural Biology, Food Safety Center of Excellence, Center for Information Technology Research, and Center for Nanophase Materials Sciences.

In addition to joint research efforts, ORNL and UT are partners in a number of initiatives outside the Laboratory. UT-Battelle sponsors the UT Academy for Math and Science, which provides development training for area teachers. UT-Battelle also funds minority scholarships in the College of Engineering, as well as the UT-Battelle Scholars program, which awards to children of ORNL staff scholarships to UT in math and science.

2000

UT-Battelle is new ORNL managing contractor; Bill Madia named ORNL director

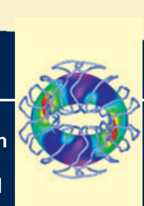
Two new super-computers brought online

UT-ORNL opens National Transportation Research Center

ORNL places in top 4% in international protein structure prediction competition

Energy-saving heat pump water heater developed

Fusion energy theorists begin design of Quasi-Poloidal Stellarator



ORNL helps sequence 3 human chromosomes

SCIENCE EDUCATION

Laying the Foundation

Since its inception, ORNL has made resources available for educational training and research opportunities. When Eugene Wigner in early 1946 became ORNL's research director, he established the Oak Ridge School of Reactor Technology. The school became the model for nuclear engineering courses at several universities and is one of ORNL's greatest contributions to nuclear energy. Among the school's graduates were leaders of the nuclear industry, including Captain Hyman G. Rickover, who came to Oak Ridge to investigate whether nuclear energy should be used by the U.S. Navy.

ORNL's educational outreach expanded in the mid-1980s with the creation of the Science Alliance, a joint program of research with the University of Tennessee. Funded by the state of Tennessee, the Science Alliance signaled a belief in the public benefit of joining the research agendas of ORNL and UT.

The relationship expanded further in 2000 when UT joined Battelle as the managing contractor for ORNL. Each year since has witnessed a growth in the number of joint faculty, graduate students and postdoctoral researchers working at both institutions. The UT-ORNL partnership includes new facilities and institutes, managed jointly, for biological sciences, computational sciences, and neutron sciences.

ORNL's close ties with UT today are complemented by partnerships with Oak Ridge Associated Universities and six core universities with which the laboratory conducts a variety of research activities. The core universities, Duke, Florida State, Georgia Tech, North Carolina State, Virginia, and Virginia Tech, provide a variety of research competencies that support the Laboratory's agenda.

ORNL's educational outreach is not confined to higher education. Each year more than 6000 area K-12 students receive science education classes sponsored by the laboratory. ORNL also is a primary sponsor of science and engineering competitions, as well as science, math and engineering scholarships to the University of Tennessee.

In 2003, as it did 60 years ago, ORNL's mission includes a commitment to share the benefits of scientific exploration.

WASTE MANAGEMENT

Closing the Circle

Sixty years after the Graphite Reactor went critical, ORNL today is helping to close the nuclear cycle by finding safe ways to isolate nuclear wastes. Perhaps the most significant work has related to repository siting for geologic disposal of spent fuel and high-level nuclear waste (HLW), part of an effort that resulted in Congressional approval of Yucca Mountain (Nevada) as the possible disposal site. The process began in 1955 with a National Academy of Sciences conference devoted to developing U.S. plans for permanent disposal of reactor waste. Among the 65 scientists attending were ORNL's Floyd Culler, Roy Morton, and Ed Struxness. The conferees recommended bedded salt as the best medium for HLW disposal, although other options existed.

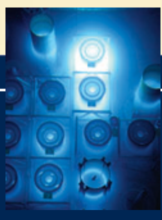
In 1958 the Atomic Energy Commission (AEC) asked ORNL to manage a repository program, largely because of its scientists' early leadership in waste management studies. In the 1960s, ORNL managed a major characterization and testing program in a Kansas salt mine. By 1970 it was announced that the nation's first demonstration repository would be sited there, but technical and political concerns reversed this position. ORNL continued to lead the AEC repository program through studies of multiple rock types and development of siting criteria. In 1976 the Office of Waste Isolation was opened in Oak Ridge before being transferred to Battelle Memorial Institute.

ORNL also has been a leader in managing low-level nuclear waste (LLW). The Laboratory served as associate leader of the Department of Energy's National Low-Level Waste Program in the late 1970s and early 1980s. Highly innovative in situ treatment technologies for reducing release of radionuclides from buried LLW have been widely accepted. Finally, disposal issues associated with mercury used at the Oak Ridge Y-12 Plant to produce enriched lithium for the hydrogen bomb program, which were largely addressed by ORNL scientists, helped motivate DOE to establish its remedial action program. From cleanup of old sites to construction of state-of-the-art new ones, responsible waste management has become a central part of the nuclear cycle.—*Steve Stow*

2001

Direct-to-digital holography for 3D defect inspection devised for semiconductor firms

HFIR resumes operation after beryllium reflector replaced, research building added

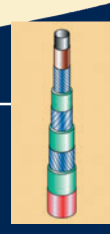


GRAIL used in *Science* and *Nature's* landmark papers on sequencing human genome

Groundbreaking for long-awaited new Mouse House

Secretary of Energy Abraham visits, transfers DOE land to ORNL for new construction

Superconducting transformer and cable developed with industrial partners



GOVERNMENT POLICIES

Aiding America's Science Agenda

ORNL research has provided important information to federal science and technology policy makers, shaping the debate and sometimes the wording of various laws, regulations, and other policies. For example, Laboratory studies since the 1960s have resulted in several regulatory criteria that have improved the safety of nuclear power plant operations. (See "Nuclear Safety" on p. 6.)

In 1974 when Alvin Weinberg, former ORNL director, headed a federal energy office that advised the Federal Energy Administration, he recommended developing technologies that use energy efficiently and studying long-term climatological effects of energy production. These recommendations were buttressed by the results of ongoing ORNL research led by Jack Gibbons, Roger Carlsmith, and Eric Hirst (who developed tools to improve energy efficiency in buildings and power delivery systems) and Jerry Olson (who studied how plants incorporate carbon dioxide from the atmosphere and return it when they die, as part of the global carbon cycle).

"ORNL has had a significant impact on the way Americans think about energy and ways to use it cleanly and efficiently," says Tom Wilbanks, an ORNL corporate fellow who has provided assistance on energy and environmental problem solving to people in 40 nations on 4 continents. This sea change in the nation's energy policy making began in the 1960s when Weinberg had a vision that ORNL could become the nation's environmental research and development laboratory. As one expression of this vision, a National Science Foundation Environmental Program was established at ORNL under the leadership of David Rose of the Massachusetts Institute of Technology, with Gibbons as his assistant director. Gibbons later served as director of the Office of Technology for the U.S. Congress and as science adviser to President Bill Clinton.

Carlsmith, Hirst, and other ORNL staff were instrumental in convincing U.S. policy makers and business leaders that energy efficiency improvements need not mean reductions in energy services. Industry leaders, in fact, began to see that energy efficiency could be good business. Firms such as Honeywell and Johnson Controls began marketing devices to monitor energy use, while the Department of Energy established national appliance efficiency standards. ORNL studies led by David Greene and others also influenced the development of policies promoting transportation energy efficiency.

ORNL also played a prominent role in cultivating the art and science of environmental impact analysis, helping to shape implementation of the National Environmental Policy Act of 1969. In addition, ORNL influenced the emergence of national environmental standards in the 1970s. Research led by Chuck Coutant concerning the effects on fish and other aquatic life of heated water discharged from power plant cooling systems was reflected in a section in the Clean Water Act of 1970 and the Environmental Protection Agency's implementation document, which remains the basic guideline for evaluating thermal-discharge effects.

Provisions of the Clean Air Act Amendments of 1990 that restrict industrial emissions of sulfur and nitrogen oxides reflect the findings of ORNL acid rain research for the National Acid Precipitation Assessment Program. Research results from ORNL also provided the technical basis for advice to DOE and EPA on setting regulations concerning safe disposal of pollutants in compliance with the Resource Conservation and Recovery Act. Studies by Steve Lindberg and others led to federal recommendations for controls of mercury emissions from sources such as coal-fired power plants.

More recently, ORNL staff members have addressed national needs for energy security, global environmental management, and competitiveness in international energy markets. Paul Leiby showed the substantial value of filling DOE's Strategic Petroleum Reserve to its capacity of 700 million barrels of oil, contributing to a recent Bush Administration decision to expand the reserve.

Related in part to conclusions of DOE national laboratory groups co-led by Marilyn Brown, who identified energy-efficient and low-carbon technologies that could slow the buildup of climate-altering atmospheric carbon dioxide, Wilbanks recently assisted DOE in preparing a strategic plan for the Clean Energy Technology Exports section of the U.S. Senate's 2002 energy bill. Further ORNL studies of strategies for U.S. energy independence by 2030 are under way.

2002

IBM Power4 supercomputer starts up; fastest supercomputer aim of ORNL-Cray partnership

Construction begins for $300-million modernization program

Groundbreaking for UT-ORNL Joint Institute for Computational Sciences

DOE approves Center for Nanophase Materials at ORNL

Habitat for Humanity home showcases ORNL energy technologies

Actinium-225 shipped from ORNL to treat leukemia patients

A Campus for the Next Generation of Great Science

In 1943, more than 6000 workers began construction of some 150 buildings that became what we know today as Oak Ridge National Laboratory. As we celebrate ORNL's 60^{th} anniversary, we are literally rebuilding the laboratory. The \$300-million modernization plan, in addition to the \$1.4-billion Spallation Neutron Source, will make it possible for ORNL to attract the next generation of world-class scientists to Oak Ridge.

Privately funded facilities: Constructed on land deeded from the Department of Energy, the 300,000 square-foot facility will house state-of-the-art labs for energy and computational science. Completion date: 2003

2003 . . .

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