OAK RIDGE NATIONAL LABORATORY

# Review



## 75 YEARS of science and technology


OAK RIDGE National Laboratory

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# Review
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## Contents




**On the Cover**

*Pioneering ORNL geneticist Liane Russell.*
DOE photo by Ed Westcott

# Science with a mission

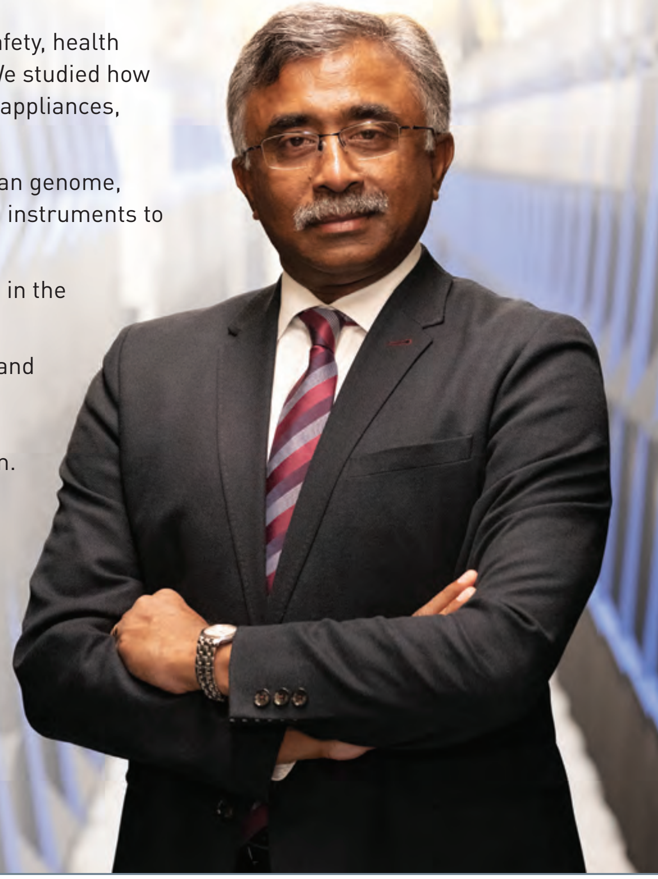
This special edition marks the 75th birthday of Oak Ridge National Laboratory, providing a survey of the lab's origin in a time of global crisis, its evolution in the decades that followed, and its leadership today.

The following pages contain an extraordinary story of American greatness, of international cooperation, of scientific discipline, collaboration, and perseverance by a research community always willing to tackle the most difficult challenges—and smart (or stubborn) enough to succeed.

In the past year—my first as lab director—I have spoken often about the sense of purpose that drives ORNL. Facing the existential threat of World War II, some of the world's brightest minds established foundational capabilities and expertise here, building an institution that has pursued knowledge wherever it might lead, in support of national missions in energy, security, technology and innovation.

We have always operated on the front lines of the possible.

From our roots at the X-10 Graphite Reactor, the first continuously operating reactor, we pioneered nuclear engineering and energy. We learned to use the neutrons produced in that reactor to probe materials and produce isotopes for medicine and other uses.



We improved materials and created new ones, and we set standards for safety, health and environmental protection. We explored other sources of energy, too. We studied how to best produce and preserve it, and we improved the efficiency of homes, appliances, vehicles and more.

We turned our expertise in fundamental science toward mapping the human genome, producing components and fuel for the exploration of space, and inventing instruments to unlock the mysteries of the materials essential for modern life.

Today, you will find our work in your smart phone, your doctor's office, and in the power grid that keeps it all running.

Our scientific facilities serve thousands of users from academia, industry and government. We build the most powerful supercomputers in the world to study energy systems, global climates, population densities and exploding stars. Our advanced instruments help to build new materials atom by atom. We test manufacturing equipment and methods for industrial partners.

We help to keep our borders secure and our airports safe. Our scientists and engineers support nuclear nonproliferation efforts globally, and we still pursue the goal of providing safe, reliable energy to a growing world.

Applying the best science and engineering to the biggest problems is a privilege and an obligation that we have taken seriously at Oak Ridge National Laboratory for 75 years. We are proud that our work continues to support American leadership and to improve the lives of people wherever they may live.

Thank you for your interest in the story of ORNL.

Thomas Zacharia

Thomas Zacharia
Laboratory Director

# The top-secret laboratory

by Katie Jones
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*Oak Ridge National Laboratory today is an open science laboratory that attracts thousands of scientists and engineers from around the globe each year. It began in the World War II Manhattan Project, which developed the first atomic bombs.*

In summer 1939, tensions were rising among European powers. Nazi Germany invaded Czechoslovakia in March. Weeks later, imperialist Italy invaded Albania. Across the Atlantic, U.S. President Franklin Roosevelt struggled with America's neutrality policies, which prevented him from providing arms to Britain.

Meanwhile, outside the world of politics, in the halls of universities and research institutes, physicists were reeling from an amazing discovery.

## The age of the atom

Scientists' understanding of the atom had rapidly taken shape in the first decades of the 20th century. Following the discovery of radioactivity by French physicist Henri Becquerel in 1896, British physicist Ernest Rutherford theorized that the phenomenon was caused by the breakdown of atoms. In 1913, Danish physicist Niels Bohr applied Rutherford's work to the relatively new theories of quantum mechanics to develop the first model of the atom with electrons surrounding the nucleus in shells.

The discovery of protons, and later neutrons, allowed scientists to assign each element an atomic number, based on the number of protons in the nucleus, and to explain the existence of isotopes, based on the number of neutrons.

By the 1930s, scientists including E.O. Lawrence at the University of California and Robert Van de Graaff at Princeton University were using new instruments called particle accelerators to study the properties of nuclei by striking them with high-energy protons. Italian physicist Enrico Fermi used neutrons instead of protons—taking advantage of the neutral particle's ability to probe the nucleus without resistance—and he produced a slew of new radioactive isotopes.

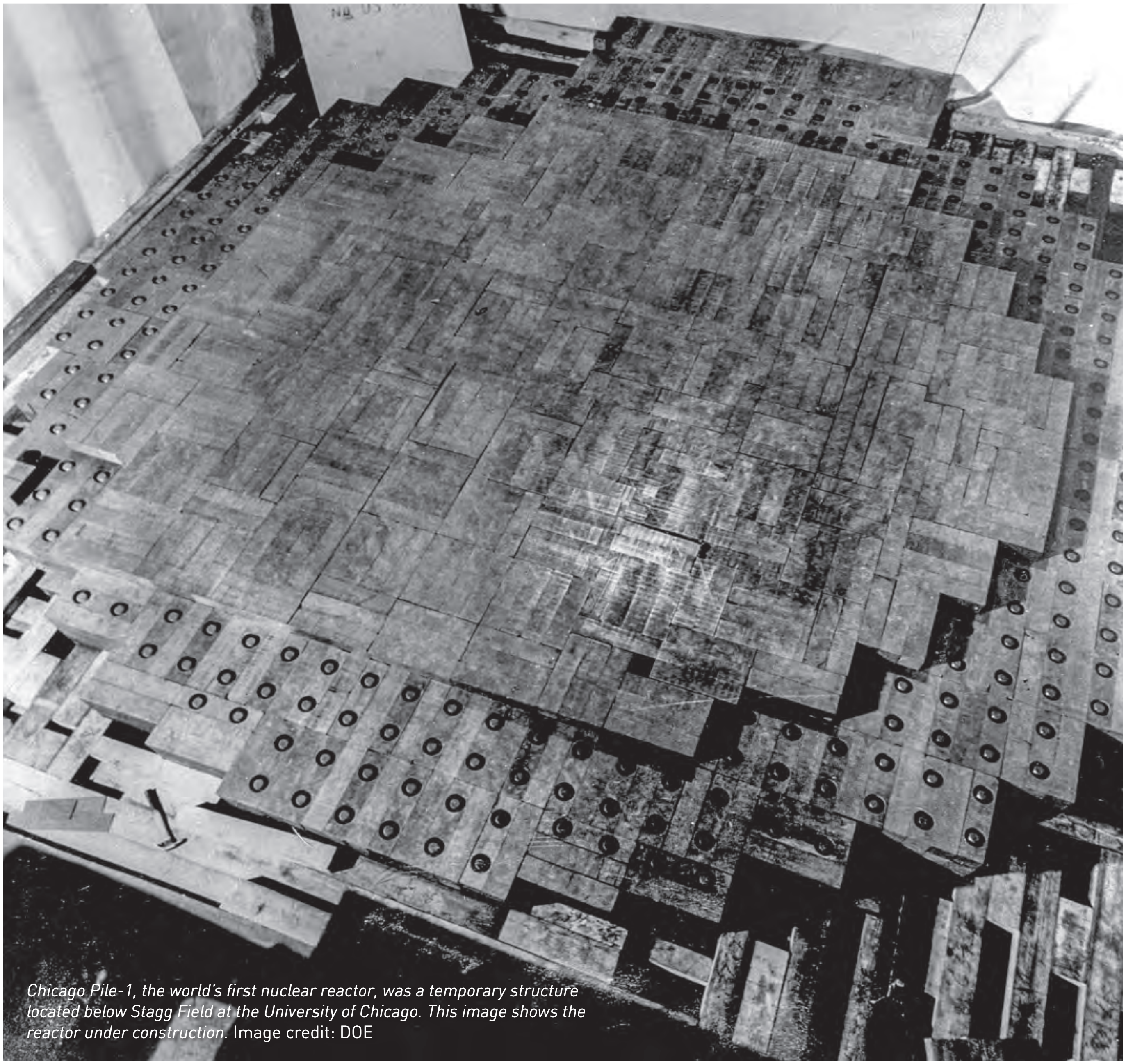
The nucleus seemed to hold limitless possibilities.

Then, in December 1938, German chemists Otto Hahn and Fritz Strassmann discovered something unusual when they bombarded uranium with neutrons: The experiment produced radioactive isotopes of the lighter element barium.

> *"Einstein understood it in half a minute. It was really uncanny how he dictated a letter in German with enormous readiness."*
>
> — Former Laboratory Director **Eugene Wigner**

Hahn described this puzzling result in a letter to his former colleague, Austrian physicist Lise Meitner, who had fled Nazi Germany for Sweden in July 1938. Meitner and her nephew, physicist Otto Frisch, discussed the problem and concluded that the neutron had split the uranium atom into lighter atoms and converted some of its mass to energy, in agreement with Albert Einstein's famous equation "$E = mc^2$." Frisch discussed their findings with Bohr, who announced the discovery of fission at a conference in St. Louis in January 1939.

Named after the technical term for cell division—binary fission—the nuclear phenomenon would become the subject of a flurry of experiments and academic papers in Europe and the United States over the next few months.



*Chicago Pile-1, the world's first nuclear reactor, was a temporary structure located below Stagg Field at the University of Chicago. This image shows the reactor under construction.* Image credit: DOE

## A chain reaction begins

While physics laboratories across the United States repeated and advanced the German discovery of fission, three physicists in particular worried how this new knowledge would influence political and military powers.

The discovery unlocked the possibility of a chain reaction in which neutrons ejected from one split atom would collide with new atoms, leading to a series of fissions. With each split, more energy would be released. "Criticality" would be achieved when the process reached a critical tipping point and continued unabated.

Hungarian-American physicists Leo Szilard, Eugene Wigner and Edward Teller feared Germany would obtain enough uranium to weaponize nuclear fission. They also realized that this discovery was not known or understood outside the scientific community. To help elevate their concerns to the government, Szilard rushed to meet with his acquaintance Einstein, who had become quite famous since moving to the United States in 1933.

Interrupting Einstein's vacation at a beach house on Long Island, Szilard and Wigner persuaded the popular genius to write a letter to the Belgian ambassador to the United States (because Belgium controlled uranium resources in the Congo),

*See TOP-SECRET LABORATORY, page 4*

*TOP-SECRET LABORATORY, page 3*

explaining the nuclear potential of the metal. As Wigner later recalled, "Einstein understood it in half a minute. It was really uncanny how he dictated a letter in German with enormous readiness." Wigner translated the letter to English.

Then a mutual friend of Szilard and President Roosevelt, the economist Alexander Sachs, offered to deliver a letter directly to the White House. In that letter, Einstein implored the president to "have some permanent contact maintained between the Administration and the group of physicists working on chain reactions in America." He ended the letter by warning that Germany had stopped the sale of uranium from the Czechoslovakian mines it had just seized, leading to an unnerving speculation that Germany was on the path to "extremely powerful bombs of a new type."

> *"What you are after is to see that the Nazis don't blow us up."*
>
> — U.S. President **Franklin D. Roosevelt**

It was two months before Sachs met with Roosevelt and shared the letter, but the president took immediate interest. "What you are after is to see that the Nazis don't blow us up," Roosevelt told Sachs.

Within a week, Roosevelt set up an Advisory Committee on Uranium. What would transpire over the next few years would be the largest collaboration between the scientific community and government in U.S. history.

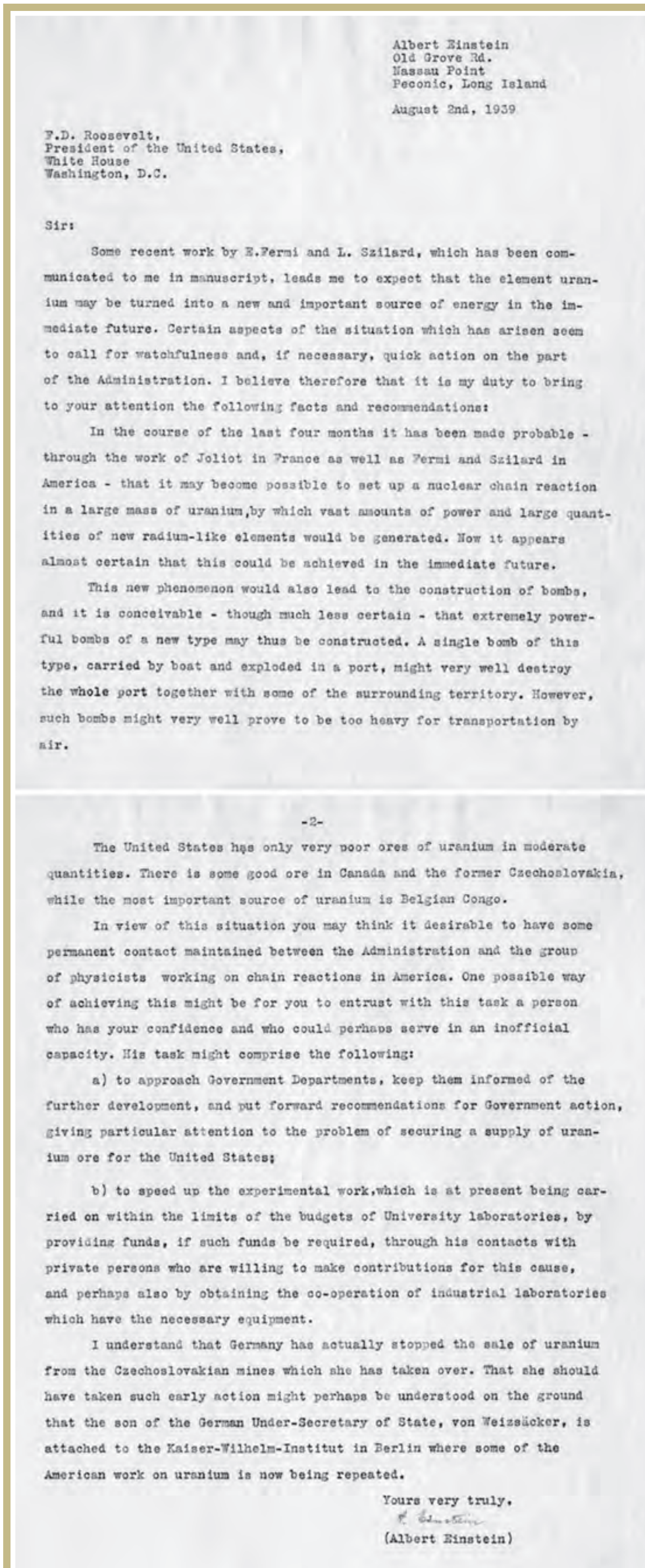
## Three paths to atomic weapons

While nuclear research continued at universities from 1939 to 1941, the federal government slowly organized its response to the uranium problem. Roosevelt's uranium committee evolved into the Section on Uranium, or S-1, of the Office of Scientific Research and Development, a new government office with authority to fund scientific missions.

After the December 7, 1941, attack on Pearl Harbor drove the United States to declare war, S-1 accelerated research on pathways for developing what had come to be called an "atomic" bomb. The biggest hurdle would be amassing enough fissionable material to generate a sufficiently powerful nuclear chain reaction.

Fissionable material is rare in nature. Less than 1 percent of natural uranium is the fissionable uranium-235 isotope; most natural uranium is non-fissile uranium-238. One of the first initiatives of U.S. physicists was to prove that it would be impossible to achieve a chain reaction using natural uranium alone. Indeed, it was impossible—which was good (because it would be difficult for Germany to develop a nuclear weapon) and bad (because it would also be more difficult and expensive for the United States to develop one first).

*See TOP-SECRET LABORATORY, page 6*



Albert Einstein
Old Grove Rd.
Nassau Point
Peconic, Long Island

August 2nd, 1939

F.D. Roosevelt,
President of the United States,
White House
Washington, D.C.

Sir:

Some recent work by E.Fermi and L. Szilard, which has been communicated to me in manuscript, leads me to expect that the element uranium may be turned into a new and important source of energy in the immediate future. Certain aspects of the situation which has arisen seem to call for watchfulness and, if necessary, quick action on the part of the Administration. I believe therefore that it is my duty to bring to your attention the following facts and recommendations:

In the course of the last four months it has been made probable - through the work of Joliot in France as well as Fermi and Szilard in America - that it may become possible to set up a nuclear chain reaction in a large mass of uranium,by which vast amounts of power and large quantities of new radium-like elements would be generated. Now it appears almost certain that this could be achieved in the immediate future.

This new phenomenon would also lead to the construction of bombs, and it is conceivable - though much less certain - that extremely powerful bombs of a new type may thus be constructed. A single bomb of this type, carried by boat and exploded in a port, might very well destroy the whole port together with some of the surrounding territory. However, such bombs might very well prove to be too heavy for transportation by air.

-2-

The United States has only very poor ores of uranium in moderate quantities. There is some good ore in Canada and the former Czechoslovakia, while the most important source of uranium is Belgian Congo.

In view of this situation you may think it desirable to have some permanent contact maintained between the Administration and the group of physicists working on chain reactions in America. One possible way of achieving this might be for you to entrust with this task a person who has your confidence and who could perhaps serve in an inofficial capacity. His task might comprise the following:

a) to approach Government Departments, keep them informed of the further development, and put forward recommendations for Government action, giving particular attention to the problem of securing a supply of uranium ore for the United States;

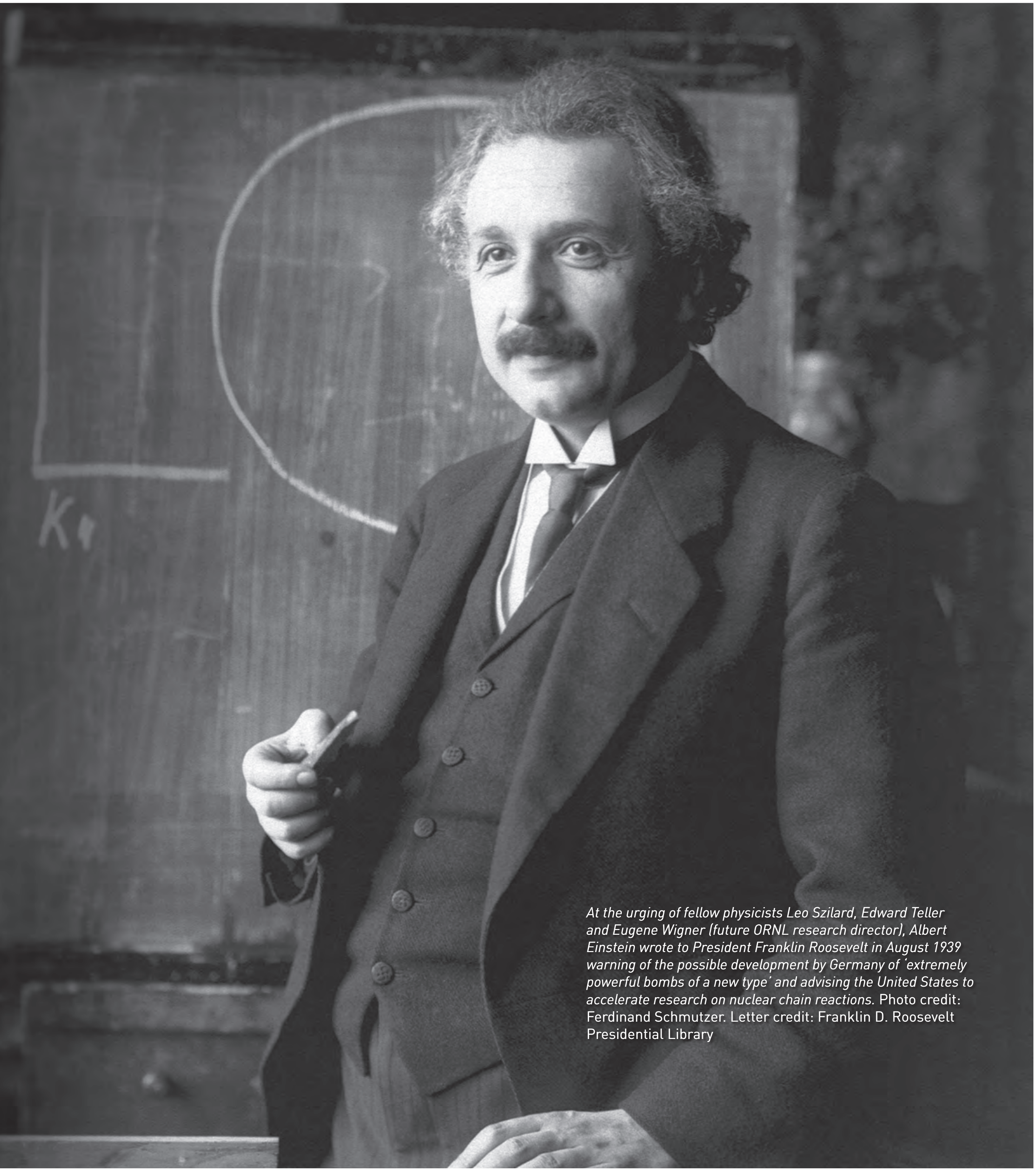
b) to speed up the experimental work,which is at present being carried on within the limits of the budgets of University laboratories, by providing funds, if such funds be required, through his contacts with private persons who are willing to make contributions for this cause, and perhaps also by obtaining the co-operation of industrial laboratories which have the necessary equipment.

I understand that Germany has actually stopped the sale of uranium from the Czechoslovakian mines which she has taken over. That she should have taken such early action might perhaps be understood on the ground that the son of the German Under-Secretary of State, von Weizsäcker, is attached to the Kaiser-Wilhelm-Institut in Berlin where some of the American work on uranium is now being repeated.

Yours very truly,

A. Einstein

(Albert Einstein)



*At the urging of fellow physicists Leo Szilard, Edward Teller and Eugene Wigner (future ORNL research director), Albert Einstein wrote to President Franklin Roosevelt in August 1939 warning of the possible development by Germany of 'extremely powerful bombs of a new type' and advising the United States to accelerate research on nuclear chain reactions.* Photo credit: Ferdinand Schmutzer. Letter credit: Franklin D. Roosevelt Presidential Library

*TOP-SECRET LABORATORY, page 4*

Because natural uranium alone would not work, physicists needed to increase the concentration of fissionable material—a process that would come to be known as enrichment—to produce enough material for an atomic bomb, as well as any peacetime application of nuclear energy.

At the end of 1941, two fissionable materials were under consideration—uranium-235 and an isotope of the recently discovered element plutonium, plutonium-239—as well as three enrichment processes. To enrich uranium-235, researchers proposed processes known as gaseous diffusion and electromagnetic separation. To extract plutonium, researchers proposed a nuclear reactor "pile" in which natural uranium bombarded by neutrons from fissile uranium-235 could be converted, in small amounts, to plutonium-239. The plutonium would then be chemically separated from the other fission products—a process that would prove just as challenging and critical to the project's mission as building the reactor.

By summer 1942, six months into America's involvement in the war, the task of building plants to produce uranium-235 and plutonium-239 was assigned to the U.S. Army Corp of Engineers. The Army created the top-secret Manhattan Project—named for the project's original office in New York City.

The first order of business for the Manhattan Project's newly appointed director, Gen. Leslie Groves, was acquiring land for the uranium enrichment plants and a pilot plutonium production facility. The Clinch River Valley in East Tennessee met the project's strategic demands. The valley was far enough inland to discourage enemy attack and remote enough to avoid attention, yet close to the nearby workforce in Knoxville. It was also equipped with abundant electrical power from the Tennessee Valley Authority and cooling water from the nearby Clinch River.

## Three secret sites

Across the country Manhattan Project sites in Washington and New Mexico would carry out full-scale plutonium production and weapon development, respectively.

Code-named "Site X," the 59,000 acres in Tennessee were roughly quartered for three production plants and a townsite to house workers.

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*Billboard from 1943.*
DOE photo by Ed Westcott

# Wigner's influence at ORNL

by Bill Cabage
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"Maybe there is something new here," Eugene Wigner said to Clifford Shull when Shull described a problem he and Ernest Wollan had encountered with their early neutron scattering experiments.

Wigner was right, and subsequent development of the neutron diffraction technique earned Shull a Nobel Prize in Physics.

Wigner was one of the celebrated European expatriates of the 1930s. He headed a group of theoretical physicists at the University of Chicago at the outset of World War II, and his contributions to the Manhattan Project coincided with his foundational work in nuclear engineering.

*Nobel Prize winner and lab Research Director Eugene Wigner.* Image credit: ORNL

Contemporaries recalled his continental manners and unwavering politeness. When he walked into the cafeteria with Edward Teller—another of the expats—Teller barged to the front of the line, but Wigner took his place at the end.

To see the impact on science made by ORNL's first scientific director, just look to the Wigner coefficient, the Wigner-Eckhart theorem, the Wigner effect, Wigner force, Wigner nuclides, the Wigner-Seitz cell, the Wigner-Seitz method, Wigner's theorem and the Wigner supermultiplet. And, of course, there is his 1963 Nobel Prize in Physics.

To know his impact on history, consider that he was instrumental, with fellow Hungarians Leo Szilard and Teller, in preparing the famous Einstein letter to President Franklin Roosevelt. The letter, which warned of potentially cataclysmic technological developments with uranium, led to the Manhattan Project.

His impact on ORNL is also immense. There are the lab's prominence in nuclear reactor engineering, its Wigner Fellowships that have established top early career researchers in productive Oak Ridge careers, and the Wigner Distinguished Lecture Series, which brings esteemed scientists to speak at ORNL—including eight Nobel laureates in its first five years.

When asked where Wigner received his remarkable insights into physics and engineering, the late ORNL Director Alvin Weinberg remarked of his mentor: "He was smarter than everybody else."

*Gen. Leslie Groves, director of the Manhattan Project.* DOE photo by Ed Westcott

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To the west, the K-25 plant for enriching uranium through gaseous diffusion separation would soon be home to the largest building in the world, containing more than 1.6 million square feet of floor space. (The much smaller S-50 plant, which used a thermal diffusion process for uranium enrichment, would be constructed near K-25 in 1944.) To the east, the Y-12 plant would house calutrons for enriching uranium through electromagnetic separation.

And to the south, X-10 would host the world's first permanent nuclear reactor and plutonium processing plant, which would serve as a prototype and training facility for larger production plants at the Manhattan Project site in Hanford, Washington.

X-10—the future ORNL—would also enable critical research on plutonium at Los Alamos Laboratory in New Mexico. Plutonium was not discovered until 1940, and no one fully understood how it might react in a fission reaction. But physicists did know that plutonium-239 was about 1.7 times more fissionable than uranium-235 and could not be overlooked. The physicists who would develop the bomb at the Los Alamos site needed samples of plutonium to study—the sooner, the better.

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# Enrico Fermi and the Chicago Pile

by Leo Williams
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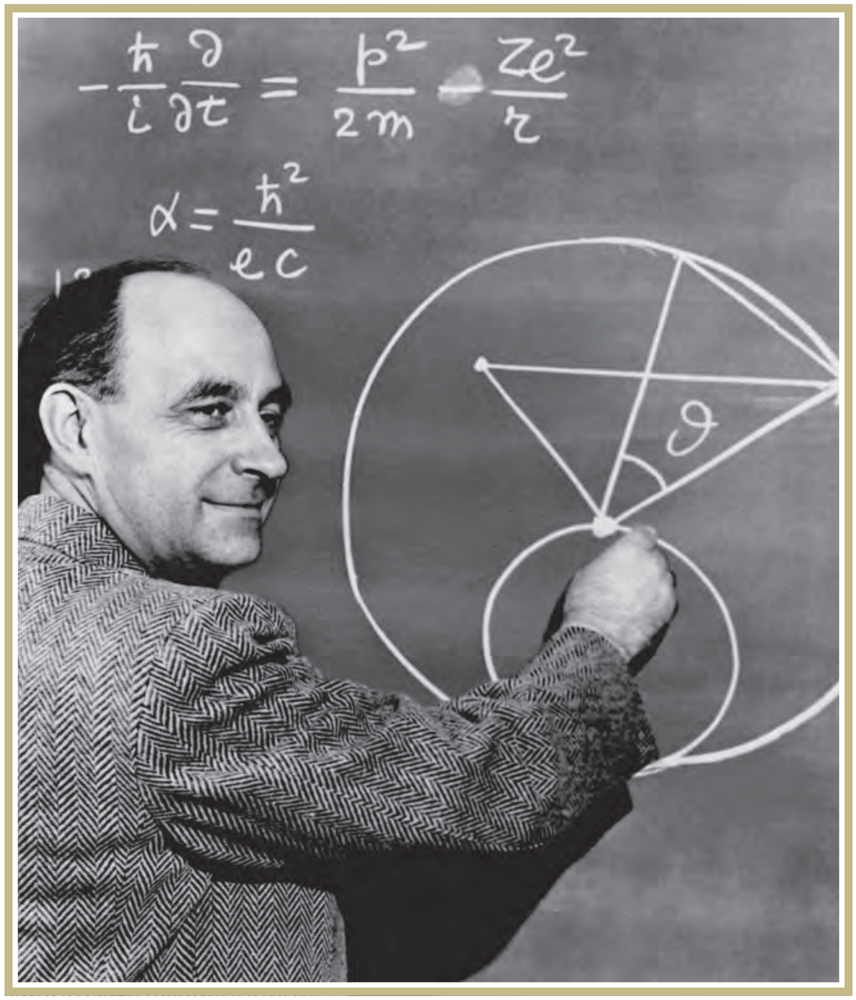
Two events in 1938 proved critically important to the course of World War II. In the first, German chemists Otto Hahn and Fritz Strassmann discovered nuclear fission. In the second, Italian physicist Enrico Fermi and his Jewish wife, Laura, left their home to avoid Italy's new Racial Laws.

The couple's decision to emigrate was a boon to the United States. Fermi picked up a Nobel Prize in Physics in Sweden that year, but rather than return to Italy, he traveled on to New York, where he took a position at Columbia University.

He also became a key player in the Manhattan Project, leading the team that created the first nuclear fission reactor, named Chicago Pile-1.

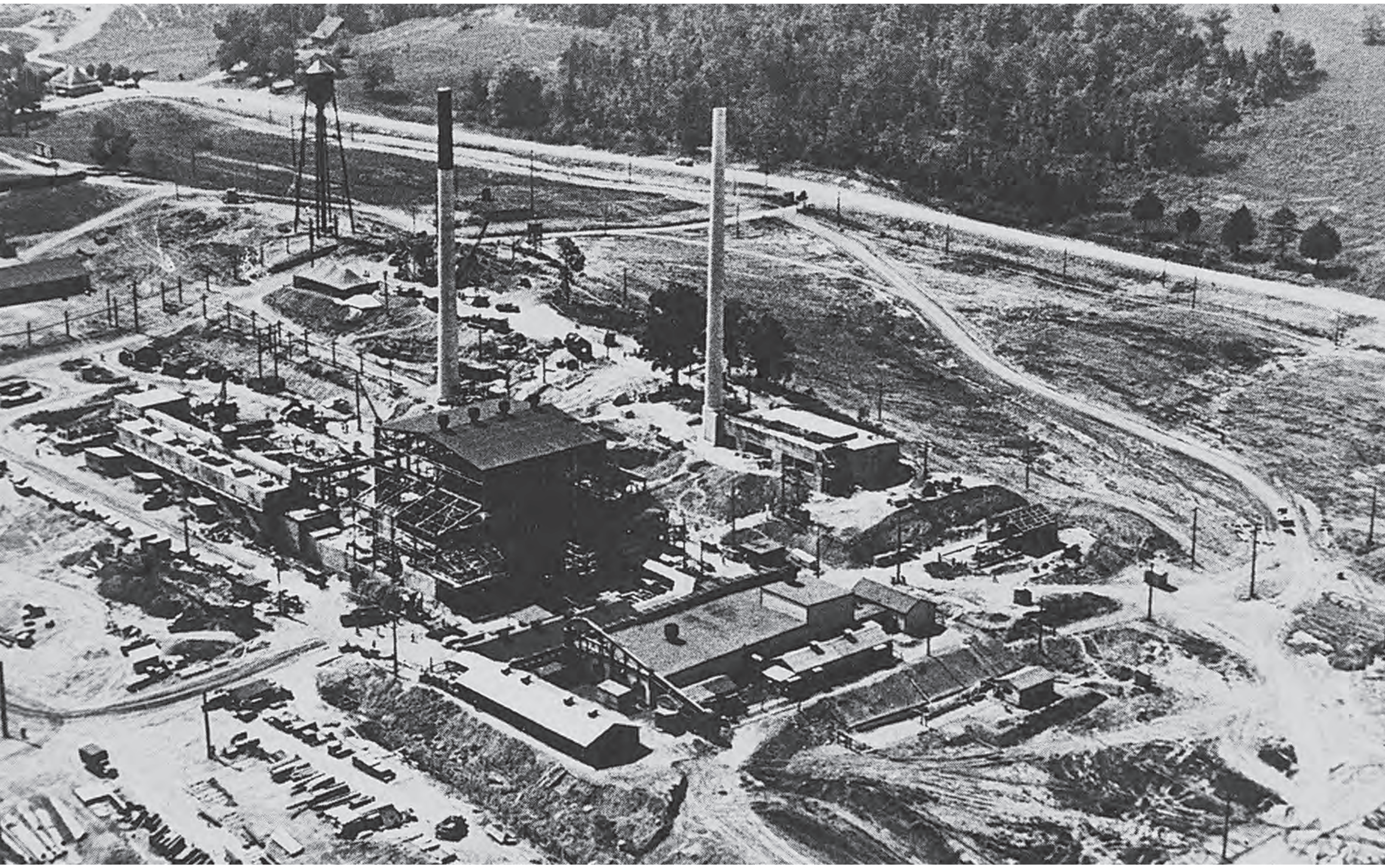
More than 385 tons of graphite and 46 tons of uranium fuel went into the pile, which was built on a rackets court beneath Stagg Field on the campus of the University of Chicago.

Forty-nine scientists and workers gathered for its momentous start-up on December 2, 1942. Most watched from a balcony while Fermi directed scientist George Weil to carefully remove the cadmium rods that had been preventing a chain reaction. The occasion included a lunch break, after which Fermi instructed Weil to pull the last control rod out another foot.




*Enrico Fermi.* Photo courtesy Argonne National Laboratory

The clacking of neutron counters verified that the reactor had indeed "gone critical," or sustained a nuclear chain reaction. That reaction lasted less than five minutes before the reactor was shut down. The group celebrated its achievement with a bottle of Chianti, provided by future ORNL R&D Director (and physics Nobelist) Eugene Wigner.



*Gen. Leslie Groves directed DuPont to mobilize personnel to build the air-cooled Graphite Reactor and a plutonium-separation pilot plant at the X-10 site in what would become Oak Ridge. The facility, shown in August 1943, was intended to demonstrate plutonium production and separation, and Groves directed the University of Chicago Metallurgical Laboratory to supply the managers and scientists to operate it.* Image credit: DOE

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Practically overnight, X-10 became a training ground for hundreds of workers, including many chemists and engineers, who were developing the fields of nuclear engineering and isotope separation.

## The world's first permanent reactor

DuPont, the industrial contractor for X-10 and the full-scale reactors at Hanford, broke ground near Bethel Valley Road on February 2, 1943. The X-10 reactor was built in just nine months and reached criticality—that is, a self-sustaining fission reaction—on November 4 that year.

Named for the lightweight element used to moderate, or slow, neutrons released during fission, the Graphite Reactor was the world's first continuously operating nuclear reactor. It had infrastructure including controls, ventilation and shielding to support a megawatt of power (and eventually 4 megawatts).

Future ORNL leaders Eugene Wigner and Alvin Weinberg contributed to the design. In particular, Weinberg, as a young researcher on Wigner's team at the Chicago Metallurgical Laboratory, calculated the layout of the graphite and uranium lattice. Wigner campaigned for the Graphite Reactor to be water-cooled, which he correctly predicted as the preferred design for future nuclear reactors (air cooling would not suffice at higher power outputs), but the Army decided to keep it air-cooled for two main reasons: First, it would be quicker to build an air-cooled reactor, and the scientists at Los Alamos in charge of developing the plutonium bomb needed samples of plutonium to study as soon as possible. Second, the air-cooled reactor could be used to study corrosion in materials for water-cooled reactors, like those being developed at Hanford.

In the Graphite Reactor, small amounts of natural uranium (primarily uranium-238) were converted to plutonium-239

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# ORNL and the University of Chicago

by Tim Gawne
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*Under this University of Chicago football stadium, scientists achieved the world's first nuclear chain reaction.* Image credit: University of Chicago Photographic Archive

In the early days of the Manhattan Project, all roads led to the University of Chicago, where some of the 20th century's most brilliant minds gathered at the Metallurgical Laboratory, the precursor of today's Argonne National Laboratory.

It was the site of the first nuclear reactor, a temporary construction named Chicago Pile-1. But even before that history-making event, scientists were making plans for a full-scale operation to produce plutonium in Hanford, Washington.

One major question was whether a pilot plant would be necessary to demonstrate the process. Some believed the pilot project would take too much time, others that it was the more prudent approach.

The prudent side won, and the Graphite Reactor and plutonium prossessing facility were built at the Manhattan Project's X-10 Site in East Tennessee, which would become ORNL a few years after the war.

The Oak Ridge reactor was created at breakneck speed, having been theorized, engineered and built in just nine months. As various facilities came online, entire organizational sections from the Metallurgical Laboratory were transferred to Oak Ridge. Many of those scientists ended up setting down roots.

The war did not end Oak Ridge's relationship with the University of Chicago. While X-10 was created as a pilot plant, the Graphite Reactor was just too well built to be abandoned. When, several years later, control rods of the Chicago Pile-3 reactor showed signs of corrosion, X-10 opened its gates to Argonne researchers needing to perform experiments and gave them priority over other external users.

*Before dawn on November 4, 1943, scientist Louis Slotin rousted Nobel laureates Enrico Fermi and Arthur Compton from the Guest House in Oak Ridge to witness the initial self-sustaining nuclear chain reaction at the Graphite Reactor. This painting by Bert Longmire portrays a worker approaching a flat-top house to notify someone that criticality was imminent. The moment was reached at 5 a.m.*

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through irradiation. Operators loaded uranium "slugs"—4-inch cylindrical pellets encased in aluminum—into some of the 1,248 channels in the 24-foot cube of graphite. The configuration of uranium and graphite helped the reactor operators predict when the reactor would reach "criticality." The reaction was further controlled through the use of seven control rods of heavy elements, including boron and cadmium, that absorbed neutrons.

The reactor was also designed to support research. Empty chambers in the graphite block enabled scientists to test materials exposed to radiation, and a 6-foot thermal column of graphite at the top of the reactor provided a strong source of thermal neutrons. Research at the reactor initially focused on testing how radiation affected materials to be used at Hanford and measuring fission products and their half-lives, but its usefulness as a research tool led to many experiments in materials, biology, chemistry and more.

Ultimately, the Graphite Reactor would outlive its wartime purpose, operating for exactly 20 years and enabling many scientific firsts after producing the first gram-sized quantities of plutonium for the war effort. During its lifetime, it was also the world's foremost source of radioisotopes for medical, industrial, and research applications.

## Processing plutonium

As operators inserted new uranium slugs into reactor channels, irradiated slugs were pushed into a trench of water, known as the canal, behind the graphite block. Immersed in water to block radiation, the slugs, now containing traces of plutonium-239, could be transported in buckets via the canal to a chemical processing facility next door, which consisted of six hot cells for plutonium separation.

Extracting plutonium-239 from the uranium mix was a problem not of nuclear science but of chemistry. The first scientist to produce plutonium, American physicist Glenn Seaborg, demonstrated possible methods for separating plutonium-239 at large scales at Chicago's Metallurgical Lab. Seaborg tested a lanthanum fluoride carrier—a rare earth compound that helped scientists tease out trace amounts of plutonium during chemical

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# Making the most of neutrons

by Bill Cabage
cabagewh@ornl.gov

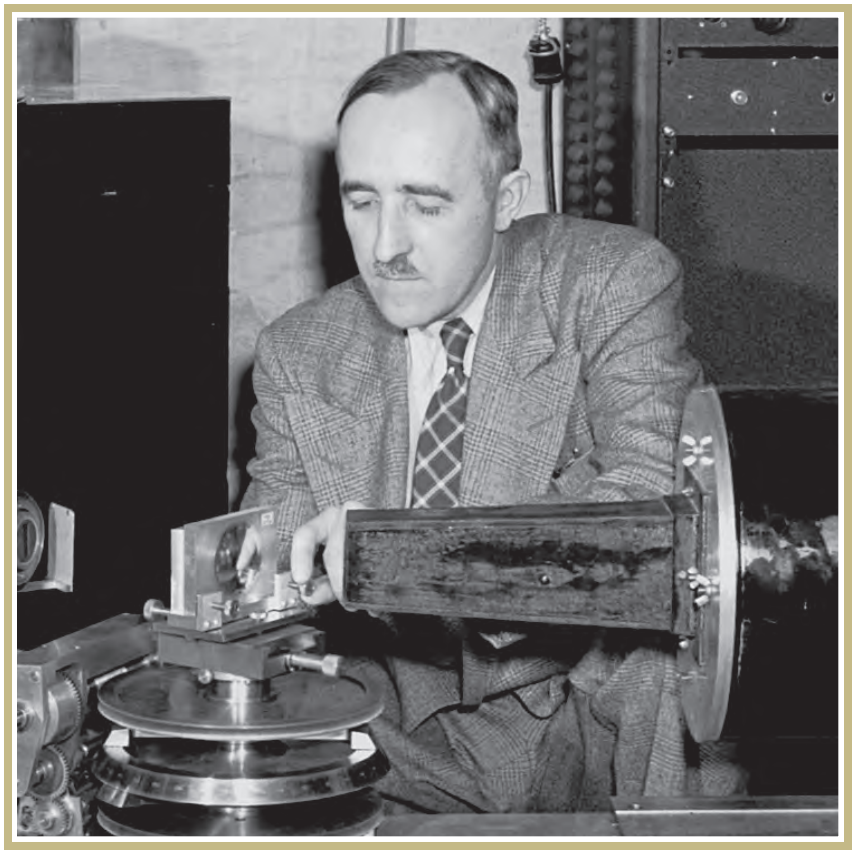
Ernest O. Wollan came to Oak Ridge from the University of Chicago as part of the top-secret Manhattan Project, but he had other ideas on what he could do with the world's first operating nuclear reactor.

"I would like to attempt to measure the diffraction of neutrons by single crystals," he wrote in a memo on May 25, 1944.

Wollan suspected neutron scattering might be useful for research, similar to X-ray diffraction. He was joined in 1946 by a young scientist named Clifford Shull, and the two used ORNL's Graphite Reactor to lay the groundwork for the fundamental principles of elastic neutron scattering.

The ORNL team was the first to measure neutron Laue patterns—regularly spaced spots—in single crystals. They opened a new understanding of magnetic materials and the magnetic properties of neutrons, and they developed some of the first powder diffraction analytical techniques to study them.

Neutron scattering research at ORNL continued, particularly at the Oak Ridge Research Reactor and later at the High Flux Isotope Reactor. But by the late 1980s the United States trailed in neutron science. Because of neutron science's role in the development of advanced materials, this was of economic concern.



*Ernest O. Wollan.* Image credit: ORNL

Two events turned the tide: Shull shared the Nobel Prize for his early ORNL work in neutron scattering in 1994, and shortly thereafter, DOE announced plans to build a new neutron source at ORNL, a solution less costly than a new nuclear reactor.

At a design power of 1.4 megawatts, the Spallation Neutron Source, combined with the refurbished HFIR, reclaimed preeminence in neutron scattering research for ORNL, where neutron analysis was initially conceived in a now-yellowed wartime memo.

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separation. Bismuth phosphate, a compound with less corrosive properties, was ultimately chosen for pilot production at X-10 based on the work of Seaborg's colleague Stanley G. Thompson.

While Metallurgical Lab scientists worked relatively freely with trace levels of these materials in an open environment, X-10 scientists worked with greater quantities of plutonium and thus had to contend with manipulating lab equipment through several feet of radiation-shielding concrete. Yet X-10 chemists managed to advance techniques for handling nuclear materials and improve the chemical separation process so that, by 1944, they could recover about 90 percent of plutonium-239 found in the uranium solution.

Hundreds of chemists and engineers trained at X-10 soon would take their expertise to Hanford, as plutonium production began at even larger scales in 1944. Developing the equipment and methods for plutonium separation and writing the first scientific textbooks and training manuals for nuclear work were major Oak Ridge contributions to the war effort.

> *"You are now a resident of Oak Ridge, situated within a restricted military area. ... What you do here, What you see here, What you hear here, let it stay here."*
>
> — Orientation to Oak Ridge, from ***City Behind a Fence***

## The secret city

Although the East Tennessee valleys chosen for the Manhattan Project production plants were appealing for their relative isolation, they were not vacant. After a 1798 treaty between the U.S. government and regional Cherokee tribes, settlers acquiring land grants had established the rural communities of Elza, Robertsville, Scarboro and Wheat. Through the 19th century, the communities grew to become home to hundreds of people who made their living through farming, milling and mining. The land was dotted with churches, general stores, schools and a liberal arts college.

Today, as employees drive into ORNL from the east, they pass the remaining structures of the Scarboro community, including Scarborough Elementary School (using the former spelling of Scarboro) that's now part of the Oak Ridge Institute for Science and Education, and New Bethel Baptist Church and the church cemetery en route to ORNL's main campus.

When the Army filed a declaration in federal court in 1942 to reclaim the land and compensate residents, the families of the Clinch River Valley were given up to 90 days (but often less) to pack up and abandon their homes. As they arrived in nearby towns like Clinton with their possessions strapped on trucks, their exodus signaled the first wave of change.

## At home in Oak Ridge

Although the Army led the Manhattan Project, Groves and other leaders recognized that the community must be a compromise between a controlled military installation and the "normal" civilian communities to which scientists and skilled laborers were accustomed.

The Army hired the national architectural firm Skidmore, Owings & Merrill to design a townsite that would provide essentials and a few modest luxuries, including two- and three-bedroom houses for families (complete with fireplaces and porches), a town center with a grocer and other commercial retailers, schools and recreational facilities.

Other residences included dormitories for unmarried or temporary workers, many of whom ended up sharing close quarters as more beds were needed. There were also trailer camps for construction workers and barracks for military personnel, including some onsite at the plants rather than in town.

Services such as a bus system, sewage and garbage disposal, utilities, schools and a hospital were managed by the Roane-Anderson Company. At the height of the project, the company oversaw the ninth-largest bus system in the United States, 17 cafeterias and a hospital with more than 300 beds.

Although the town design surpassed some expectations—the Army was particularly pleased with the prefab housing built with cemesto (a mix of cement and asbestos) that met cost and design requirements—Oak Ridge would be plagued with logistical issues during the war, particularly the never-ending demand for more housing.

In early 1943, the Army estimated Oak Ridge would grow to about 13,000 people, for whom a small number of stores would suffice at "Townsite," later named Jackson Square. By the fall of 1943, however, the estimate increased to 42,000 people and would rise again in early 1945 to 66,000.

Ultimately, 75,000 people would live in Oak Ridge at the height of operations in summer 1945. More residences were built throughout the war, and five more neighborhood centers appeared. The city went from nine commercial businesses in 1943 to 165 businesses in 1945.

The population boom greatly affected residents who were moved to makeshift housing, including all African-American residents. Initially, a neighborhood of cemesto houses was planned for African-American workers, but as housing demands increased, these homes were rented to white workers, and "hutments"—one-room plywood huts with four to five beds and a stove—were rented to African-American residents, as well as to some white residents working temporary or labor jobs.

Because wages at the plants in Oak Ridge could be about twice the pay in the surrounding area, many African-American workers came to live and work in the Secret City. Their experience was not the same as most employees, however. Oak Ridge

*See TOP-SECRET LABORATORY, page 16*

# Radiation and you

by Tim Gawne
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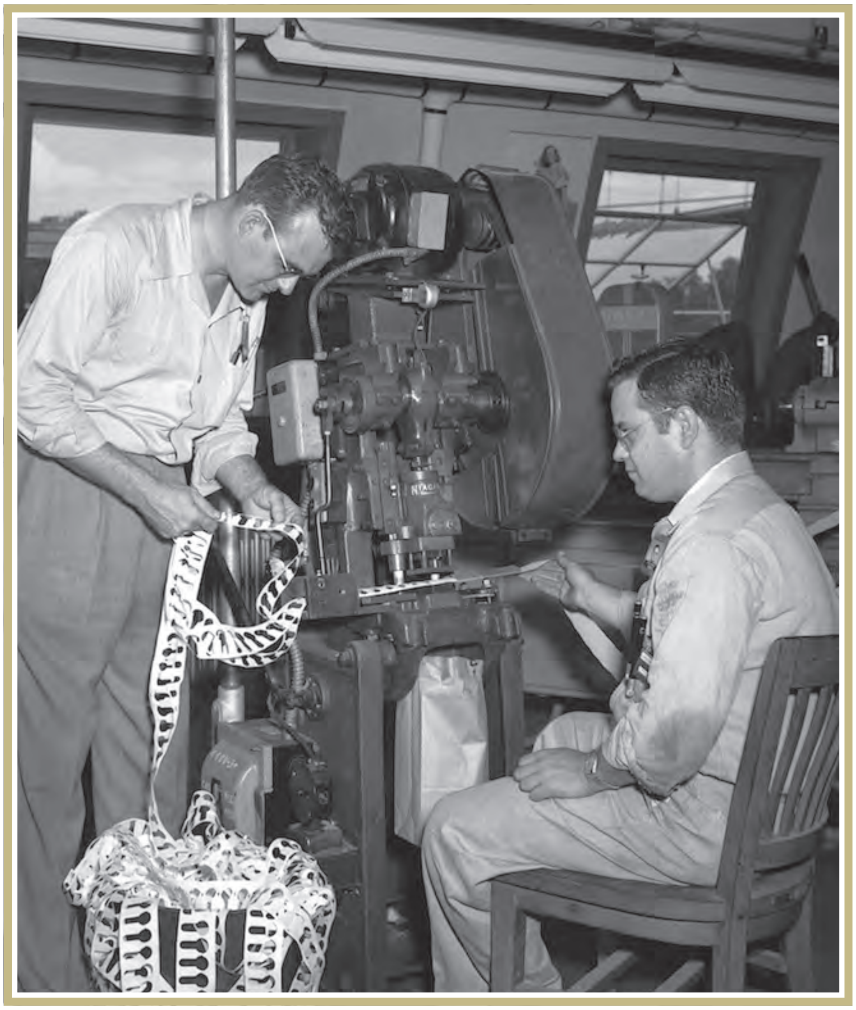
People were aware of ionizing radiation's potential dangers well before World War II and the Manhattan Project. The death of radiation pioneer Marie Curie had been linked to radiation exposure, as had the diseases and deaths of workers who painted watch faces with radium paint.

Dose limits had, therefore, been in place for nearly a decade before the creation of Oak Ridge and the Graphite Reactor. Even so, the challenges presented by the Manhattan Project were fundamentally different. Never before had scientists contended with the energy levels that would be present.

To ensure the safety of workers, an entire section was established at Chicago's Metallurgical Laboratory to create detectors and other devices that could monitor worker exposure. It was a big job. Not only did such devices not exist—at least not in a form that workers could wear—but the health studies that informed later dose limits had not been conducted.

Pioneering Oak Ridge neutron scientist Ernest Wollan and his colleagues invented the film badge worn by radiological workers. The badge allowed a technician to determine the exposure of someone who had been in a known place for a known time. One of the first real-time personal radiation monitors was invented by ORNL's P. R. Bell. That device had a meter and would emit an audible alarm if radiation exceeded a set threshold.



*Paul E. Galyon, left, holds filter paper with stamped smear tabs used to collect samples of radioactivity.* Image credit: ORNL

Radiation safety became a major responsibility for ORNL. Biologists conducted thousands of experiments at the Graphite Reactor using mice. The results led to a reduction in human exposure limits.

After the war, ORNL's Liane Russell discovered that fetuses are particularly at risk from radiation. Her work led to special radiation exposure limits for pregnant women.

*TOP-SECRET LABORATORY, page 14*

was located in the segregated South of the 1940s, and the town was also segregated, with separate public facilities for African-Americans, such as cafeterias and recreation halls. African-American spouses lived in separate housing and were not permitted to bring their children to Oak Ridge until 1945. However, gradual change came after the war and, in 1955, the city became the first in the South with an integrated high school.

## 'Let it stay here'

*"You are now a resident of Oak Ridge, situated within a restricted military area. ... What you do here, What you see here, What you hear here, let it stay here." – Orientation to Oak Ridge, from* City Behind a Fence

As soon as plant construction began in February 1943, the Army began staffing its "Safety Forces." By 1945, Safety Forces grew to include about 750 military police, more than 400 civilian law enforcement officers, and about 4,900 civilian guards. Oak Ridge residents outnumbered these forces by only about 12 to 1.

One of the most common interactions among residents, plant employees and security officers happened during identification and vehicle checks at gated entrances to the town and plant sites. Badge and identification checks were also common within the townsite; even children 12 and older had badges.

Civilian law enforcement also patrolled the commercial centers and residential neighborhoods. Even if no Safety Force personnel were in sight, bulletins and billboards cautioned residents to remain vigilant in their work—and silent.

Resident directories, copies of the town newspaper The Oak Ridge Journal and photographs were not allowed outside the barbed wire fences. Some residents were even recruited to mail in reports on suspicious activities they witnessed at work or around town.

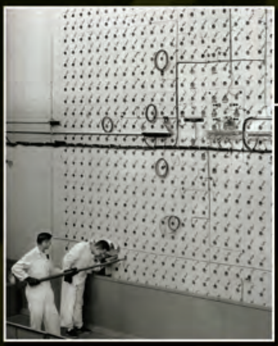
But despite the secrecy—and in some ways, because of it—Oak Ridge would become a permanent home for some residents. The town brought together people from across the country who shared the same sense of purpose and lived through truly unique circumstances.

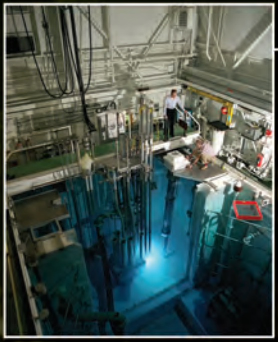
*Crowds gather at Jackson Square in Oak Ridge to celebrate the end of the war.* DOE photo by Ed Westcott


WAR ENDS
EXTRA The Knoxville Journal EXTRA
TRUMAN REPORTS TO NATIO

# ORNL's 13 nuclear reactors

ORNL got its start 75 years ago as a nuclear facility charged with supporting the Manhattan Project war effort. In the meantime, the lab has built and operated more than a dozen nuclear reactors for research and isotope production.





## Oak Ridge Graphite Reactor (1943-63)

The world's first permanent nuclear reactor (and the second of any type, after the Chicago Pile), the Graphite Reactor was created to study how to produce plutonium for the Manhattan Project. During its operating lifetime, it was also used in materials testing, materials production and early neutron scattering experiments.

## Low-Intensity Test Reactor (1950-68)

Originally a mockup for a reactor built in Idaho, the LITR became famous when the now-famous blue glow of Cherenkov radiation was photographed in the pool above the reactor. A photo of that glowing reactor pool made the cover of *Scientific American* in October 1951.

## Bulk Shielding Reactor (1950-87)

This was a "swimming pool reactor" built to develop shielding for nuclear submarines. The reactor proved useful for an array of experiments including studies of the effects of radiation on materials.

## Homogeneous Reactor Experiment (1952-54)

Uranium fuel for this reactor was dissolved in water, which served as both coolant and moderator (slowing fast neutrons to increase their ability to sustain a chain reaction). The reactor generated 150 kilowatts of electricity, thereby earning its operators the honorary title "Oak Ridge Power Company."

## Aircraft Reactor Experiment (1954-55)

The government's Aircraft Nuclear Propulsion program explored the feasibility of nuclear-powered aircraft. The Aircraft Reactor Experiment reactor was fueled with uranium, cooled with molten sodium and moderated with beryllium oxide. While nuclear planes never got off the ground, the ARE expanded our knowledge of molten salts and drove advances in materials and shield design.

## Tower Shielding Reactor I & II (1954-92)

The Aircraft Nuclear Propulsion program needed air-scattering data that the Bulk Shielding Reactor could not provide, so a Tower Shielding Facility was built to suspend a reactor between two 315-foot-tall towers. The first Tower Shielding Reactor operated from 1954-58, with the reactor placed in a water-filled tank. The second reactor was placed in an aluminum pressure vessel and operated from 1958-92.

## Homogeneous Reactor Test (1957-61)

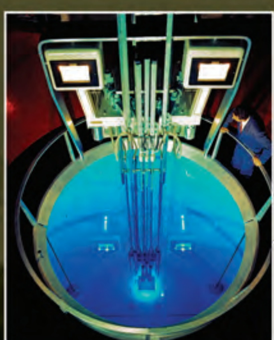
A homogeneous reactor that was more powerful than the Homogeneous Reactor Experiment, this reactor was installed in the same building as the HRE.

## Health Physics Research Reactor (1963-87)

This research reactor was designed to produce short, intense pulses of power and radiation. It was used to research the effects of radiation and develop dosimeters.

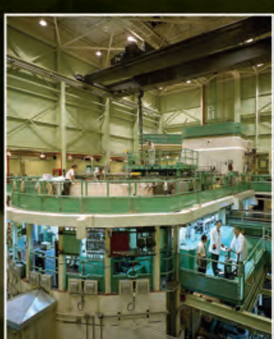
## Molten Salt Reactor Experiment (1965-69)

Fuel for MSRE was contained in molten salts that flowed through the reactor and also served as coolant. After three years of operation, MSRE also became the first reactor ever to run on the isotope uranium-233. The Atomic Energy Commission shut down its molten-salt program in 1973 in order to focus on other designs, but molten salt reactors are receiving a lot of interest as a possible approach to future advanced reactors.



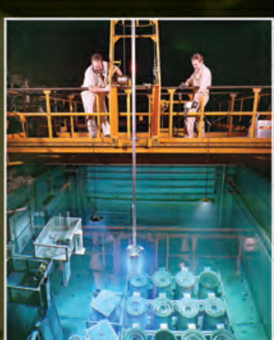
## Geneva Conference Reactor (1955)

Built in Geneva, Switzerland, for the United Nations-sponsored International Conference on the Peaceful Uses of Atomic Energy, the reactor was essentially the same design as the Bulk Shielding Reactor, except that the fuel enrichment was substantially lower.



## Oak Ridge Research Reactor (1958-87)

Similar to the Low-Intensity Test Reactor, this reactor allowed researchers to perform neutron scattering research, fundamental investigations of the behavior of metals and ceramics under radiation, and the testing of materials for reactor fuel elements and for fusion devices.



## High Flux Isotope Reactor (1965-present)

This reactor was first envisioned as a tool for producing californium-252 and other valuable isotopes, but it has also proven to be an invaluable tool for neutron scattering research. HFIR has been operating successfully for more than 50 years and is the only reactor operating at ORNL today.

Image credit: Brett Hopwood, ORNL

# A nuclear lab in peacetime

by Katie Jones
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Although World War II ended in 1945, the study of nuclear energy had just begun. A federal agency was created in 1946 to manage the development of nuclear energy for both military and civilian purposes, and Gen. Leslie Groves handed over the keys for X-10 and its Graphite Reactor to the new Atomic Energy Commission.

The scientists who had worked at X-10—called Clinton Laboratories and briefly Clinton National Laboratory before becoming Oak Ridge National Laboratory in 1948—had big ideas for a nuclear laboratory free from the Manhattan Project's air of secrecy. The Graphite Reactor's potential for creating new isotopes and expanding scientific knowledge was too precious a resource to waste.

To help define the lab's new mission, the AEC needed someone to lead scientific research. On a year's leave from Princeton University in 1946 and 1947, Eugene Wigner served as ORNL's research director. During his short time in Oak Ridge, Wigner charted the lab's peacetime trajectory by estab-

*See A NUCLEAR LAB IN PEACETIME, page 22*

*Members of the management team of the then-Clinton Laboratories review the site in 1946. Shown are Frederick Seitz, Director James Lum, Research Director Eugene Wigner, and Alexander Hollaender.* Image credit: Monsanto

# Weinberg saves ORNL

by Tim Gawne
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It's hard to overstate all that ORNL owes to Alvin Weinberg, its longest-serving director.

Weinberg took over the lab's Physics Division in 1947 at a moment of great uncertainty. The Atomic Energy Commission was consolidating reactor research at Chicago's Argonne National Laboratory, threatening ORNL's reason for existing.

Instead of bemoaning the decision, Weinberg went into action. It is unclear whether he had the blessing of his management, but he traveled to Argonne to strike a gentleman's agreement with then-Director Walter Zinn. Weinberg said Oak Ridge would concentrate on exotic research reactors instead of power reactor projects. Zinn let his managers in Washington know he was OK with the arrangement.

The deal was a boon for Oak Ridge, which would build 13 special-purpose research reactors in all, plus critical and subcritical assemblies.

Later that same year, Weinberg became ORNL's research director. At the time, he told Eugene Wigner that it felt like taking care of a child he had created and brought into the world. Weinberg was named lab director in 1955, and for the next 18 years he concerned himself with the development of ORNL, the quality of its people and programs, and the evolution of its mission in response to changing national needs and concerns.

*Alvin Weinberg.* Image credit: ORNL

His genius was often turning iffy situations to gold. Take the Aircraft Reactor Experiment; under Weinberg's leadership, the lab took a very odd idea and flipped it into years of groundbreaking research and development.

His 1994 autobiography is titled, "The First Nuclear Era: The Life and Times of a Technological Fixer," an apt self-description given his record at ORNL.

*In August 1946, the lab's research director, Eugene Wigner, second from left, handed the first shipment of a reactor-produced radioisotope, a container of carbon-14, to the director of the Barnard Free Skin and Cancer Hospital of St. Louis, Missouri.* DOE photo by Ed Westcott

*A NUCLEAR LAB IN PEACETIME, page 20*

lishing a nuclear training school and overseeing the design of a high-flux reactor that could produce powerful neutron fluxes for research and enable scientists to test materials for power reactors. Wigner also recruited Alexander Hollaender to establish the ORNL Biology Division and established a solid-state research group and a division to investigate the effects of radiation on metals.

When Wigner returned to academic life, reactor physicist Alvin Weinberg took his place as research director and later became laboratory director. Weinberg had worked with Wigner on the development of the Chicago Pile and Graphite Reactor, and, like Wigner, he was eager to pursue peaceful uses of nuclear energy. Weinberg had testified before Congress on the topic in 1945 and moved to Oak Ridge to work with Wigner on reactor development. During his nearly 30 years at the laboratory, Weinberg was an important visionary in the new nuclear era (See "Weinberg saves ORNL," page 21).

## Nuclear medicine

Isotope production for nuclear medicine was one of the primary applications of the Graphite Reactor after the war. In 1946, ORNL sent the first official shipment of a medical radioisotope, carbon-14, to a hospital—Barnard Free Skin and Cancer Hospital in St. Louis.

The invention of the nuclear reactor enabled the development of an expansive catalog of isotopes with unique properties. By the end of the decade, the lab was producing and distributing more than 50 isotopes created at the Graphite Reactor, generating up to $1 million of revenue for the U.S. government each year.

The advent of reactor-produced isotopes—such as iodine-131 for radiation therapy of hyperthyroidism and phosphorus-32 for imaging tumors and treating cancer—showed that nuclear medicine could radically improve medical diagnosis and treatment. Today, the lab continues to support DOE's isotope mission through its current nuclear reactor, the High Flux Isotope Reactor. ORNL produces californium-252, used by industry and in cancer treatment, and actinium-227, which is used in treatments of metastatic prostate cancer. With the recent approval of lutetium-177 as a treatment for certain types of pancre-

*See A NUCLEAR LAB IN PEACETIME, page 24*

# Oak Ridge spreads the nuclear knowledge

by Jim Pearce
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At the end of World War II, most people who knew anything about generating nuclear power were located at Manhattan Project sites like Oak Ridge.

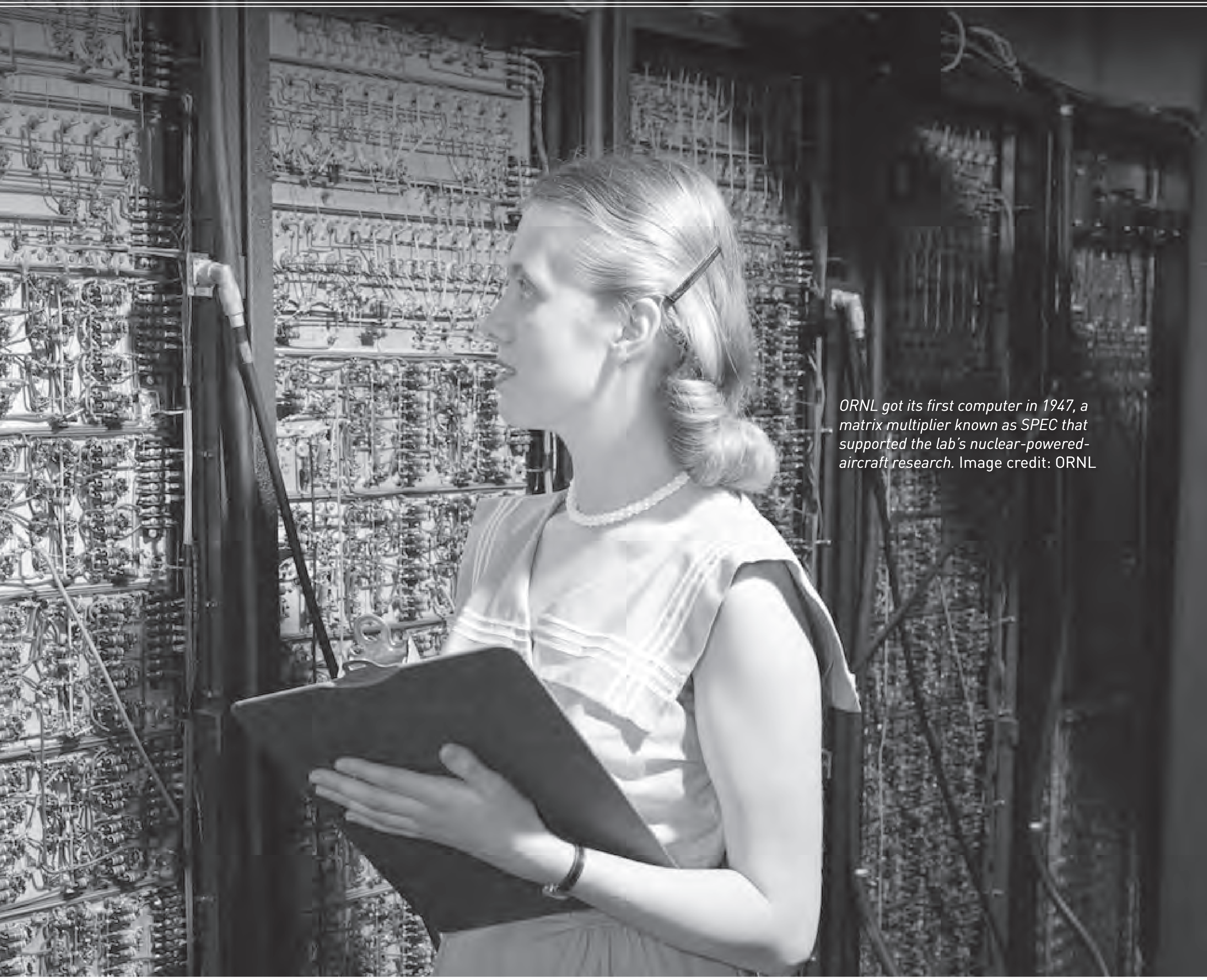
That's where a young naval officer named Hyman Rickover found himself attending nuclear engineering classes with a handful of other students at the newly created Clinton Laboratories' Training School. Rickover, who would become known as the "father of the nuclear Navy," was sent to Oak Ridge to determine whether a nuclear reactor would be capable of powering a naval destroyer.

His time in Oak Ridge convinced him that nuclear power was a viable option for naval propulsion. What was missing were the hundreds of nuclear-savvy engineers needed to turn this dream into reality.

In 1950, with that need in mind, Rickover and ORNL research director (and later lab director) Alvin Weinberg founded the Oak Ridge School of Reactor Technology, which offered 12-month intensive programs in reactor hazards analysis and reactor operations. The school produced nearly 1,000 graduates.

*Future ORNL Laboratory Director Alvin Weinberg teaches at the Clinton Laboratories' Training School in 1954.* Image credit: ORNL

Rickover was put in charge of both the Navy's program to develop a nuclear-powered submarine and the government's reactor development activities. Under his guidance, and with graduates from the Oak Ridge school playing key roles, the world's first nuclear submarine, Nautilus, was launched in 1954, and the Shippingport Atomic Power Station, the world's first full-scale nuclear electric power plant, went online in 1959.



*ORNL got its first computer in 1947, a matrix multiplier known as SPEC that supported the lab's nuclear-powered-aircraft research.* Image credit: ORNL

*A NUCLEAR LAB IN PEACETIME, page 22*

atic cancers, ORNL is investigating how to produce this radioisotope with HFIR.

Isotopes also enabled a range of new scientific techniques. Radioactive tracers, made up of short-lived radioisotopes linked to chemical compounds, make it possible to observe specific physical, chemical and biological processes at the molecular level. The ability to track the progress of the compound through a living organism by measuring the decay of the radioisotope has enabled advances in medicine, health physics and organic chemistry.

## Health physics

The hazards of radioactivity were not lost on the physicists who studied nuclear energy during the Manhattan Project. Marie Curie had died in 1934 from leukemia resulting from her work with radium, and the effects of X-rays and natural radioactivity had been under scrutiny for decades.

A "health physics" group to study radiation exposure and detection was established at the Metallurgical Laboratory in Chicago in 1942. Led by Ernest Wollan, it would move with Wollan to Oak Ridge before the Manhattan Project was over. This group would also lead the development of "film badges" to monitor worker exposure.

It was clear in 1946 that if nuclear energy were to be the future of power production and scientific research, scientists needed a deeper understanding of the effects of radiation on living organisms. A formal Health Physics Division was established that year, and division staff began monitoring radiation in

*See A NUCLEAR LAB IN PEACETIME, page 27*

# A successful project never gets off the ground

by Bill Cabage
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Travel eastbound on Interstate 40 in Tennessee and you can glimpse a reminder of a project that, while it literally never got off the ground, had monumental influence on the direction of R&D at ORNL.

The two towers of the Tower Shielding Facility, briefly visible from the interstate, were built in 1954 to conduct shielding experiments for the Aircraft Nuclear Propulsion project—an effort to determine the feasibility of a nuclear-powered airplane.

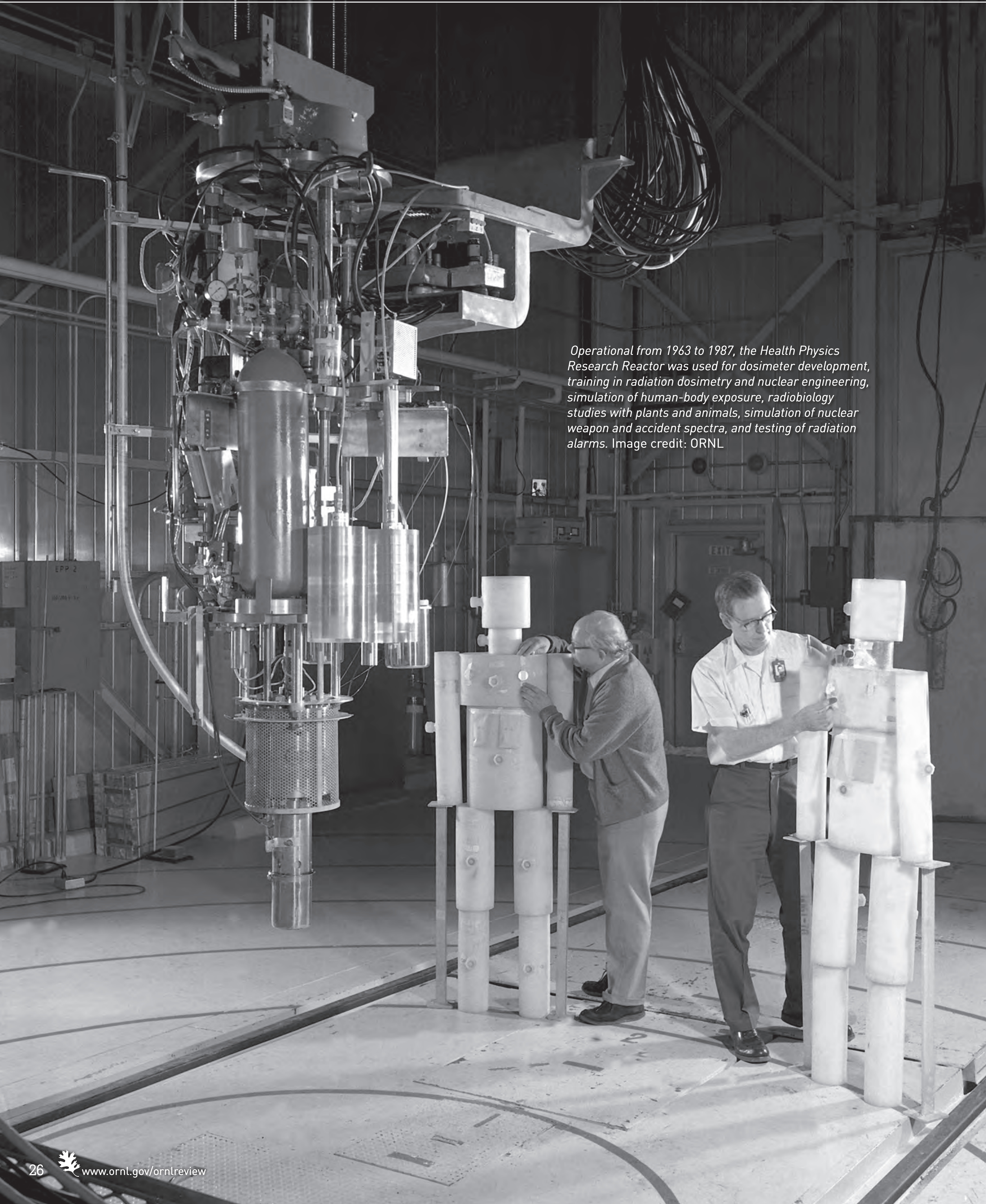
The facility hoisted a reactor in the air to eliminate radiation backscattering from the ground, which interfered with instruments used to gather data on shielding. It was essential that researchers determine exactly how much material would be required to shield passengers from radioactivity.

Many dismissed the idea of a nuclear-powered aircraft—including longtime ORNL Director Alvin Weinberg, who once described the concept as a "contradiction in terms"—but such an aircraft could remain aloft almost continuously, it was theorized.

With $1 billion put up by the U.S. Air Force to explore the idea, ORNL applied its considerable nuclear engineering expertise. The ANP program provided the foundation for lab R&D strengths in advanced lightweight materials, biology and health physics. ORNL's Molten Salt Reactor Experiment grew from the ANP, too.

*Tower Shielding Facility.* Image credit: Curtis Boles, ORNL

The advent of ballistic missiles rendered the idea of nuclear aircraft obsolete. But the knowledge gained in biology and shielding is timeless, and lightweight materials gained relevance when energy efficiency became prominent in subsequent decades. Even the molten salt technology has received renewed interest in recent years. For something that never flew, the ANP was incredibly fruitful.



*Operational from 1963 to 1987, the Health Physics Research Reactor was used for dosimeter development, training in radiation dosimetry and nuclear engineering, simulation of human-body exposure, radiobiology studies with plants and animals, simulation of nuclear weapon and accident spectra, and testing of radiation alarms.* Image credit: ORNL

*A NUCLEAR LAB IN PEACETIME, page 24*

work areas and the Oak Ridge environment and developing new radiation detection devices, such as dosimeters.

The value of work done at ORNL toward nuclear safety and radiation monitoring is immense. Early textbooks on radiation safety, reference manuals to calculate safe and unsafe exposure levels, and computer models for predicting the transport of radiation through the environment were all developed at ORNL.

A nuclear reactor would allow submarines to stay under water for almost unlimited periods, greatly expanding the Navy's reach. After his time at Clinton Laboratories, and particularly after discussions with Weinberg, Rickover recommended in 1950 that the Navy build a pressurized water reactor for submarine propulsion. The design was compact, and water was an abundant, familiar resource.

The first nuclear-powered submarine, the USS Nautilus, went to sea in 1955 and subsequently broke many speed and distance records. By cruising under the Arctic ice pack, it was also the first vessel to cross the North Pole. Following the success of the nuclear submarine, companies looking to build nuclear power reactors for generating commercial electricity also focused on pressurized water reactors, eventually leading to the dominant design for the nuclear power plants that provide 20 percent of U.S. electricity today.

*After the war, naval officers visited Clinton Laboratories and enrolled in the Clinton Training School. Among these officers was Hyman Rickover, who would become known as the 'father of the nuclear navy.'*

To better understand the effects of radiation on mammals, the lab established the Mammalian Genetics Program in 1947. This program would become the foundation for a world-leading genetics laboratory, housed in a facility known as the "Mouse House" for the thousands of mice deliberately exposed to low-dose radiation and later to other carcinogenic and teratogenic substances. In 1952, the mouse studies resulted in guidelines to avoid the increased risks of diagnostic X-rays during early pregnancy that were adopted worldwide (see "The house the Russells built," page 31).

## Power reactors—for land, air, and sea

In 1948, ORNL researchers produced electricity from nuclear power for the first time using a toy steam generator connected to a water supply at the Graphite Reactor. Four years later, ORNL researchers sent the first nuclear-generated electricity to the grid from the Homogeneous Reactor Experiment. Although it was the role of industry to provide nuclear power for millions, ORNL and other national labs would work out the foundations of nuclear energy and power generation through many reactor experiments, some of which were one-of-a-kind.

### *The nuclear navy*

The Navy was interested in nuclear power from the beginning and started funding nuclear research during the dizzying breakthrough year of 1939, following the discovery of fission. Researchers at the Naval Research Laboratory even contributed to the Manhattan Project by developing a second diffusion process for enriching uranium: thermal gaseous diffusion, for which the S-50 plant—located at the Oak Ridge K-25 site—was built.

After the war, naval officers visited Clinton Laboratories and enrolled in the Clinton Training School (see "Oak Ridge spreads the nuclear knowledge," page 23). Among these officers was Hyman Rickover, who would become known as the "father of the nuclear navy." By many accounts, including Weinberg's memoirs, Rickover could be a rude and difficult character, but his passion for building a nuclear reactor for marine propulsion helped ignite the widespread adoption of nuclear power.

### *The nuclear aircraft project*

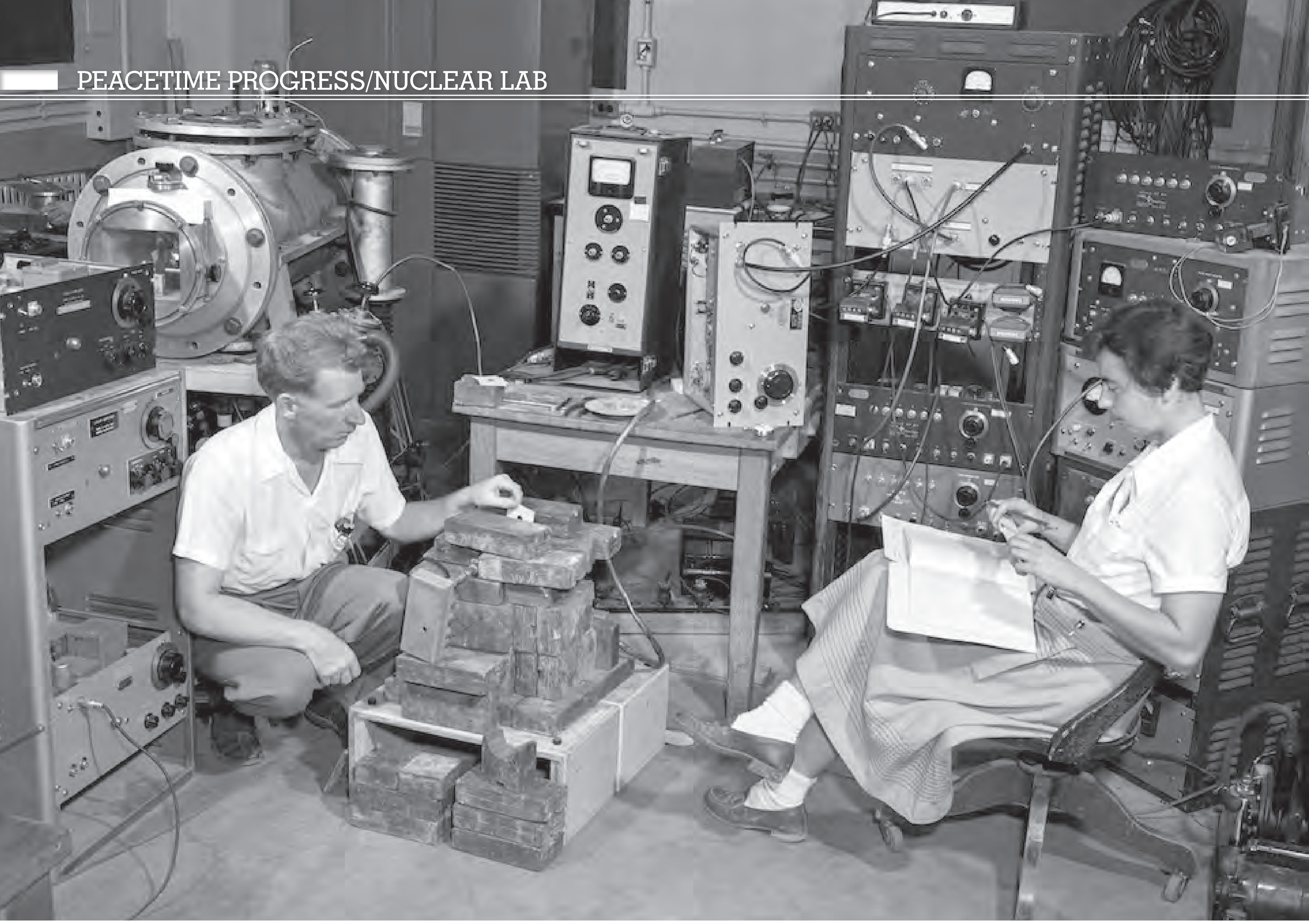
Likewise, the Army dreamed of nuclear-powered planes that would not need to land for refueling. In 1946, the Army Air Forces established the Aircraft Nuclear Propulsion program to develop a compact reactor that would power a jet engine. An aircraft reactor was a significant challenge. The reactor needed to be small enough to fit on a plane, encased in shielding to protect passengers, and able to withstand the high temperatures necessary to generate enough power for flight.

After years of experimenting and several innovations, ORNL physicists and engineers built a prototype reactor in 1955 called the "fireball," a spherical, 60-megawatt reactor that glowed red-hot at 1,500 degrees Celsius. The "fireball" reactor and a previous Aircraft Reactor Experiment prototype successfully demonstrated key components of the ORNL design: a tightly packed honeycomb of beryllium-oxide blocks for a moderator and molten salt coolants that flowed in thin channels of the corrosion-resistant, nickel-based Hastelloy-N. The alloy was developed at the lab in partnership with industry for use at high temperatures and later was commercialized for a range of industrial applications.

Although the two prototypes were a technical success, the AEC began to question the entire enterprise of nuclear-powered flight. Designing a lightweight reactor to operate at such high temperatures while meeting all safety requirements was ultimately viewed as unrealistic.

Over the course of nearly a decade, however, Aircraft Nuclear Propulsion program funding supplied ORNL with several critical research tools, including a powerful particle accelerator and

*See A NUCLEAR LAB IN PEACETIME, page 28*



*Arthur Snell and Frances Pleasanton measured the half-life of neutrons in 1950 to provide the first experimental proof that a neutron decays into a proton, an electron and an electron antineutrino.* Image credit: ORNL

*A NUCLEAR LAB IN PEACETIME, page 27*

computer, that the lab would leverage to attract new research during the tough times after the aircraft program shut down.

During the height of the Aircraft Nuclear Propulsion project in the 1950s, researchers decided they needed to test possible aircraft reactors and shielding in the air to minimize the scattering of radiation from the reactor by the ground or structures. For this purpose, ORNL built the Tower Shielding Facility, which included four 300-foot towers connected by cables that could hold a reactor and a variety of shield samples up to 200 feet above ground.

From 1954 to 1958, researchers tested the Tower Shielding Reactor-1, which was a smaller version of the Bulk Shielding Reactor—a 500-kilowatt water-cooled reactor encapsulated in a 12-foot-diameter tank. A spherical reactor, the TSR-II, was built in 1958 so researchers could test the spherical design they thought would work best for an aircraft reactor. Eventually the TSR-II operated at 1 megawatt of power.

Despite the end of the nuclear-powered aircraft project, several uses were found for the unique facility—including studies of shielding for space reactors, the effects of radiation on a jet engine, the stability of casks used to transport radioactive fuels (which were dropped from the towers in one dramatic study), and other shielding and radiation projects—until the facility was permanently closed in 1992. The towers are still in place and are visible from the visitor overlook at TVA's Melton Hill Dam.

### *The test reactors*

**The Low-Intensity Test Reactor**. ORNL's Low-Intensity Test Reactor was never meant to be an operational reactor. Instead, it was built as a shell to test the mechanical design of the Materials Test Reactor—a 40-megawatt water-cooled reactor principally designed at ORNL with significant influence from Wigner. Soon after Wigner departed Oak Ridge in 1947 but before the Materials Test Reactor was built, the AEC announced plans to transfer all power reactor projects, including the Materials Test Reactor, to Argonne National Laboratory—the Chicago-based lab that evolved from the Metallurgical Laboratory.

The reactor design called for ordinary (or "light") water to serve as both a moderator and coolant, with uranium fuel packed between aluminum plates surrounded by beryllium to reflect neutrons. In 1950, Weinberg convinced the AEC that

*See A NUCLEAR LAB IN PEACETIME, page 30*

# A swimming pool reactor in Geneva

by Tim Gawne
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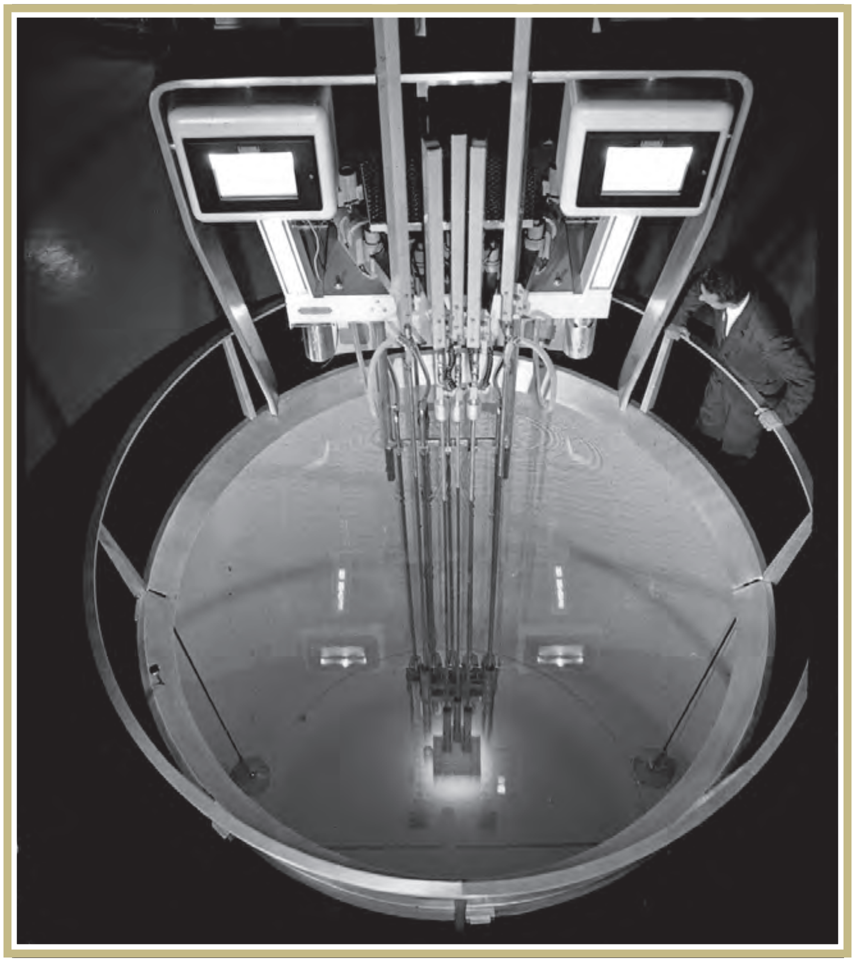
The Cold War was fought on many fronts.

The United States and Soviet Union avoided direct military conflict, as that would include the very real risk of nuclear war. Instead, the two sides competed in less catastrophic realms.

In an environment that saw the development of the hydrogen bomb, the Korean War and the atmospheric testing of nuclear weapons, the Eisenhower administration sought, through its Atoms for Peace doctrine, to pivot away from escalating tensions and toward the use of atomic energy for peaceful purposes.

To further reduce tensions, the Geneva Conference of 1955 gave world leaders an opportunity to discuss global security and to showcase their nations' nuclear science and technology. At the time it was the largest meeting ever organized by the United Nations.

The Soviets showed up to the meeting with a scale model of a reactor, but the Americans had a different idea. Months earlier, U.S. scientists and engineers began designing a small reactor, between 10 and 100 kilowatts. The simple swimming pool reactor, dubbed "Project Aquarium," was built at ORNL. It was small enough to fit in a military cargo plane but big enough to make an impression.



*ORNL built the Geneva Reactor for the First International Conference on the Peaceful Uses of Atomic Energy in 1955.* Image credit: ORNL

So how do you bring a reactor home? Well, you don't. It was sold to the Swiss government, which used it for public demonstrations and research. The reactor was later moved from the United States pavilion and renamed "SAPHIR."

The name was inspired by the blue glow of the Cherenkov radiation visible during operation. The little reactor operated until 1994.

*President Truman selected ORNL nurse Doris Scott to serve on the Industrial Health Section of the Presidential Commission for Health in 1952. The commission's purpose was to inventory and study national health needs and related education.* Image credit: ORNL

*A NUCLEAR LAB IN PEACETIME, page 28*

ORNL should add uranium fuel and the beryllium reflector elements to the LITR so they could make measurements to predict and improve the future Materials Test Reactor's performance. Once the fuel was added to the LITR, the world was introduced to the blue glow known as Cherenkov radiation. The image of the glowing reactor core was published on a 1951 cover of *Scientific American* and became a popular symbol of nuclear power. (It certainly helped that Weinberg and colleagues sent the magazine the photograph.)

*In 1954, President Dwight D. Eisenhower opened the floodgates to nuclear commercialization through an amendment to the Atomic Energy Act as part of his 'Atoms for Peace' policy.*

Over its 20 years of operation, the full-scale Materials Test Reactor—which was eventually built at the AEC's National Reactor Testing Station in Idaho, where it was operated by Argonne—was an important precursor to commercial nuclear power plants and a testbed for nuclear submarine materials. At least part of its success can be attributed to the "poor man's pile," as Wigner called the LITR, at Oak Ridge.

**The Homogeneous Reactors**. Concerned that uranium would become increasingly scarce, the physicists who had worked on the wartime uranium-fueled reactor designs conceived of "breeders"—reactors that used fission to produce more fuel than the reactors consumed.

In 1954, President Dwight D. Eisenhower opened the floodgates to nuclear commercialization through an amendment to the Atomic Energy Act as part of his "Atoms for Peace" policy. Private industry followed the example of the Navy and focused on water-cooled reactors. It made sense for the national laboratories to develop a more "long-term" solution to nuclear power; Weinberg and others in the mid-20th century believed breeder reactors could meet that long-term need.

Meanwhile, Britain, which had fallen behind in reactor development during World War II, built a series of gas-cooled reactors in the early 1950s. In reaction, the AEC tasked its laboratories with researching different gas-cooled designs, and ORNL was appointed the task of researching homogeneous reactors.

*See A NUCLEAR LAB IN PEACETIME, page 32*

# The house the Russells built

by Stephanie Seay
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Two years after the detonation of the atomic bombs at Hiroshima and Nagasaki, Bill and Liane Russell came to Oak Ridge with a purpose: to explore the genetic effects of radiation on mammals.

The work of this husband-and-wife team shaped our modern-day understanding of how radiation affects the body and extended to foundational genetic breakthroughs. To accomplish their research, the Russells designed and oversaw one of the largest mouse research facilities in the world: the ORNL Mouse House.

*Bill and Liane Russell.* DOE photo by Ed Westcott

The laboratory, located at the nearby Y-12 facility, housed more than a quarter-million mice at its peak, enabling research on genetic mutations that set occupational dose limits for humans. Liane Russell's work led to the standard precautions observed today for the exposure of pregnant women to diagnostic X-rays. She and her colleagues also discovered that maleness in mice and humans depends on the presence of the Y chromosome and is unrelated to the number of X chromosomes.

As ORNL's work expanded to human exposure to chemicals, Bill Russell led research that identified ethylnitrosourea as a "supermutagen," or chemical that is the most effective at inducing mutations. As a result, the chemical later became the gold-standard reagent for the discovery and cloning of genes associated with human diseases.

The mouse genetics program extended for nearly 60 years, until 2009. Today, biomedical research at ORNL builds on this rich legacy and leverages resources in biology, supercomputing, and neutron science to spur critical discoveries impacting human health.

These efforts include computing and data approaches to understand the genetic underpinnings of ailments such as Alzheimer's disease, heart disease and opioid addiction, as well as machine learning algorithms to uncover previously hidden relationships between disease factors such as genes, biological markers and environment. In addition, investigators are looking for ways to use the body's own immune system to help fight cancer.

*A NUCLEAR LAB IN PEACETIME, page 30*

As the name suggests, homogeneous reactors rely on the same solution for fuel, moderator and coolant. This mixed solution circulates continuously, so a homogeneous reactor does not need to be stopped to discard spent fuel. However, because the fuel solution circulates through the entire reactor, not just the core, workers must contend with more radioactive components, which can make maintenance tedious and costly.

In 1952, ORNL built the Homogeneous Reactor Experiment to demonstrate that a homogeneous reactor was a feasible design for producing power. The experiment would turn out to be one of the more heart-pounding—literally. Some of the pumps used to draw waste gas from the HRE "made a horrible racket that reverberated through the control room of the reactor and almost gave us heart failure, because we feared the diaphragm would burst," Weinberg wrote in his book "The First Nuclear Era."

Despite the noise, the reactor proved to be remarkably self-regulating, able to maintain a natural balance between temperature, pressure and power. This discovery, along with others, proved the project a success. However, more research was needed to solve remaining technical challenges, including the frustrating maintenance of radioactive parts and the tendency of the reactor's many pumps and valves to leak from fuel buildup.

In 1957, the lab built a larger homogeneous reactor, called the Homogeneous Reactor Test, which reached its full power of 5 megawatts in 1958. At the time, the HRT beat the record for the longest continuous reactor operation at 105 days, but by 1959 corrosion caused a hole in the tank, leading to reactor shutdown—and tanking the aqueous homogeneous reactor project, as well.

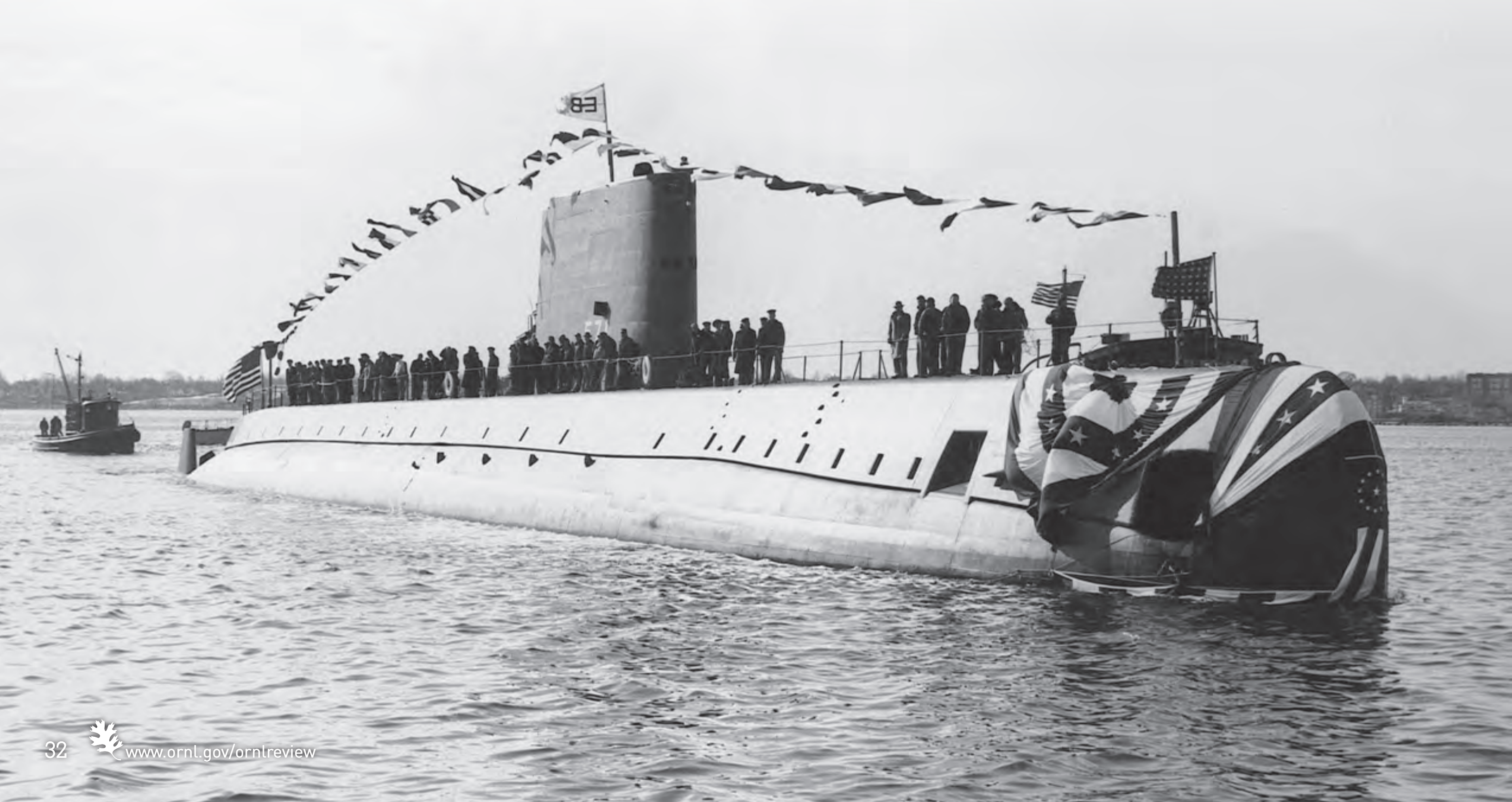
**The Molten Salt Reactor Experiment**. Although the nuclear-powered aircraft project was abandoned in 1961, the molten salt fuel developed to power a reactor at extremely high temperatures had been a technical success. In 1960, ORNL began designing the Molten Salt Reactor Experiment, in which a fluoride-mix fuel ran along channels in a graphite core.

All of the pumps and components that touched the radioactive molten salt fuel were built from Hastelloy-N. Learning from the laborious maintenance required for the homogeneous reactors, the ORNL development team installed additional shielding around the reactor and carefully laid out the components so they could be accessed using long-handled tools.

Perhaps the most significant achievement of the MSRE occurred in 1966 when fissile uranium-233 fuel was added to the reactor fuel—making the MSRE the first reactor to operate on uranium-233. Glenn Seaborg, who had codiscovered uranium-233 during the early days of the Manhattan Project, came to ORNL to start up the reactor for uranium-233 operation.

Years earlier, Wigner had proposed a thermal breeder reactor using a uranium-233 and thorium-232 fuel cycle. In MSRE, Weinberg saw a stepping stone to building a thermal breeder reactor, but the AEC shut down the molten salt program in 1973 in favor of another type of breeder reactor: the fast breeder. ORNL's expertise in molten salt chemistry has become

*Navy Capt. Hyman Rickover approached ORNL in 1947 to assist in development of the USS Nautilus, the Navy's first nuclear-powered submarine. It was built using Alvin Weinberg's pressurized-water reactor concept and launched on January 21, 1954.* Image credit: U.S. Navy



newly relevant as the technology is considered for cooling conventional fission reactors and as concepts for new liquid-fueled reactors are developed.

*Reactors for research: Reactor design and radiation safety*

**The Bulk Shielding Reactor**. Until the development of the "swimming pool" reactors, as they would be named because of their open tanks of water, researchers relied on either lower-power reactors or small channels in higher-power reactors for conducting experiments. Testing the effects of radiation on bulky shielding materials was difficult. After conducting shielding tests for nuclear Navy projects including the Nautilus, ORNL's Everett Blizard proposed submerging a reactor vessel in a large tank of water to allow room for testing different material configurations.

In 1950, the lab converted the Materials Test Reactor design to a swimming pool reactor: the 2-megawatt Bulk Shielding Reactor. At the BSR facility, two bridges over a 20-by-40-foot pool of water enabled engineers on one bridge to move the reactor vessel around the pool with a crane while researchers worked on experiments from the other bridge. A small reactor assembly, known as the Pool Critical Assembly, was stationed in the corner of the tank for small-scale experiments. The BSR's simple design and versatility supported a broad range of radiation and materials research for more than 30 years, and the design was replicated in about 100 research reactors around the world.

**The Health Physics Research Reactor**. From 1963 to 1987, the lab operated a fast-burst reactor that could produce pulses of radiation for health physics research. By adjusting the reactor's pulse mode, researchers could simulate a range of radioactive conditions over 15 orders of magnitude (up to 100,000 megawatts). This versatility enabled them to better study radiation's impact on the human body and other organisms and develop improved dosimeters for measuring radiation exposure. Studies using the reactor to irradiate the "organs" of human-simulating phantoms contributed significantly to the establishment of safe exposure limits.

*Reactors for research: Isotopes and neutrons*

**Oak Ridge Research Reactor**. In 1958, after more than a decade, ORNL researchers finally got a high-flux nuclear reactor like the Materials Test Reactor they once hoped for. Similar to the Materials Test Reactor, the Oak Ridge Research Reactor was a 30-megawatt water-cooled reactor. Like the BSR, it was adapted to include a water tank that enhanced access for research. The tank also prompted the design of an "observation deck," and an "SS ORR" life preserver was hung on the side. The facility was a popular draw for politicians and dignitaries, including three future U.S. presidents and foreign royalty.

The ORR operated for almost 30 years and was an important tool for advancing American science, particularly in the fields of isotope production and neutron science (see "Making the most of neutrons," page 13). At the ORR, scientists confirmed the electron-neutrino theory of beta decay (which introduced an imbalance in the Standard Model that occupies particle physicists to this day) and conducted strings of studies on the properties of rare earth elements and crystals, among many other achievements.

> *Although the AEC approved HFIR as an isotope production reactor, Weinberg—always looking for ways to amplify and diversify the lab's research capabilities—saw an opportunity to expand neutron science research as well.*

**High Flux Isotope Reactor**. In 1965, ORNL would get another high-flux reactor and the most intense neutron source for research in the world. HFIR was built to produce superheavy elements. A Transuranium Processing Plant, now part of the Radiochemical Engineering Development Center, was built next door to recover the superheavy elements and radioisotopes produced at HFIR.

Although the AEC approved HFIR as an isotope production reactor, Weinberg—always looking for ways to amplify and diversify the lab's research capabilities—saw an opportunity to expand neutron science research as well. He managed to get approval for ORNL to add four beam holes for neutron research. The reactor became an early version of a user facility, introducing scientists from many disciplines to neutrons as tools for studying materials, through a collaboration with the National Science Foundation known as the National Center for Small-Angle Scattering Research, which also provided access to X-ray scattering resources. Today, HFIR is ORNL's only remaining nuclear reactor and is still a world-leading resource for materials irradiation, isotope production and neutron science.

As the commercial nuclear power industry developed, the lab, under Weinberg's guidance, turned its tools and expertise to new challenges facing the nation, including growing demands for environmental protection and energy conservation, but the lab's roughly 20 years of involvement in reactor research and development led to many achievements in materials, chemistry and the physical sciences that would enable further advances during the next quarter-century.

# 11 ORNL neutron achievements

1948

## Diffraction photo

Neutron scattering pioneers Ernest Wollan and Clifford Shull (along with Milton Marney) use the Graphite Reactor to produce the first photograph of a neutron Laue diffraction pattern using sodium chloride (aka table salt).

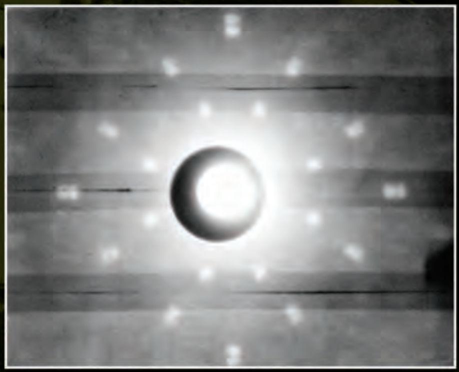
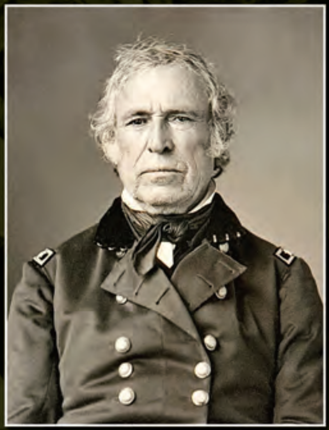


*Photo of neutron Laue diffraction pattern.* Image credit: ORNL



*ORNL researchers used neutron analysis at HFIR to determine that President Zachary Taylor was not poisoned with arsenic.*

1991

## Criminal Forensics

President Zachary Taylor's opposition to slavery was one reason some suspected foul play in his 1850 death in office. ORNL researchers Larry Robinson and Frank Dyer use the High Flux Isotope Reactor to perform neutron activation analysis on fingernail and hair samples from Taylor's body, determining that arsenic poisoning was not the cause of death.

1951

## Antiferromagnetism

Clifford Shull shows the magnetic structure of manganese oxide, which leads to the discovery of antiferromagnetism.

1955

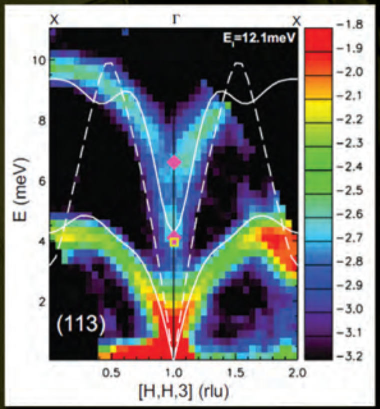
## Scattering

By this year, Shull and Wollan had measured scattering patterns from more than 100 elements and 60 different isotopes.

2011

## Thermoelectrics

Lead telluride's low thermal conductivity makes it a compelling thermoelectric material (i.e., one that converts temperature difference directly into electricity). ORNL researchers use SNS and HFIR to find the cause of this material's low thermal conductivity.




*Neutron scattering experiments performed at ORNL show that lead telluride exhibits a strong anharmonic coupling between its optical and acoustic lattice vibrations, with a drop in thermal conductivity resembling a waterfall in this data image.* Image credit: ORNL

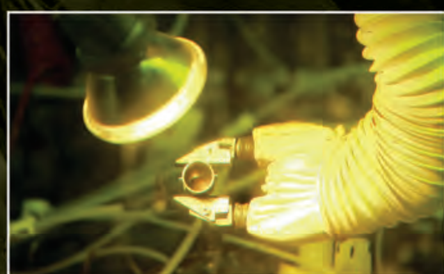
## 2015

### Space Flight

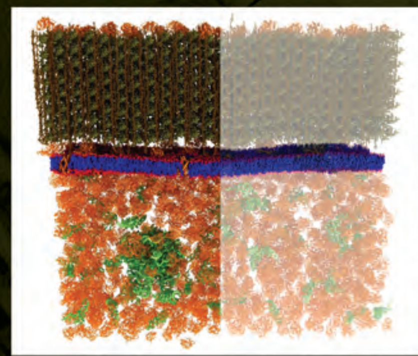
After nearly 30 years, researchers at HFIR resume production of plutonium-238 as a fuel source for deep space missions. The heat generated from plutonium-238 decay can be used to power systems used by NASA and private companies.

### Magnetism in plutonium

Neutron scattering at SNS reveals that plutonium's magnetism exists in a constant state of flux, helping to explain abnormal changes in plutonium's volume in its different phases.



*By producing 50 grams of plutonium-238 at HFIR, ORNL researchers demonstrate the nation's ability to provide a valuable energy source for deep space missions.* Image credit: Jason Richards, ORNL



*An ORNL team made nonmembrane cell components practically invisible to neutrons (right) by combining specific levels of heavy hydrogen (deuterium) with normal hydrogen within the cell.* Image credit: Xiaolin Cheng and Mike Matheson, ORNL

## 2017

### Cell membranes

Neutron scattering conducted at HFIR and SNS provides the first nanoscale look at a living cell membrane, resolving a long-standing debate regarding the existence of "lipid rafts," a likely key to cell functionality.

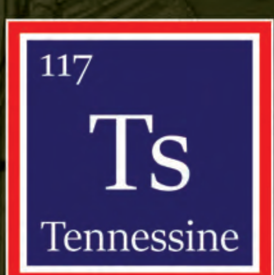
### Running engines

Because neutrons are deeply penetrating, researchers at SNS are able for the first time to perform neutron scattering on a new aluminum alloy used in a gasoline-powered engine—while the engine is running.

## 2016

### New Element

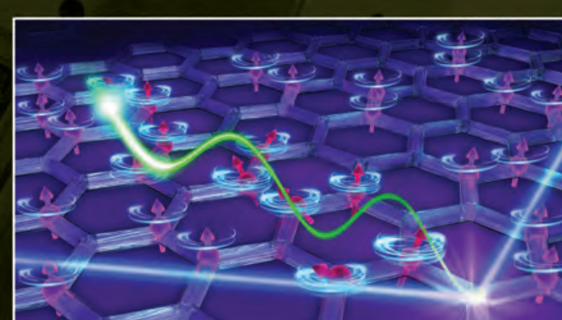
The newest element on the Periodic Table, element 117, is named tennessine in honor of ORNL, the University of Tennessee and Vanderbilt University. The production of tennessine requires berkelium-249, which is only available from HFIR.




*HFIR played a key role in the discovery of tennessine.*

### Quantum materials

Neutron scattering at HFIR and SNS revealed evidence for magnetic Majorana fermions associated with materials exhibiting long-sought Kitaev quantum spin liquid behavior. Theory suggests that such particles might be used as the basis of "qubits" for use in quantum computers.



*As neutrons (blue line) scatter off the graphene-like honeycomb material, they produce a magnetic Majorana fermion (green wave) that moves through the material, disrupting or breaking apart magnetic interactions between "spinning" electrons.* Image credit: Jill Hemman, ORNL

Image credit: Brett Hopwood, ORNL

# New challenges

by Katie Jones
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While ORNL researchers produced isotopes for medicine, designed and tested nuclear power reactors, and studied the biological effects of radiation, the advent of nuclear weapons transformed global politics.

During the four-decade Cold War, new feats of science and technology fed threats and fears, while outside the political theater, discoveries in biology, nuclear physics, materials science and more transformed daily lives.

## The Cold War and the space race

In 1957, the Soviet Union launched the first artificial satellite, Sputnik, and the "space race" began. Four years later, American President John F. Kennedy challenged the nation to be the first to put a man on the moon—a feat he said would demand "a major national commitment of scientific and technical manpower."

*To protect astronauts from damaging radiation in space, ORNL researchers repurposed the Tower Shielding Facility from the canceled nuclear aircraft project and used it to develop lightweight shields for the Apollo crews.*

That technical manpower included ORNL. When Apollo 11 landed on the lunar surface in 1969, the crew carried Oak Ridge-designed scoops and a vacuum-sealed box for collecting moon rocks. When the crew returned safely to Earth, fulfilling President Kennedy's moonshot vision, some of the lunar samples came to the lab for analysis; they were assayed for uranium, thorium and other indicators of their age.

To protect astronauts from damaging radiation in space, ORNL researchers repurposed the Tower Shielding Facility from the canceled nuclear aircraft project and used it to develop lightweight shields for the Apollo crews. Lab biologists sent blood samples on satellites to study the biological effects of space travel, and physicists used the fast-burst Health Physics Research Reactor to determine the radiation dose an astronaut's internal organs might receive.

Once man reached the moon, NASA wanted to go farther—through the solar system via unmanned probes that would require decades of power. ORNL contributed to research that evaluated possible nuclear generators. When NASA chose a radioisotope generator of plutonium-238 oxide fuel, the lab designed a high-temperature, corrosion-resistant iridium alloy cladding that secured the radioactive fuel and a carbon fiber insulation that maintained the cladding's temperature. The ORNL technology was used in the Voyager 1 and 2 probes that launched in 1977 and transmitted the first images of Jupiter's ring system and Saturn's moons. Today, the iridium-based cladding and other Voyager components drift farther than any other humanmade material, as Voyager 1 has crossed into interstellar space.

## Civil defense and the arms race

Although the Cold War space race captured America's imagination, the Cold War nuclear arms race incited new fears. The Cuban Missile Crisis in 1962 ended peacefully but led the American people, including the nation's scientists, to ask, "What if?"

Former research director Eugene Wigner returned to ORNL for a year in 1964 to organize and lead a civil defense project that evaluated how Americans could prepare themselves for a nuclear attack. The project looked at the technical, political, military and social aspects of defense.

The lab hired its first social scientists to study how people respond to stress. The project's engineering challenges included designing protective underground tunnels with power and ventilation, shelter from chemical hazards, and radiation shielding for livestock. Lab scientists simulated radioactive fallout and studied the possible effects of "nuclear winter"—the prolonged, cloudy darkness created by spreading fires.

Fortunately, the Cold War ended without the use of nuclear weapons. Even so, some of the civil defense strategies developed at ORNL have been applied in the years since to natural disasters and other emergencies.

## Technology for public health

By the late 1960s, ORNL's Biology Division was at its largest, with more than 400 employees. The Health Physics Division was studying nuclear energy's impact on health and the environment. New technologies were also developed and applied to the fundamental study and betterment of human health.

Centrifuges developed to separate isotopes inspired technology to purify vaccines by removing foreign proteins. This ORNL technology was used to produce safer vaccines for millions of people. In 1972, lab cryobiologists developed a

*As part of its civil defense work, ORNL hired demographers to understand the number and age distribution of populations being protected by civil defense systems, such as underground shelters. Pictured is a mock-up of a bomb shelter in August 1965.* Image credit: ORNL

method of freezing mouse embryos, then implanting them into female mice that gave birth to healthy mouse pups. This technique was used in the cattle industry to increase the quantity and quality of meat for a growing population and eventually was used to preserve human organs for transplants.

A defining health issue of the 1960s and '70s was the relationship between smoking and cancer. Mounting evidence suggested that cigarettes increased the risk of lung cancer, and the National Cancer Institute, American Cancer Society and tobacco industry funded different laboratory smoking studies, including research to find less hazardous ingredients for cigarettes.

As part of this effort, ORNL built "smoking machines" that burned standardized cigarettes to produce usable quantities of tar to identify chemicals responsible for cancer and other adverse health effects. Lab researchers also exposed animals to cigarette smoke and other irritants, such as smog and pesticides, to understand additional contributors to lung cancer.

## The environmental movement

Beginning after World War II and escalating during the 1950s and '60s, environmental issues became a central topic of debate, public protest and policymaking in the United States. Pesticides, smog, oil spills, and nuclear safety and waste disposal emerged as national social and scientific conversations. Legislation addressing water and air pollution gave the government the right to regulate pollutants and led to government, nonprofit and citizen protective efforts.

The first photo of Earth, taken by Apollo astronauts in 1968, became a symbol for the first Earth Day on April 22, 1970, in which 20 million people demonstrated across the country on environmental issues. That same year, President Richard Nixon

*See NEW CHALLENGES, page 38*

*In 1977 Carolyn Young studied the effects of warm effluents from Bull Run Steam Plant on Melton Hill Lake milfoil, an aquatic plant.* Image credit: ORNL

*NEW CHALLENGES, page 37*

created the National Resources Defense Council, the Environmental Protection Agency and the National Oceanic and Atmospheric Administration. The federal environmental shakeup also affected the future of ORNL, which once considered itself primarily a nuclear laboratory.

As part of the National Environmental Policy Act that created the EPA, federal agencies were newly required to provide environmental impact assessments detailing how the agency's actions might affect the environment. In 1971, a federal court ruled that the Atomic Energy Commission had to provide environmental impact assessments in just a year's time for about 90 nuclear power plants either operating or underway. The AEC turned to its national laboratories, including ORNL, which had built a reputation for radiation and nuclear safety expertise. About 200 staff members at the lab worked on the assessments, which stimulated innovative research in areas ranging from sensor development to energy demand forecasting.

In 1973, an oil embargo by the Organization of the Petroleum Exporting Countries led to an energy crisis, with Americans lining up at the pumps for gas and turning down the heat in their homes and offices. At the same time, ORNL faced not only an energy crisis but a change in leadership: Longtime lab director and nuclear pioneer Alvin Weinberg left his position after 18 years.

One year later, the AEC was abolished by the Energy Reorganization Act of 1974, which created two new agencies to handle energy matters: the Energy Research and Development Administration to manage the AEC's programs in energy research and development, nuclear weapons, and naval reactors, and the Nuclear Regulatory Commission to regulate the nation's new fleet of nuclear power plants.

The lab adapted its nuclear roots to study a range of energy sources and applications. With this change came a new lab director, Herman Postma, a fusion (rather than a fission) scientist and the first lab director who did not have Manhattan Project experience.

*See NEW CHALLENGES, page 40*

# Where no one has gone before

by Bill Cabage
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In outer space, beyond what is considered our solar system, a small spacecraft that looks like a TV satellite dish is still transmitting back to Earth.

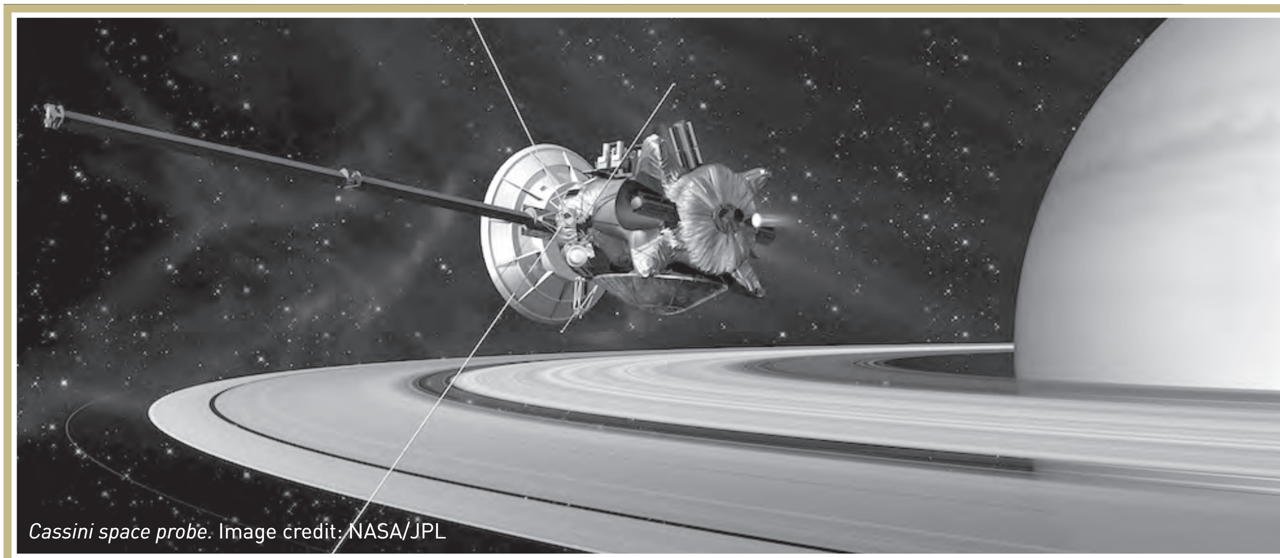
Deep-space missions have revealed the secrets of the solar system and beyond for nearly a half century. ORNL technology helps make these missions possible by providing power in the frozen void.

Spacecraft on missions near the sun can use solar collectors for power, but on ventures to the outer planets, sunlight becomes too dim to provide necessary wattage.

ORNL developed and provided NASA with "clad vent sets" that contain the plutonium oxide fuel that powers the spacecraft. As the plutonium decays, residual heat is converted to electric power for the craft's instruments. The clad vent sets are made from a virtually indestructible iridium alloy, developed at ORNL, that's able to survive an unplanned reentry in the event of a launch accident.

These radioisotope thermal generators, or RTGs, entered the popular culture when movie star Matt Damon's stranded character used them to warm himself on Mars in 2015's "The Martian." But NASA's true-life missions have thrilled and fascinated the public for decades, unlocking the secrets of the cosmos and providing dazzling images, from the Voyager missions of the 1970s that provided the first closeups of outer planets, to the Jupiter probe Galileo, to Saturn's Cassini, to the Mars Curiosity rovers, to the New Horizons Pluto mission.

With the critical plutonium oxide fuel in short supply, ORNL now is gearing up to produce plutonium-238 for future missions, expanding ORNL's role in further understanding our universe.



*Cassini space probe.* Image credit: NASA/JPL

A team led by Norman Anderson—pictured with Warren Harris—demonstrated that rapidly spinning centrifuge technology previously developed to produce enriched uranium for nuclear reactor fuel can purify vaccines by 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. Image credit: ORNL

*NEW CHALLENGES, page 38*

The lab mirrored the creation of ERDA with creation of its own Energy Division for energy and conservation research. By 1977, President Jimmy Carter elevated energy research to an executive department and established the Department of Energy, which today manages 17 national laboratories, including ORNL.

During the energy crisis, public and scientific opinion identified two overarching solutions: first, increase U.S. energy independence through the creation of new energy sources, and second, reduce energy consumption.

## New sources of energy

In light of rising environmental concerns and the energy crisis, scientists began exploring energy sources beyond nuclear fission and petroleum energy. For fuels, they looked in the 1970s and '80s primarily to coal liquefaction, as coal was an abundant American resource. For electricity, they looked to solar, wind and geothermal energy. Research also continued into nuclear fusion, which promised to provide limitless energy if only the technology could be developed to support it.

*See NEW CHALLENGES, page 42*

*ORNL built 'smoking machines' that burned standardized cigarettes to produce usable quantities of tar to identify chemicals responsible for cancer and other adverse health effects.*

# Plugged into battery safety

by Jennifer Burke
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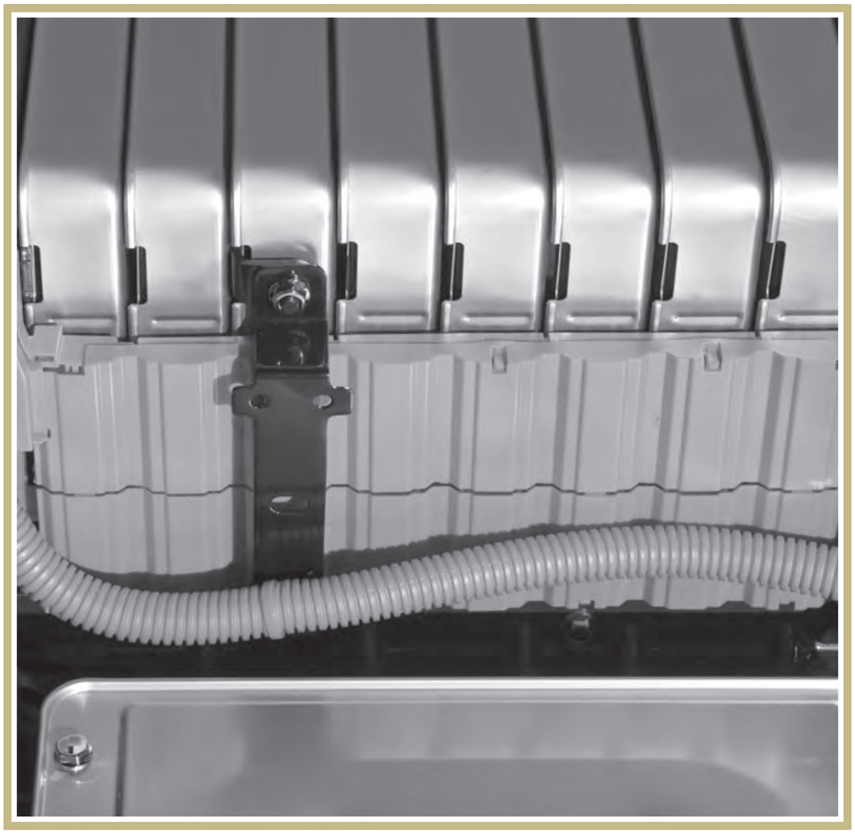
As use of electric vehicles grows, ORNL is working to make them better.

A battery research team led by chemist Nancy Dudney, an internationally recognized leader in energy storage, focuses on technologies that make EV batteries crash-tolerant while keeping them relatively lightweight and cost-effective.

Two of the team's projects have developed novel ways to ensure batteries survive a vehicle collision, requiring less protective casing than that of traditional batteries and reducing the manufacturing cost while increasing EV affordability.

In the first project, ORNL chemist Gabriel Veith and colleagues created the Safe Impact Resistant Electrolyte, which changes from liquid to solid during collisions, eliminating the need for an expensive polymer separator to prevent electrical shorts. During a collision, the separator keeps the battery's positive and negative ends from touching each other and causing fires or other safety problems.

A second approach, Dudney's Safety Foil current collectors, ensures that large, damaged electrodes break into smaller fragments—electrically isolating them and avoiding an uncontrolled increase in temperature—thus allowing undamaged areas within the battery to continue to function.



*Batteries for an electric vehicle.*

Both inventions aid in the construction of safer batteries in any part of the EV, including spaces most likely to suffer damage during impact.

Through a deep understanding of the fundamentals of materials, the ORNL battery team has conducted translational research, turning basic science into applied science for practical applications.

*With the Aircraft Reactor Experiment showing the feasibility of molten salt fuel, the Atomic Energy Commission funded the Molten Salt Reactor Experiment to demonstrate key elements needed for a civilian power reactor. The reactor operated from 1965-69. Shown are Atomic Energy Commission Chairman Glenn Seaborg, left, and ORNL Director Alvin Weinberg.* Image credit: ORNL

*NEW CHALLENGES, page 40*

*Alternative fuels*

Until the mid-20th century, when U.S. petroleum consumption spiked, the United States relied largely on coal power. Because coal was plentiful, researchers looked for ways to turn it into liquid fuel to supplement imported petroleum. Using chemical processes, scientists could convert it to liquid or gas to create a synthetic fuel. Increased coal research led to fundamental studies of the structure and properties of coal. Related ORNL research revealed that the chemicals produced during the conversion of coal to liquid or gas at that time could lead to adverse health effects.

Much of ORNL's work for DOE's fossil energy program was materials related. ORNL worked with industry to modify an existing steel alloy for use in advanced breeder reactors and to qualify the new alloy, known as Grade 91 steel, for commercial use in fossil energy applications. ORNL has also developed other alloys for ultrasupercritical steam power plants and other high-temperature applications, plus ceramic membranes, carbon fiber composite molecular sieves, and corrosion-resistant coatings to increase the efficiency of fossil energy systems.

In the 1970s and '80s, ORNL environmental scientists who had been studying plant and aquatic life to evaluate the impacts of nuclear energy also began studying how they could produce fuel from plants. Researchers helped identify two promising feedstocks for converting wood to fuel—poplar and switchgrass. ORNL led a study for DOE that produced its first "Billion-Ton" report in 2005, projecting that the United States has the potential to produce a billon tons of biomass annually by 2040. Later, ORNL researchers helped tackle bioenergy's stubborn problem of recalcitrance, or the resistance of the plant cell wall to breaking down and releasing energy. To support targeted research on bioenergy breakdown and processing, DOE established a multi-institutional BioEnergy Science Center led by ORNL in 2007.

*Solar and geothermal*

The idea of solar energy is nothing new. Early studies of the photovoltaic effect to convert sunlight into energy date to the 19th century. By the 1950s, several technology companies were developing their own silicon photovoltaic cells. The challenge for the national laboratories was to determine how to make solar energy production economical.

At ORNL, researchers tapped into their background and experimented with the use of solar energy to heat liquid sodium and molten salts to generate electricity, but the technique proved too expensive. Then they turned to the task of making silicon solar cells more efficient and used the Bulk Shielding Reactor to develop a new method for modifying silicon's semiconducting properties. The method—neutron transmutation doping—uniformly distributed phosphorus ions in the silicon, increasing efficiency. Researchers also improved the efficiency of heat exchangers that produced electricity using geothermal energy from hot water and steam trapped in the ground.

*Fusion*

Although it took only four years from the discovery of nuclear fission to build the first operating fission reactor, harnessing nuclear fusion—producing energy by combining or "fusing" the nuclei of light atoms, rather than by splitting heavy atoms—proved more elusive. Building a reactor that creates more energy than it uses turned out to be an enormous technical challenge, and the hot plasma in a fusion reaction was the hottest medium ever handled, requiring new heat-resistant materials.

ORNL had begun exploring fusion energy in the 1950s and constructed a series of experimental devices to test various ways to contain a fusion plasma using powerful magnetic fields. In 1968, the Soviet Union built the world's first tokamak, a promising configuration that confines the fusion plasma in a doughnut-shaped, or toroidal, vacuum vessel, and the United States soon set out to build its own. In 1971, the Oak Ridge Tokamak, or ORMAK, Oak Ridge's first experimental tokamak, reached a plasma temperature of 20 million kelvin (about 35 million degrees Fahrenheit). A thin, but vacuum-tight, stainless steel liner, gold plated to minimize impurities, surrounded the ORMAK plasma. This liner was enclosed in a cooled aluminum shell. ORMAK demonstrated the feasability of heating a fusion plasma by injection of energetic neutral particles. Neutral beam injectors are now standard equipment on all magnetic confinement devices.

The lab constructed a slightly larger tokamak, the Impurity Study Experiment, that began operating in 1977. Also in 1977, ORNL embarked on construction of the International Fusion Superconducting Magnet Test Facility, or IFSMTF. Using conventional copper electromagnets to create the strong magnetic fields needed to confine a fusion plasma requires enormous amounts of electrical power, but magnets made of superconducting materials, in which electrical resistance vanishes at low temperatures, offer a solution to this challenge.

The IFSMTF was used to test six 20-foot magnets—three built by the United States and three by international partners Japan, Switzerland and the European Atomic Energy Community—that were supercooled using liquid helium at a temperature of 4.2 kelvin, or roughly minus 452 degrees Fahrenheit. Another enduring ORNL contribution to fusion energy was the development of hydrogen pellet injection, a technique in which frozen pellets of neon, argon, or hydrogen are injected into the plasma to add fuel or control plasma instabilities.

As the energy crisis eased in the 1980s, funding for the U.S. fusion program declined. ORNL's last large-scale fusion experiment was a stellarator called the Advanced Toroidal Facility, which operated from 1987 to 1994. ORNL remained actively involved in fusion research and currently manages the American contributions to ITER for DOE's Office of Science. ITER, which will be eight times larger than the biggest current tokamak, is considered the next major step for fusion energy development. The international project is a collaboration among the United States, the European Union, the People's Republic of China, India, Japan, the Republic of Korea and the Russian Federation.

Construction is advancing on the ITER tokamak complex in France, while components are in fabrication by the ITER partners around the globe. Among the components being supplied by the United States are superconducting magnets and a pellet injection system.

ORNL also continues to develop materials to withstand the extreme fusion environment, conducting irradiation experiments in HFIR and operating the Prototype Materials–Plasma Exposure Experiment, or Proto-MPEX. MPEX, which will soon succeed Proto-MPEX, will develop materials for devices beyond ITER, including the first generation of experimental fusion power reactors.

*Construction is advancing on the ITER tokamak complex in France, while components are in fabrication by the ITER partners around the globe. Among the components being supplied by the United States are superconducting magnets and a pellet injection system.*

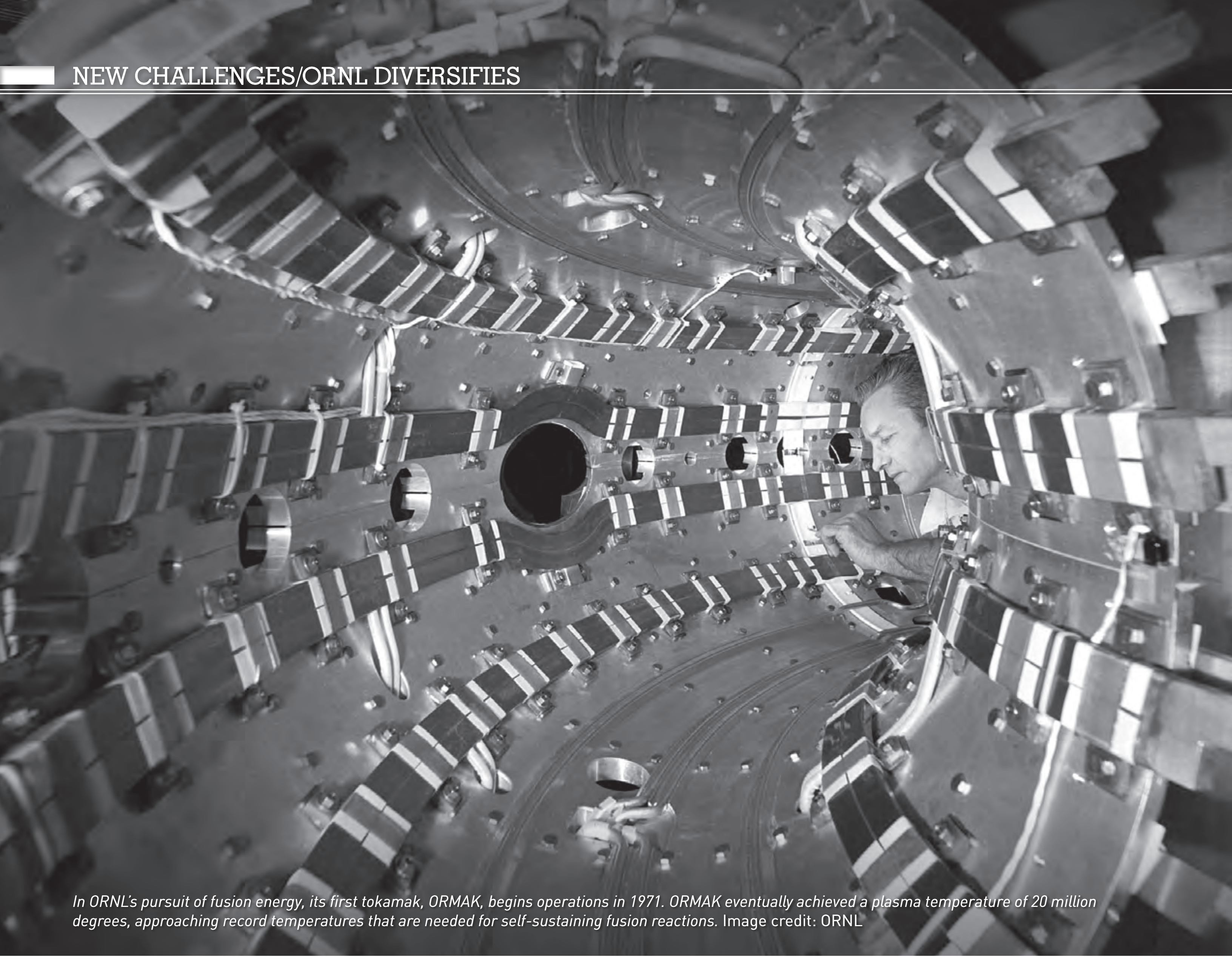
## Energy efficiency

Buildings still consume most of the energy produced in the United States, but they have come a long way in terms of efficiency. In the 1970s, researchers identified insufficient insulation and inefficient heating and cooling systems as home energy sinks.

After analyzing data from an instrumented mobile home, ORNL researchers recommended tighter insulation and storm windows to reduce the leaking of hot and cold air—a standard that improved the design of manufactured homes. By the end of the 1980s, ORNL recommendations for insulation thickness, or R-values, were widely adopted across the country.

Following a tip from a lab retiree, ORNL researchers developed a heat pump connected to an underground water tank that used stored water to heat and cool a home. By partnering with the University of Tennessee in 1976 to build a demonstration home with this Annual Cycle Energy System, researchers observed that the system could cut home heating and cooling costs by as much as half. Later, the lab developed a new design for a geothermal heat pump that used an ecofriendly heat-exchange fluid to reduce electrical use in retrofitted homes by more than 30 percent.

*See NEW CHALLENGES, page 44*



*In ORNL's pursuit of fusion energy, its first tokamak, ORMAK, begins operations in 1971. ORMAK eventually achieved a plasma temperature of 20 million degrees, approaching record temperatures that are needed for self-sustaining fusion reactions.* Image credit: ORNL

*NEW CHALLENGES, page 43*

Although there were big gains to be made in improving insulation and heating and cooling systems, the impact wouldn't be significant until homeowners and businesses replaced those systems over time. To start reducing household energy consumption in the short run, researchers looked to appliances such as refrigerators, water heaters and furnaces, which are replaced more frequently. Through partnerships with industry, many ORNL innovations have entered the marketplace.

As computer workstations became more common and powerful at the lab, scientists developed computer models to analyze and optimize the energy efficiency of home appliances. By the 1980s, ORNL estimated that most American homes had at least one appliance that was more energy efficient because of ORNL research. In the 1990s, researchers also developed more environmentally friendly and energy-efficient refrigerant blends that did not contain chlorofluorocarbons, which damaged the ozone layer.

In 1987, ORNL built a Roof Research Center that allowed researchers to install instrumented roof panels and collect data for computer models on how heat traveled through roofing structures. The center included a climate simulator that allowed researchers and industry users to examine roofing systems in different weather conditions—work that continues to this day at the Building Technologies Research and Integration Center. In 1999, the EPA released its first Energy Star whole-building-performance energy-rating tool based on the benchmarking methods developed at ORNL.

With significant energy efficiency improvements in home construction and appliances, DOE set a goal for the 21st century of combining insulation, energy-efficient appliances and solar cells to design "zero energy" homes that collect and generate as much energy as they use.

## Nuclear safety

In 1979, at the end of an inventive decade of energy conservation research at ORNL, nuclear power and safety came back to the forefront when news broke of a reactor failure at the Three Mile Island nuclear power plant in Pennsylvania.

A mechanical or electrical failure led to an automatic shutdown of the plant's Unit 2 reactor. Then, a pressure valve that was supposed to close as reactor core pressure dropped remained open, even though instruments in the control room indicated it was closed. With no cooling, the reactor core overheated and partially melted down. Although radiation was contained and not released into the environment, the Three Mile Island accident was considered the worst nuclear accident in U.S. history and came at a time when environmentalists were already questioning the safety of nuclear power.

*By the 1980s, ORNL estimated that most American homes had at least one appliance that was more energy efficient because of ORNL research.*

During the 1960s and '70s, ORNL's reactor physicists and engineers had increasingly focused on safety-related projects. The lab built a nuclear safety pilot plant for studying fission product behavior under accident conditions and a heat-transfer facility for testing fuel elements. Researchers designed stable containers for shipping radioactive materials, simulated the impact of earthquakes on reactor stability, and developed more sophisticated robotic servomanipulators (robotic arms and hands) for safely handling materials in radioactive environments. The lab also designed and built a high-sensitivity isotope ratio mass spectrometer in 1976 to measure nuclear samples from around the world and ensure compliance with the Treaty on the Nonproliferation of Nuclear Weapons.

ORNL's nuclear reactor and safety experts were deployed to the Three Mile Island plant as onsite analysts. They monitored radiation emissions after the accident and added chemicals and filters that helped prevent radioactive releases. ORNL experts also analyzed and removed fission products from contaminated water stored at the site.

Seven years later, ORNL researchers investigated a far more serious nuclear accident: the Chernobyl disaster in the Soviet Union. After the accident, U.S. researchers modeled the Chernobyl reactor and determined that the operators did not fully understand the system.

In response to the two accidents, DOE shut down many of its reactors, including ORNL's Bulk Shielding, Health Physics Research, High Flux Isotope, Oak Ridge Research and Tower Shielding reactors, for stringent safety evaluations. Only two of the five reactors were brought back on line: HFIR, because of its critical role in producing isotopes, and the Tower Shielding Facility, which was not permanently shut down until 1992.

## A national resource

With the dissolution of the Soviet Union in 1991, Cold War tensions gave way to a booming international marketplace, spurred by rapid developments in materials and technology, particularly communication. The presidential administration of George H.W. Bush was interested in strengthening U.S. economic competitiveness through science and technology while creating new international partnerships to share knowledge and ideas.

At ORNL, new user facilities welcomed thousands of scientists each year from universities and industry to use the lab's unique, state-of-the-art resources. Cooperative Research and Development Agreements, a product of the Superconductivity Pilot Centers established by DOE in 1988 to accelerate development and commercialization of newly discovered high-temperature superconducting materials, enabled companies to collaborate with the lab and license lab inventions to bring new technologies to the marketplace faster. Once renowned primarily as a nuclear science and engineering laboratory, ORNL had become a national and global resource for energy-related research and development.

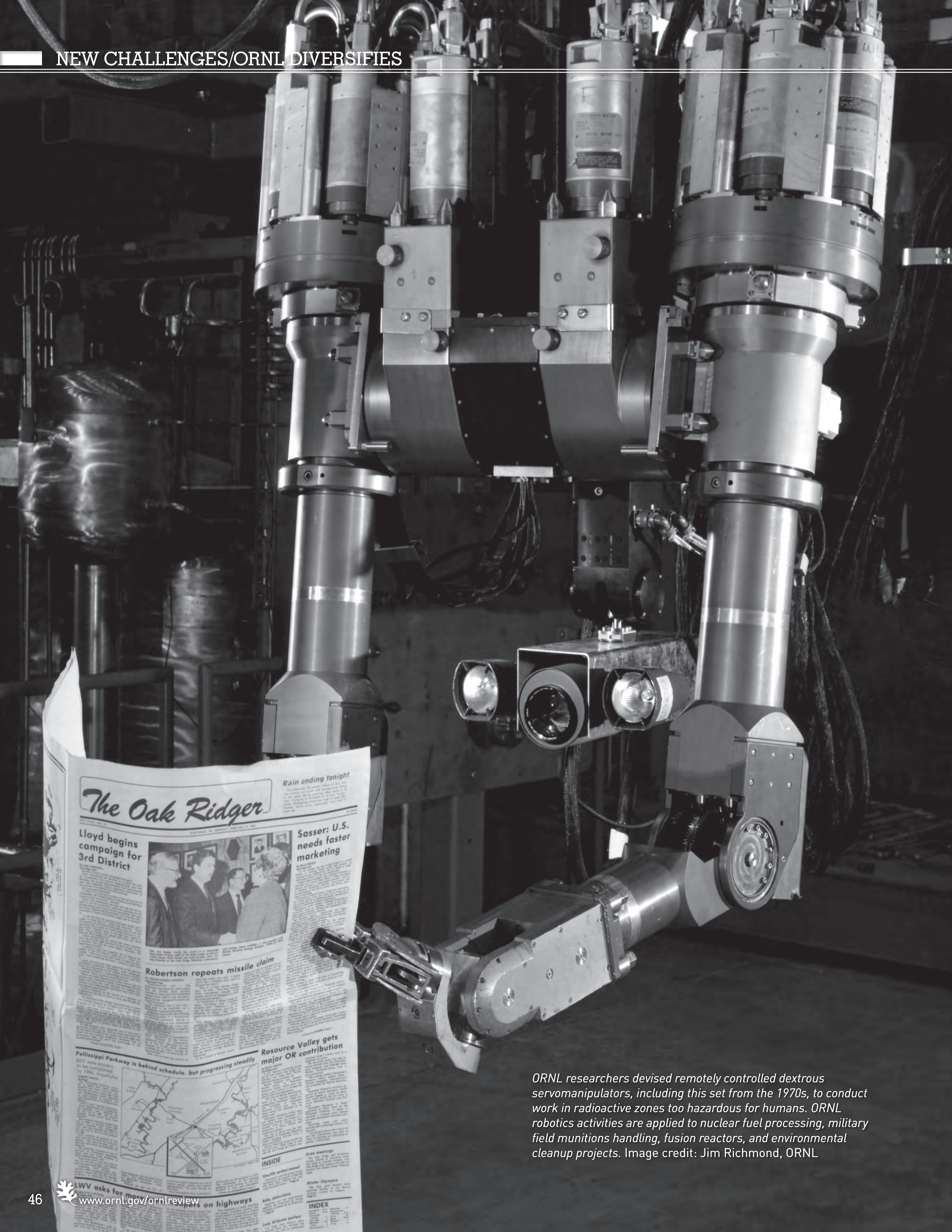
### *Accelerating physics*

Underlying all matter—whether fissile uranium, semiconducting silicon or organic carbon—are complex nuclei. The tools created for the Manhattan Project offered scientists the opportunity to learn more about the fundamentals of nuclear structure and reactions. Drawing on their recently acquired expertise in electromagnetic separation of isotopes, ORNL researchers started building cyclotrons and using them not only to produce new isotopes but also to understand the processes involved in the formation and motion of ions in electric and magnetic fields. In 1962, one of the world's first strong-focusing accelerators, the Oak Ridge Isochronous Cyclotron, began producing ions for research. The existence of the giant quadrupole resonance—a collective vibration of nuclei important to quantum physics studies—was confirmed at ORIC in 1972.

Shortly after the ring-shaped cyclotron was built, the lab added the Oak Ridge Electron Linear Accelerator. Located 20 feet below ground, ORELA provided short-pulse neutrons at an intensity about 10 times that of any other linear accelerator in the world, enabling neutron cross-section measurements for nuclear criticality safety, nuclear reactor and fuel cycle analysis, stockpile stewardship, weapons research, medical diagnosis, and nuclear astrophysics. Several experiment stations for physics research were located at the ends of neutron beam flight tubes extending radially from the ORELA target room.

In 1980, the lab added a 25-million-volt tandem accelerator to the ORIC facility, creating the Holifield Heavy Ion Research Facility, which was again upgraded in 1997 as the Holifield Radioactive Ion Beam Facility to support production of short-lived radioactive isotopes. During the facility's five decades of operation, beginning with ORIC, ORNL was able to provide researchers from around the world with 70 ion species and 200 rare isotopes for unprecedented nuclear and astrophysics research.

*See NEW CHALLENGES, page 48*




*ORNL researchers devised remotely controlled dextrous servomanipulators, including this set from the 1970s, to conduct work in radioactive zones too hazardous for humans. ORNL robotics activities are applied to nuclear fuel processing, military field munitions handling, fusion reactors, and environmental cleanup projects.* Image credit: Jim Richmond, ORNL

# Zachary Taylor's deadly snack

by Bill Cabage
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Conspiracy theories are nothing new. When President Zachary Taylor took sick and died 16 months into his presidency in 1850, he had been a relatively healthy war hero. A fatal gastric malady struck after he consumed fruit and iced milk at a July 4th celebration.

Slavery was the issue of the day, and Taylor was a unionist, so some suspected he might have been poisoned by pro-slavery conspirators. In 1991, Taylor's descendants agreed to have Old Rough and Ready's body exhumed for chemical analysis.

Hair and nail samples were sent to ORNL, where researchers Frank Dyer and Larry Robinson of what was then the Analytical Chemistry Division subjected them to neutron irradiation in the High Flux Isotope Reactor.

Dyer had previous experience with investigations of presidential deaths. He was part of an ORNL team that analyzed bullet samples from the Kennedy assassination and confirmed they came from the same gun.

*Larry Robinson (left) and Frank Dyer.* Image credit: ORNL

All human bodies have traces of arsenic, so the amount of arsenic in Taylor's remains was key. Robinson, who went on to become president of Florida A&M University, and Dyer sent their results to a medical examiner in Kentucky, who determined that Taylor's arsenic levels were hundreds of times lower than what would have been necessary to kill him.

Whatever killed Taylor—most likely dysentery or cholera, which was in an outbreak at the time—neutron science ruled out arsenic poisoning for all but the most steadfast conspiracy theorists.

*ORNL's Henry Wilson studies the composition and mobility of trace contaminants found in residues from various coal conversion processes.* Image credit: ORNL

*NEW CHALLENGES, page 45*

*Microscopy*

Advances in microscopes enabled new discoveries in biology and materials. Sophisticated electron microscopes allowed researchers to peer inside the cell and observe and image proteins and DNA. In 1967, a high-powered experimental microscope allowed ORNL researchers to observe genes making RNA in frog eggs. Using an electron microscope in 1974, researchers discovered the nucleosome, which revealed how DNA is wrapped and packaged into chromosomes in the cell nucleus.

*At ORNL, new user facilities welcomed thousands of scientists each year from universities and industry to use the lab's unique, state-of-the-art resources.*

New imaging techniques also improved the study of materials, contributing to the lab's development of strengthened steel alloys and heat-resistant ceramics. In the early 1970s, transmission electron microscopy was used to study radiation damage in metallic structural alloys for breeder and fusion reactor applications. Other microanalytical tools followed, and in 1977, ORNL created the Shared Research Equipment User Facility, sponsored by DOE's Basic Energy Sciences program, to provide access to its state-of-the-art resources for examining metallic, ceramic and other structural materials. In 1987, ORNL opened the High-Temperature Materials Laboratory user facility with cutting-edge microscopes and laboratories for solving materials problems limiting the efficiency and reliability of advanced energy conversion systems. Industry and university collaborations at HTML led to new and improved materials for electronics, superconducting magnets, energy-efficient engines and other demanding applications.

ORNL scientists not only used microscopes to make discoveries but also improved the microscopes themselves. During the 1980s, researchers created a method to precisely curve crystals for focusing 20 times more X-ray radiation than other imaging sources at the time, and their method came to be used in X-ray facilities worldwide. In 1998, ORNL researchers developed the MicroCAT scanner, an X-ray computed-tomography system designed for rapid and accurate mapping of the internal organs of mice and other small animals used in biomedical research. The scanner was commercialized and has since been used by universities and companies for medical research.

In 2006, researchers from ORNL and industry increased the speed and accuracy of atomic force microscopy, used to map the fine-grained surface of materials, by inventing a new technique, band excitation scanning probe microscopy. That same year ORNL opened a new user facility, the Center for Nanophase Materials Sciences, to provide cutting-edge microscopy and imaging resources for scientists creating, studying and manipulating materials at the molecular level.

*See NEW CHALLENGES, page 50*

# Pioneering mass spectrometry

by Leo Williams
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*Analytical chemist and future deputy for science and technology Michelle Buchanan works with Knoxville police fingerprint specialist Art Bohanan to understand that children's fingerprints contain more volatile chemicals than adults' and, therefore, disappear more quickly than adults' fingerprints in crime scenes.* Image credit: ORNL

You can gain a lot by creating and sorting ions.

Mass spectrometry, as the technique is known, was the basis for the calutrons at the nearby Y-12 Plant that enriched uranium for Little Boy, the bomb dropped on Hiroshima, and it continues be a powerful analytical tool today.

"From the very origins of the Manhattan Project in Oak Ridge, mass spectrometry was a key technology, although we didn't call it mass spectrometry back then," explained Michelle Buchanan, ORNL's deputy for science and technology.

Besides separating isotopes, it's a powerful tool for determining the relative abundance of isotopes, providing both quality control and a means of verifying that governments abide by agreements not to create bomb-grade uranium.

In the 1970s, ORNL researchers worked with the new Environmental Protection Agency to use mass spectrometry to identify contaminants. Mass spectrometry also identified hazardous materials in tobacco smoke and coal liquids.

Buchanan came to ORNL in 1978, leading the lab's Organic and Biological Mass Spectrometry Group for more than a decade and bringing mass spectrometry to biology research at the lab.

Over the years, ORNL researchers have developed and perfected a variety of mass spectrometry techniques, from small devices for the Army to detect chemical and biological weapons to tandem methods for biological analysis that connect two consecutive devices.

In 1994, Mike Ramsey and Stephen Jacobson of the Chemical and Analytical Sciences Division invented a "lab-on-a-chip" to provide a quick and cheap method for DNA sequencing. As thin as a microscope slide, it uses a process called electrokinetic transport, in which charged molecules are separated by size and electric charge, exposed to a fluorescent dye, then sorted by light intensity for computer analysis.

More recently, a team led by Gary Van Berkel invented a self-cleaning mass spectrometry device that requires no sample preparation or laboratory expertise, making it attractive for a wide range of applications such as food and water safety, forensics, and disease diagnosis. The Open Port Sampling Interfaces for Mass Spectrometry technology was commercialized in 2016.

"The best thing about it is it can't be easily fooled," Buchanan said, "because you are actually measuring a mass. It's the gold standard for identifying unknown compounds."

*NEW CHALLENGES, page 48*

*Computing*

Although ORNL in the 1950s was home to two of the world's largest "electronic brains," or vacuum-tube computers, computing resources lagged during the 1970s and '80s. Nevertheless, ORNL researchers developed computer programs to model nuclear structures, recreate crystal structures in 3D, enhance nuclear criticality safety, model the transport of radiation through organisms, simulate fusion plasmas and analyze the energy efficiency of home appliances, among other programs.

By the end of the 1980s, however, materials researchers and nuclear scientists were running into a significant problem: Confirming their theories and calculations with laboratory experiments was becoming increasingly difficult. Despite powerful microscopes and accelerators, scientists needed to test theories that reached across many physical scales—from the behavior of small particles to large complex processes like climate.

Scientists across the nation were encountering the same problem, and in 1991, Congress signed the High-Performance Computing and Communication Act, which called for government funding to create supercomputing centers at the national labs. Several labs, including ORNL, and partnering universities submitted a proposal describing their scientific computing needs, citing materials modeling, quantum structure and groundwater remediation. By the early 1990s, ORNL researchers already had a stake in high-performance computing due to their development of Parallel Virtual Machine software that could help computing codes scale across many linked (or parallel) computers. The lab's materials scientists were also writing record-breaking codes for computing material structures that leveraged parallelism to increase their problem size.

In the following years, ORNL built massive supercomputers with industry partners such as Intel, IBM and Cray. In 1992, ORNL launched the 5-gigaflop Intel Paragon, which computed 5 billion calculations per second. The Paragon was later upgraded to a 150-gigaflop system, the fastest in the world at the time.

In 1999, ORNL introduced the first teraflop system in the DOE Office of Science, an IBM Power3 supercomputer called Eagle, followed by an 18-teraflop Cray system called Phoenix. In 2004, the computing center was designated DOEs first Leadership Computing Facility. Thousands of researchers from around the world have accessed its top-ranked supercomputers for solving the largest computational problems in science. The lab's contractor, UT-Battelle, built a new computing building in 2003 to house even larger supercomputers, including the No. 1 systems in the world in 2009, 2012 and 2018, the 3.3-petaflop Cray XT5 Jaguar, the 27-petaflop Cray XK7 Titan and the 200-petaflop IBM AC922 Summit, respectively.

> *By the early 1990s, ORNL researchers already had a stake in high-performance computing due to their development of Parallel Virtual Machine software that could help computing codes scale across many linked (or parallel) computers.*

*Neutrons*

Building on neutron diffraction experiments performed by Ernest Wollan and Clifford Shull at the Graphite Reactor, ORNL researchers continued to push their understanding of the structure and dynamics of materials, study the elementary properties of the neutron and develop new experimental techniques. A triple-axis spectrometer at the Oak Ridge Research Reactor, which began operating in 1958, revealed new information about the dynamic properties of solids and the interatomic forces in crystals. A future Nobel laureate, Norman Ramsey of Harvard University, came to ORNL during the 1960s to study the electrical charge characteristics of neutrons at the ORR in collaboration with a team of ORNL researchers.

Dense streams of neutrons from HFIR illuminated not only crystal structures but also the excited states of atoms, and the high-flux facility's triple-axis spectrometers supported research, first in low-temperature superconductivity and magnetism, then in high-temperature superconductivity. In 1980, the National Center for Small-Angle Scattering Research opened at HFIR; this early user facility offered researchers access to both X-ray and neutron scattering for comprehensive studies of material structure and behavior, and its sensitive detectors improved scattering measurements.

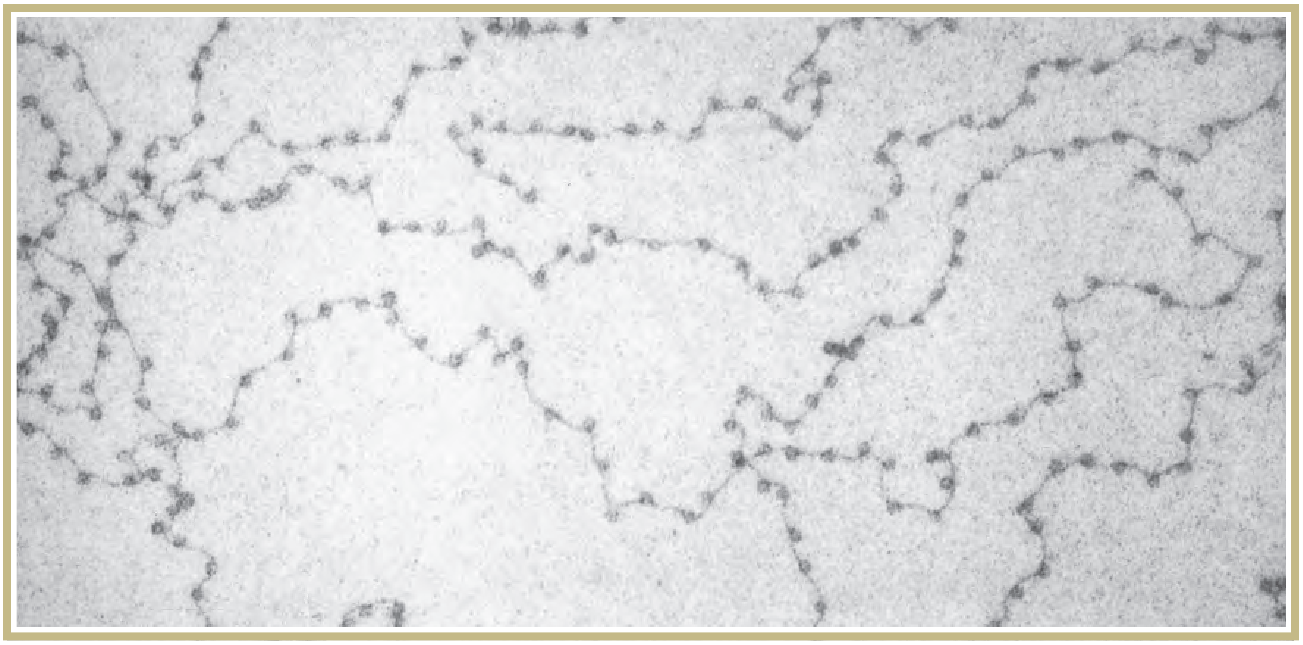
At the turn of the century the lab began the construction of a preeminent neutron science facility that would permit hundreds of users to study materials at specialized instrumentation stations. The Spallation Neutron Source, providing the world's most intense pulsed neutron beams, was completed in 2006. Simultaneously, HFIR was upgraded with new instruments and a cold neutron source. Together, SNS and HFIR are a one-of-a-kind neutron science complex for researchers studying a range of materials at different conditions, such as extreme pressure or magnetism.

*Technology today*

As the lab entered the 21st century, the nation once again encountered grave national challenges, including the terrorist attacks of September 11, 2001, devastating natural disasters, and public health crises. In this century, ORNL remains a unique national resource with experts who are called to solve these great challenges.

# Beads on a string:

# Discovering the nucleosome



*University of Tennessee and ORNL researchers Ada and Don Olins discovered the nucleosome by electron microscopy in the 1970s, publishing their results in a 1974 issue of* Science. Image credit: Ada Olins and Donald Olins, University of Tennessee/Oak Ridge Graduate School of Biomedical Sciences

by Kim Askey
askeyka@ornl.gov

In the early 1970s, scientists at laboratories worldwide raced to unravel the mystery of how billions of miles of DNA are packaged inside the cells of the human body.

ORNL's Don and Ada Olins were the first to discover the critical structure—the nucleosome—that winds DNA around proteins like thread around a spool.

The Olinses, a husband-and-wife research team in ORNL's Biology Division and professors at the University of Tennessee–Oak Ridge Graduate School of Biomedical Sciences, used electron microscopy to identify the nucleosome structures, describing them as "beads on a string." This compact, orderly structure is at the heart of our genetic makeup as it forms the fundamental, repeating unit in chromosomes.

Capturing images of the nucleosomes and deducing their structure was no easy feat. The Olinses used an ORNL-developed method to study genetic material from chicken blood, rat liver and calf thymus with electron microscopy. They published groundbreaking micrographs in *Science* in 1974 along with a proposed nucleosome structure (a dyad particle, like DNA, with pairs of basic proteins called histones) that was later confirmed.

The couple, who sign their communications with the apt shorthand "DnA," continue to study these structures at the University of New England.

The discovery of the nucleosome revolutionized perceptions of DNA and DNA-related processes, including how genes are transcribed, replicated, repaired and expressed. It is a legacy that impacts research at ORNL today as scientists examine complex relationships among genes, the environment and physical traits, in fields as diverse as bioenergy and human health.

# 14 achievements in leadership computing at ORNL

*The Intel Paragon XP/S 150 with future Oak Ridge Leadership Computing Facility Program Director Buddy Bland.* Image credit: Curtis Boles, ORNL

## Parallel Virtual Machine

ORNL writes the first version of Parallel Virtual Machine, a software tool that enables a collection of heterogenous computers to be used in parallel to solve large computational problems.

1989

1995

## Intel Paragons

After receiving the Intel Paragon XP/S 5 and XP/S 35 in 1992, ORNL accepts the 150-gigaflop Intel Paragon XP/S 150, the fastest machine in the world when it is delivered, able to perform 150 billion calculations a second.

## Quantum Materials

Using the LSMS electronic structure code for materials, a team led by Malcolm Stocks calculates the total energy of copper by modeling as many as 1,024 atoms on the Intel Paragon XP/S 150.

1999

## Eagle Takes Flight

The IBM RS/6000 SP Eagle initially operates at a peak performance of 99.2 gigaflops but will become the first Office of Science system with a peak performance exceeding 1 teraflop (1 trillion calculations per second) in 2000.

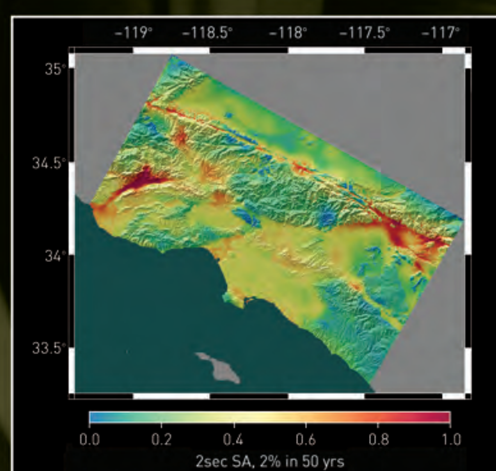
2005

## Phoenix Soars

ORNL accepts the 18.5-teraflop Cray X1E Phoenix, capable of 18.5 trillion calculations per second, which will be used to solve "grand challenge" science problems in areas such as combustion, plasma energy research, and accelerator design.

## Jaguar Era

A series of Cray machines, the Jaguar systems evolve from the Cray XT3 to the XT5, which will become the fastest supercomputer in the world on the TOP500 in 2009 at 1.78 petaflops, or about 1.8 thousand trillion calculations per second.




*Earthquake simulation shows the Los Angeles area.* Image credit: Southern California Earthquake Center

### The Milky Way

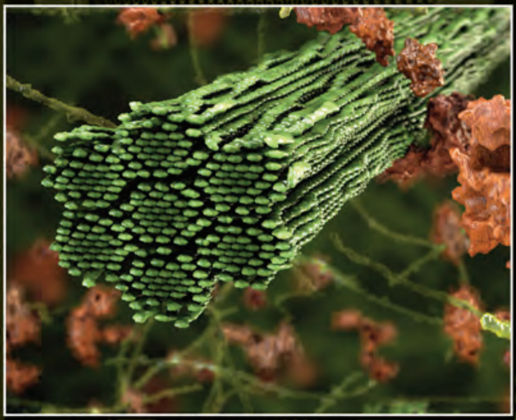
Using the Cray XT3 Jaguar, a team led by Piero Madau carries out the largest simulation ever of the Milky Way's dark matter and its evolution over 13 billion years.

### Detailing Combustion

Jackie Chen's combustion simulations on the Cray XT4 Jaguar—and later the Cray XK7 Titan—help pave the way for automobiles that could use 25 to 50 percent less fuel than those today.

### Biomass to Biofuel

Jeremy Smith uses the Cray XT5 Jaguar and, eventually, the Cray XK7 Titan to capture interactions between major components of the plant cell wall to provide insights for biofuel researchers.



A graphical representation of lignocellulosic biomass. Image credit: Thomas Splettstoesser, scistyle.com


ORNL's Summit supercomputer is the world's fastest. Image credit: Carlos Jones, ORNL

### Advances in AI

Dan Jacobson and Wayne Joubert run a comparative genomics calculation on Summit at 1.88 exaops, nearly 2 billion billion calculations per second, using mixed precision calculations.

### Stepping up to Summit

The IBM AC922 Summit, a 200-petaflop system featuring NVIDIA V100 GPUs, hits #1 on the TOP500 list in June 2018 with a LINPACK benchmark performance of 122.3 petaflops.

2007 2010 2012 2018

### Earthquake Simulations

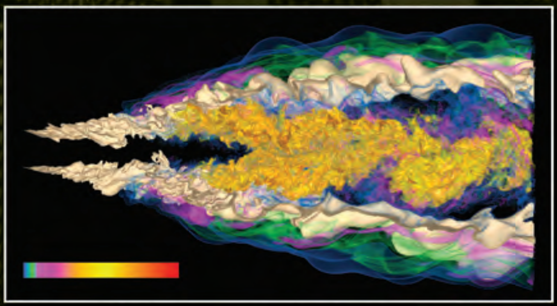
Thomas Jordan performs simulations on the Cray XT5 Jaguar and, ultimately, on the Cray XK7 Titan to predict the intensity of ground shaking in earthquake prone Southern California.

### SmartTruck

A collaborative team uses the Jaguar supercomputer to create "SmartTruck" add-on components for Class 8 tractors and trailers that decrease drag and increase highway fuel efficiency by more than 10 percent.

### Unveiling Titan

The Cray XK7 Titan supercomputer becomes #1 on the TOP500 list 2 months after it is launched.



Combustion simulation. Image credit: Jacqueline Chen, Sandia National Laboratories

Image credit: Brett Hopwood, ORNL

# ORNL in the 21st century and beyond

by Leo Williams
williamsjl2@ornl.gov

ORNL was built on Big Science—a term coined in 1961 by Alvin Weinberg—and 75 years later the lab is still dedicated to that approach.

By gathering thousands of talented scientists and engineers and giving them access to uniquely powerful research facilities, ORNL accelerates both our access to fundamental knowledge and our society's ability to use that knowledge to provide clean, new technologies.

Seventy-five years ago, the lab hosted the world's first permanent nuclear reactor—the Graphite Reactor—and helped bring World War II to an end. Today, ORNL is home to a range of facilities that make Oak Ridge a focus for research into supercomputing, materials, manufacturing, nuclear science and myriad other fields. It stands up world-class research facilities—many of which are beyond the means of even the largest universities—and provides them to more than 3,000 scientists each year from universities, government laboratories and private industry.

Consider:

- ORNL's Summit supercomputer is the most powerful system in the world, capable of 200 million billion calculations each second.
- The Spallation Neutron Source provides the most intense pulsed neutron beams in the world, while the High Flux Isotope Reactor is the country's highest flux reactor-based source of neutrons for research.
- The Center for Nanophase Materials Sciences provides world-class microscopes and other equipment, allowing users to study and manipulate materials at the scale of atoms and molecules.
- The Manufacturing Demonstration Facility is pushing boundaries in 3D printing, carbon fiber technology, materials composites and battery technology.

## Supercomputing and artificial intelligence

ORNL scientists not only operate the world's most powerful supercomputer, they are also pioneering a computing future that will look very different from the field as we've come to know it.

> *"Computing has fundamentally changed the way that we do big science. Twenty years ago, people were saying modeling and simulation was the third leg of science, on equal footing with experiment and theory. Now you don't write down equations. You've got data, and you use the data to create models. So all of a sudden, the way we do science has fundamentally shifted again. Data science has become the fourth paradigm of scientific discovery."*
>
> — ORNL Associate Laboratory Director for Computing and Computational Sciences **Jeff Nichols**

Two especially promising areas are artificial intelligence and quantum computing.

Data scientists are taking the enormous power of Titan and using it to solve problems in ways that were previously unheard of. Traditionally, scientific computing involves simulating a problem using a model derived by researchers from first principles—usually solutions from partial differential equations. In the new world of artificial intelligence, supercomputers use big datasets to develop models from the data—many times automatically—without a scientist's input.

*See ORNL IN THE 21ST CENTURY AND BEYOND, page 56*


*The klystron gallery supplies power to SNS's linear accelerator by taking electricity from the main power lines and converting it to the levels needed to power various linac accelerating modules located directly underneath.* Image credit: Genevieve Martin, ORNL


*ORNL's Summit is the world's most powerful supercomputer.*
Image credit: Carlos Jones, ORNL

*ORNL IN THE 21ST CENTURY AND BEYOND, page 54*

"Computing has fundamentally changed the way that we do big science," said Jeff Nichols, ORNL's associate laboratory director for computing and computational sciences. "Twenty years ago, people were saying modeling and simulation was the third leg of science, on equal footing with experiment and theory. Now you don't write down equations. You've got data, and you use the data to create models. So all of a sudden, the way we do science has fundamentally shifted again. Data science has become the fourth paradigm of scientific discovery."

*See ORNL IN THE 21ST CENTURY AND BEYOND, page 58*

# The growth of computing at ORNL

by Leo Williams
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What do you do when you can't test your technology?

The United States faced that question when it halted nuclear weapons testing in 1992. The answer came in the form of virtual tests using high-performance computers.

Although "stockpile stewardship," as it was known, drove the rapid development of massively parallel supercomputers, it was certainly not the only scientific discipline to benefit from them.

One person to see further potential in scientific computing was Alvin Trivelpiece, ORNL's director through the '90s. Current lab Director Thomas Zacharia credits Trivelpiece with placing ORNL on the road to becoming a major supercomputing power.

Trivelpiece recruited Ed Oliver, who created ORNL's new Office of Laboratory Computing. It was Oliver who asked Zacharia in 1998 to step in as director of the lab's Computer Science and Mathematics Division, a position others had turned down.

"He said, 'Most likely you'll fail in six months. Don't worry about it. I'll find you another job somewhere else,'" Zacharia recalled. "So that was my interview."

*Thomas Zacharia, now ORNL lab director, headed an ORNL research team that dismantled, measured and weighed each component of a new Ford Explorer to create a computer model and run simulated crash tests.* Image credit: ORNL

Needless to say, Zacharia did not fail, and in 2002 he became ORNL's first associate laboratory director in the new Computing and Computational Sciences Directorate. For all of the past dozen years, ORNL has had supercomputers among the world's 10 most powerful—including the world's fastest with Jaguar in 2009 and Titan in 2012. The lab's newly unveiled Summit system is again the world's fastest as well as an ideal tool for developing the growing field of artificial intelligence.

Along the way, ORNL's strength in supercomputing has aided scientists both around the world and around the lab, and it has become central to the lab's identity.

"Seventy percent of the scientific staff today at Oak Ridge National Laboratory have been here less than 10 years," Zacharia noted. "They have joined Oak Ridge National Laboratory knowing and expecting Oak Ridge National Laboratory to be a preeminent computing institution in the world."

*ORNL IN THE 21ST CENTURY AND BEYOND, page 56*

## Turning particles into computers

While big data research is taking traditional systems in new directions, quantum computing researchers are working on systems unlike anything we've seen.

You can make a quantum computer out of any particle that obeys the laws of quantum mechanics: an atom, say, or a photon, or an electron. As a result, early development of these systems is taking a variety of directions, according to Travis Humble, who leads ORNL's quantum computing research team.

Quantum computers are fundamentally different from the computers that most of us know. Whereas a standard computer chip recognizes information as a series of bits (1s and 0s), a quantum computer recognizes the wave form of a quantum particle, otherwise known as a qubit (pronounced CUE-bit).

> *"We've already seen that quantum computers would be capable of solving some problems in the simulation of physics, biology, chemistry, much more quickly. A key challenge, though, is how will those types of computers integrate with our existing ways of solving problems?"*
>
> — ORNL quantum computing scientist **Travis Humble**

The differences continue. Because a qubit is quantum, it behaves strangely. The Heisenberg uncertainty principle dictates that we can't know its position and its momentum at the same time. The principle of superposition tells us that it can be in mutually exclusive states at the same time—for instance, spinning in opposite directions. And because quantum data cannot be copied and pasted, quantum computer users have to learn new tricks for programming.

Nevertheless, these systems—now in very early stages of development—hold the potential to make a big impact on scientific computing applications. Recently, an ORNL team demonstrated the first application of quantum computing to nuclear physics.

"We've already seen that quantum computers would be capable of solving some problems in the simulation of physics, biology, chemistry, much more quickly," Humble said. "A key challenge, though, is how will those types of computers integrate with our existing ways of solving problems?"

## Exploiting the neutron

ORNL's first neutron scattering research predated the end of World War II—and the name "Oak Ridge National Laboratory."

Ernest Wollan began working with neutron diffraction at the lab's Graphite Reactor in 1944 and was joined by colleague

*See ORNL IN THE 21ST CENTURY AND BEYOND, page 61*

*The target system Inner Reflector Plug at SNS (center right) captures and slows energetic neutrons to the energies needed by scientists. Surrounding it are mechanical shutter drives that open and allow neutrons to strike experimental samples.* Image credit: Genevieve Martin, ORNL


*ORNL's Bernadeta Srijanto outside a clean room at the Center for Nanophase Materials Sciences.*
Image credit: Genevieve Martin, ORNL

*ORNL IN THE 21ST CENTURY AND BEYOND, page 58*

Clifford Shull in 1946. Five decades later Shull and Bertram Brockhouse were jointly awarded the 1994 Nobel Prize in Physics "for pioneering contributions to the development of neutron scattering techniques for studies of condensed matter." Unfortunately, Wollan had died a decade earlier.

Today ORNL is a world center for neutron research and hosts two of the world's leading neutron sources: SNS, which provides the world's most intense pulsed neutron beams, and HFIR, which is the United States' highest flux reactor-based source of neutrons for research. As an added bonus, HFIR also produces much-needed isotopes (see below).

ORNL's neutron facilities are highly sought after by scientists and engineers alike. For every one available research opportunity, there are between two and three applicants.

Health researchers, for example, used neutrons to better understand an enzyme involved in the replication of HIV to make drugs that more effectively treat AIDS. Researchers from Corning used them to study how silica behaves as it heats and cools, the better to design smartphone screens, windshields and TV screens. And NASA and Honeywell Aerospace used them to study alloys for use in aircraft components like jet and rocket engines.

*"We're not just trying to discover the answer to the universe. We do a lot of practical research that involves solving everyday problems, that benefits industry and our everyday lives. Almost every part of your cell phone—the glass screen, the alloy that's used in your cell phone case, the electronic technology, the battery—we contribute to basic research and development of it."*

— ORNL Neutron Sciences Associate Laboratory Director **Paul Langan**

Neutrons are one of two particles found within an atom's nucleus (the other being protons). When neutrons pass through a sample—of an electrical component, a material or a collection of cells, for instance—they scatter much like balls in a microscopic game of pool. By measuring the energies and angles of the scattered neutrons, scientists can glean details about the fundamental nature of materials that cannot be obtained with other techniques.

For example:

- Neutrons have a magnetic moment, like the north and south poles of a magnet. This makes them uniquely sensitive to magnetism at the atomic scale.
- Neutrons are highly penetrating and do not destroy samples, which makes possible the study of materials in more detail, in real time and under more realistic environmental conditions than those of other techniques.
- Being highly sensitive to small atoms such as hydrogen (with only one proton) and lithium (with three protons), neutrons are good at analyzing biological systems and battery materials.

"Neutrons, because they are sensitive to magnetism, because they can see small elements like hydrogen and lithium, because they are highly penetrating, can do things that other techniques can't do," said Paul Langan, ORNL's associate laboratory director for neutron sciences.

Because the lab offers two very different neutron sources—SNS, which delivers pulsed beams, and HFIR, which delivers a continuous beam—as well as over 30 world-leading neutron scattering instruments, researchers are able to choose what facility or instrument best suits a given project, Langan explained.

A neutron scattering sample can even be alive, as when an ORNL team performed the first-ever direct nanoscale examination of a living cell membrane. Or it can be moving, as when another ORNL team used neutrons to look at the performance of a new aluminum alloy in a running engine.

Langan stressed that neutron research at ORNL encompasses both basic science and applied engineering.

"We're not just trying to discover the answer to the universe," he said. "We do a lot of practical research that involves solving everyday problems, that benefits industry and our everyday lives. Almost every part of your cell phone—the glass screen, the alloy that's used in your cell phone case, the electronic technology, the battery—we contribute to basic research and development of it."

## Exploring materials, atom by atom

The most exciting research in materials tends to take place at the scale of atoms and molecules—otherwise known as the nanoscale. Much of what you observe in this world obeys the strange laws of quantum mechanics, where each particle is also a wave. In addition, nearly every atom of a nanoparticle is near that particle's surface, where the chemistry takes place.

"In most materials, only a tiny percentage of all of the atoms will see the neighboring material, because they're on the inside," noted Hans Christen, who was until recently CNMS director. "At the nanoscale that's not the case. If you make your material small enough, almost all of the atoms are close to the surface. So that fundamentally changes the chemical interactions."

Researchers from ORNL and around the world gather at CNMS to explore matter at this tiny scale. The center hosts a

*See ORNL IN THE 21ST CENTURY AND BEYOND, page 62*

ORNL materials scientist Kinga Unocic with a scanning electron transmission microscope. Image credit: Jason Richards, ORNL

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staff of materials experts and a variety of world-class equipment and facilities, including electron microscopes, scanning probe microscopes, and fabrication and synthesis laboratories.

With that combination of talent, equipment and facilities, researchers are able explore not only where the atoms are but also what they are doing.

At that scale, for instance, materials can sometimes be combined to do a job that neither is good at alone. That's what happened when ORNL researchers developed a catalyst consisting of copper nanoparticles embedded in carbon spikes. While neither carbon nor copper is an especially good catalyst, this new structure was able to convert carbon dioxide—a greenhouse gas—into ethanol.

In another project, researchers used an electron beam to place a silicon atom into a graphene structure, opening the door to unbelievably fine manipulation of materials.

"It's not quite like playing with Legos," Christen explained. "You have to know how to remove things and how to move things around so that the material will do what you want it to do. Understanding that interaction between an electron beam and a solid is not a trivial thing."

## Keeping people healthy and happy

Much of ORNL's work can improve human health and wellbeing. For instance, the ability to crunch huge datasets offers a wide variety of highly practical applications, ranging from population studies to the treatment of diseases.

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# ORNL hosts VIP visitors

by Bill Cabage
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In 1959, then-Senator John F. Kennedy and his wife, Jacqueline, became surely the most glamorous couple ever to stand on the viewing platform of the Oak Ridge Research Reactor.

The Kennedys are just two of the host of dignitaries from around the world who have made ORNL a destination because of its pioneering role in the peaceful uses of atomic energy and its global leadership in science.

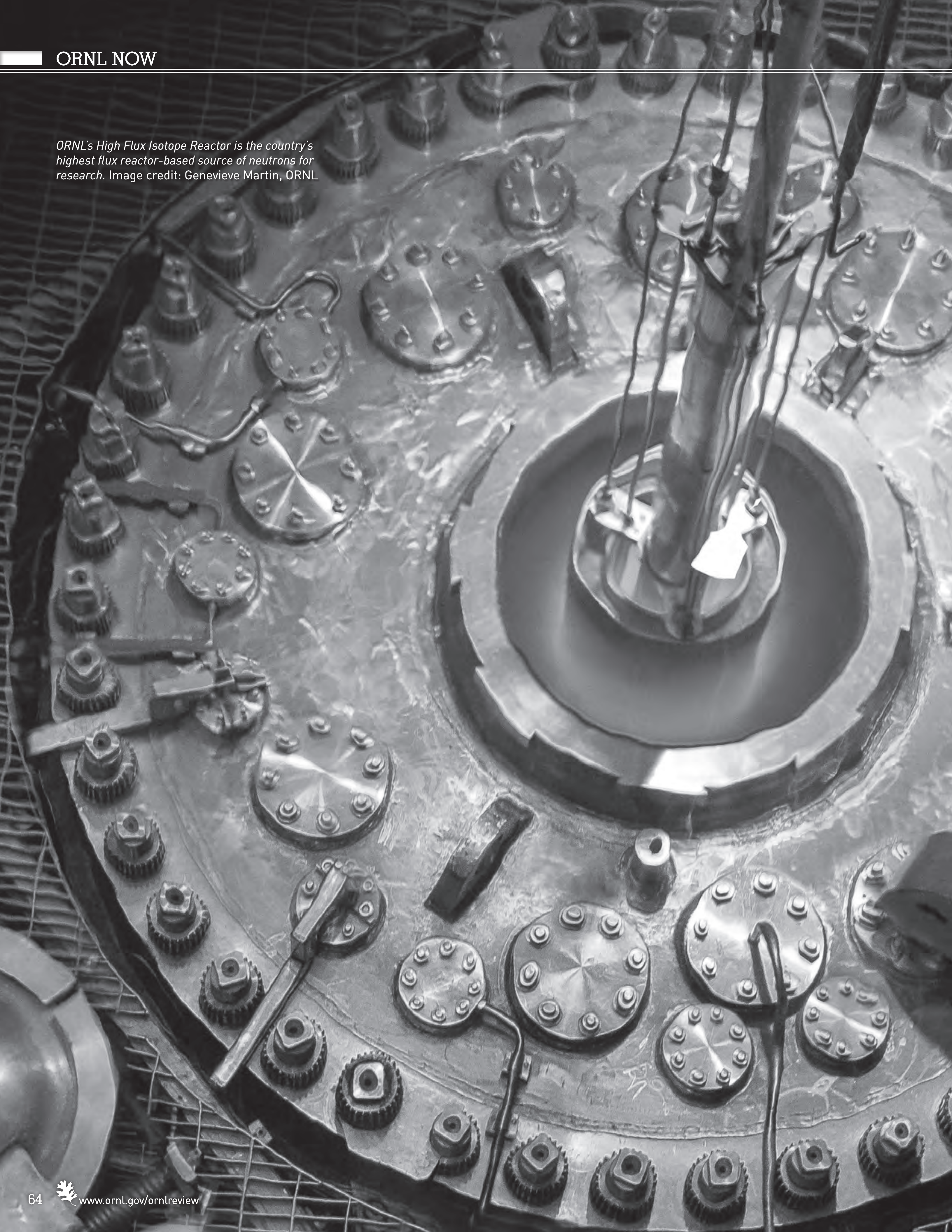
Presidents Jimmy Carter, George H.W. Bush and George W. Bush spoke here in 1978, 1992 and 2004, respectively. Vice President Hubert Humphrey visited in 1965, and Vice President Al Gore, a Tennessee native, made a couple of visits.

Other prominent political visitors have included Lyndon Johnson and Gerald Ford (before either was president), Albert Gore Sr., favorite-son-senator and Ambassador Howard Baker (several times), and Ambassador Andrew Young.

Royalty have dropped in as well. Former King Leopold of Belgium visited in 1957, Queen Frederika of Greece in 1958, a young King Hussein of Jordan in 1959, and King Bhumibol Adulyadej of Thailand in 1960. International visitors also included Ambassador Indira Nehru (later Prime Minister Indira Gandhi) of India in 1963.

Renowned physicist and Fermilab architect Robert Wilson spoke in 1999. Visiting Nobel Laureates include Glenn Seaborg, Gertrude Elion and Leon Lederman. Nobel winners Harry Kroto and Bill Phillips gave lectures in the 1990s, then returned as two of the eight Nobelists who have given Eugene P. Wigner Distinguished Lectures since the lecture series was established in 2014.

*Then-Sen. John Kennedy and Jacqueline Kennedy visit the Homogeneous Reactor Experiment in 1959 with ORNL Director Alvin Weinberg.* DOE photo by Ed Westcott



*ORNL's High Flux Isotope Reactor is the country's highest flux reactor-based source of neutrons for research.* Image credit: Genevieve Martin, ORNL

*ORNL IN THE 21ST CENTURY AND BEYOND, page 62*

ORNL's Geographic Information Science and Technology group uses satellite data—along with information such as social media and cellphone use—to identify where people are across the globe.

The effort is especially important for remote areas in underdeveloped and developing countries, noted GIST group leader Budhendra Bhaduri, because countries in the Southern Hemisphere often do not have good census data.

The group is mapping every building on the globe from satellite images with a resolution of half a meter—about 20 inches—and using that information to predict where people live and in what densities. Along the way it has identified human settlements that were unknown to public officials.

"It's a unique challenge," Bhaduri said, "because 3 percent or less of the world's landmass is actually populated by humans, so when you're trying to find where people are, it's much harder than it sounds."

The information produced by this effort helps both in the short term—for instance, in knowing where to send help in case of a disaster—and in the longer term, by informing the location of infrastructure and services.

As an example, ORNL has teamed with the Bill & Melinda Gates Foundation to estimate the locations of children under 5 years old in Nigeria, so they can be vaccinated against polio. The collaboration is indispensable, Bhaduri noted, because Nigeria's last official census was a dozen years back, in 2006, and the last official population estimate was in 2012.

Looking forward, he said, researchers are working to understand how they can process a new global collection of images each day, providing what he calls dynamic observation and analysis. The images will have resolutions of 5 meters or finer. It will be a big job.

"When you have 700 trillion pixels thrown at you every day, there are a lot of stories that are captured in those pictures," he added.

## Keeping track of cancer

ORNL's data skill also allows health researchers to improve our approach to cancer and other diseases.

Working with the National Cancer Institute, an ORNL team is developing the means to automate and scale the collection of cancer information from state cancer registries around the country.

Cancer is a reportable disease, meaning all diagnosed cancer cases in a given state are reported to the state's cancer registry, explained Gina Tourassi, leader of ORNL's Biomedical Sciences, Engineering, and Computing group. From the time a case is diagnosed, the patient's progress is followed step by step, through every procedure and every diagnosis.

> *"The legacy of Oak Ridge is turning science to manufacturing—taking fundamental scientific discovery and scaling it up to full-scale manufacturing. That's what the Manhattan Project was all about. Nowhere else is there this conglomeration of fundamental scientific tools and talent that, brought together, can really leapfrog the world in terms of additive manufacturing."*
>
> — ORNL Manufacturing Systems Research Group leader **Lonnie Love**

Cancer registries rely on manual review of clinical documents to collect patients' information. This is laborious and time-consuming, particularly as the number of cancer cases grows.

In response, Tourassi and colleagues have developed artificial intelligence tools to automate information collection. Effectively, the ORNL team trains computers to understand complex cancer reports and pull out the relevant information. Currently the researchers are working with experts to validate the process, improving it iteratively to meet rigorous standards.

"This is one of those AI applications where the performance bar is very high," Tourassi said. "There is no room—or there is very little room—for error. I would put it on the same level as the self-driving cars; the room for error is very low."

Tourassi noted that the AI tools being developed are applicable not only to cancer but also to a wide range of other health crises that require time-efficient and accurate comprehension of clinical text documents, including Alzheimer's disease and opioid and other drug addictions.

## Isotopes for a better world

Enhanced human health is only one of the benefits we get from the production of isotopes at ORNL. This program produces isotopes for medical, industrial and even interplanetary purposes.

For example,

- ORNL is the primary producer of californium-252, which is used by industry to determine the potential of new oil wells and for calibrating radiation detectors.
- ORNL produces actinium-225, actinium-227 and other medical isotopes that are showing promise in treating a variety of cancers.

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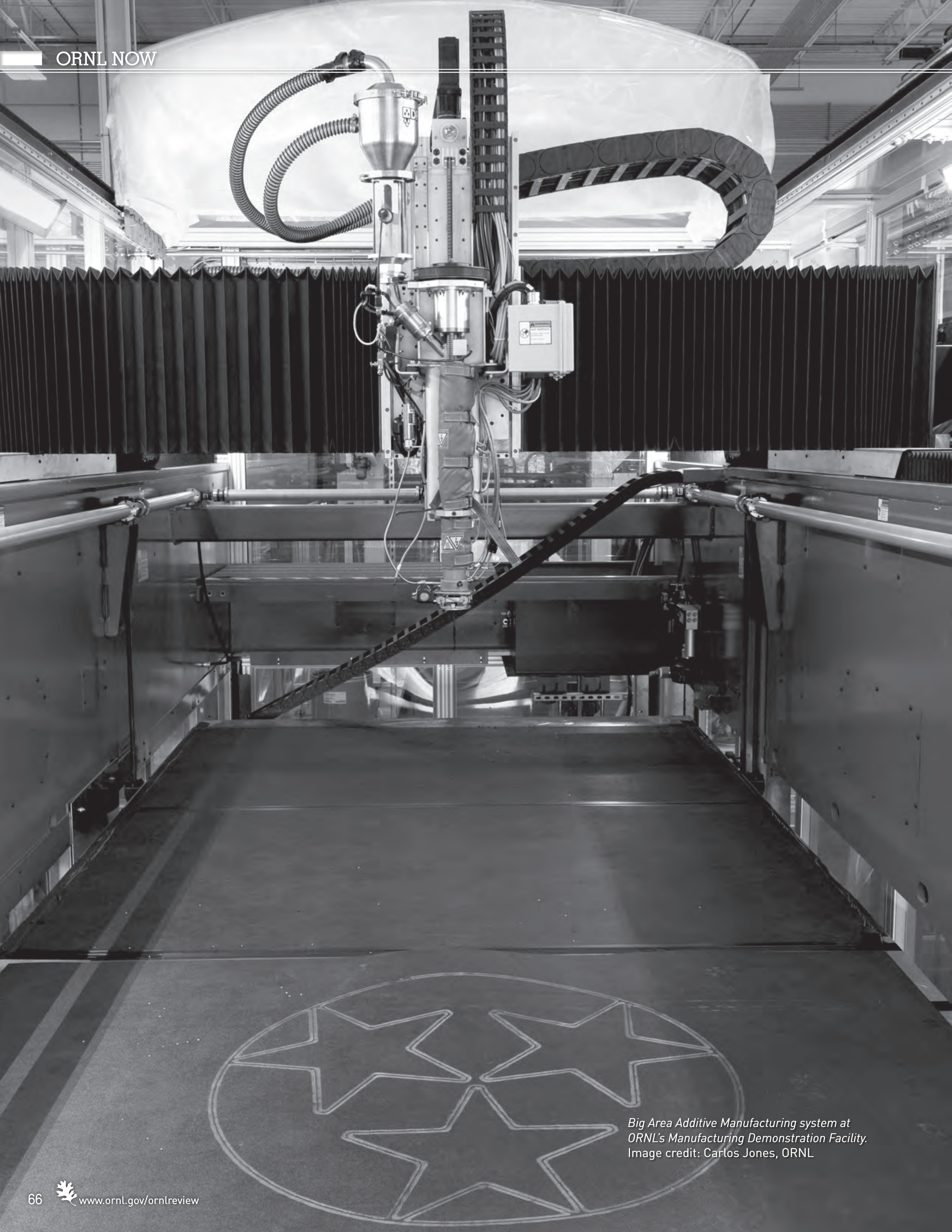

*Big Area Additive Manufacturing system at ORNL's Manufacturing Demonstration Facility.*
Image credit: Carlos Jones, ORNL

# Materials for nuclear environments

by Leo Williams
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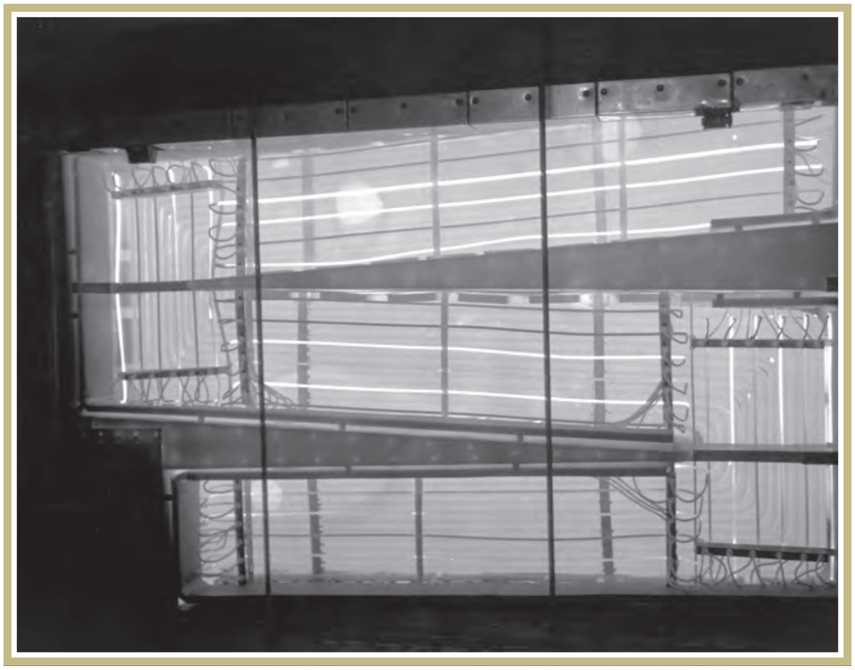
ORNL's nuclear pioneers understood early on that this new technology would demand the hardiest of materials.

Nuclear reactors—with high temperatures and pressures, corrosive and oxidizing liquids, and heavy neutron bombardment—are a uniquely hostile environment for the materials that go into their fuels, reactor vessels and other equipment.

Eugene Wigner made the point in a 1946 paper in the *Journal of Applied Physics*: "Clearly, the collision of neutrons with the atoms of any substance placed into the pile will cause displacements of these atoms."

As a result of these challenges, ORNL's mission since the 1950s has included a focus on the materials used in nuclear environments.

"That's something that ORNL has been in the forefront of ever since," noted Jeremy Busby, director of the lab's Materials Science and Technology Division. "We've worked on water reactors, molten-salt reactors, gas and sodium reactors, reactors for submarines and aircraft carriers. We've dabbled with aircraft and spacecraft applications. We're a leading laboratory in the United States for fusion. So we have a wide range of expertise."

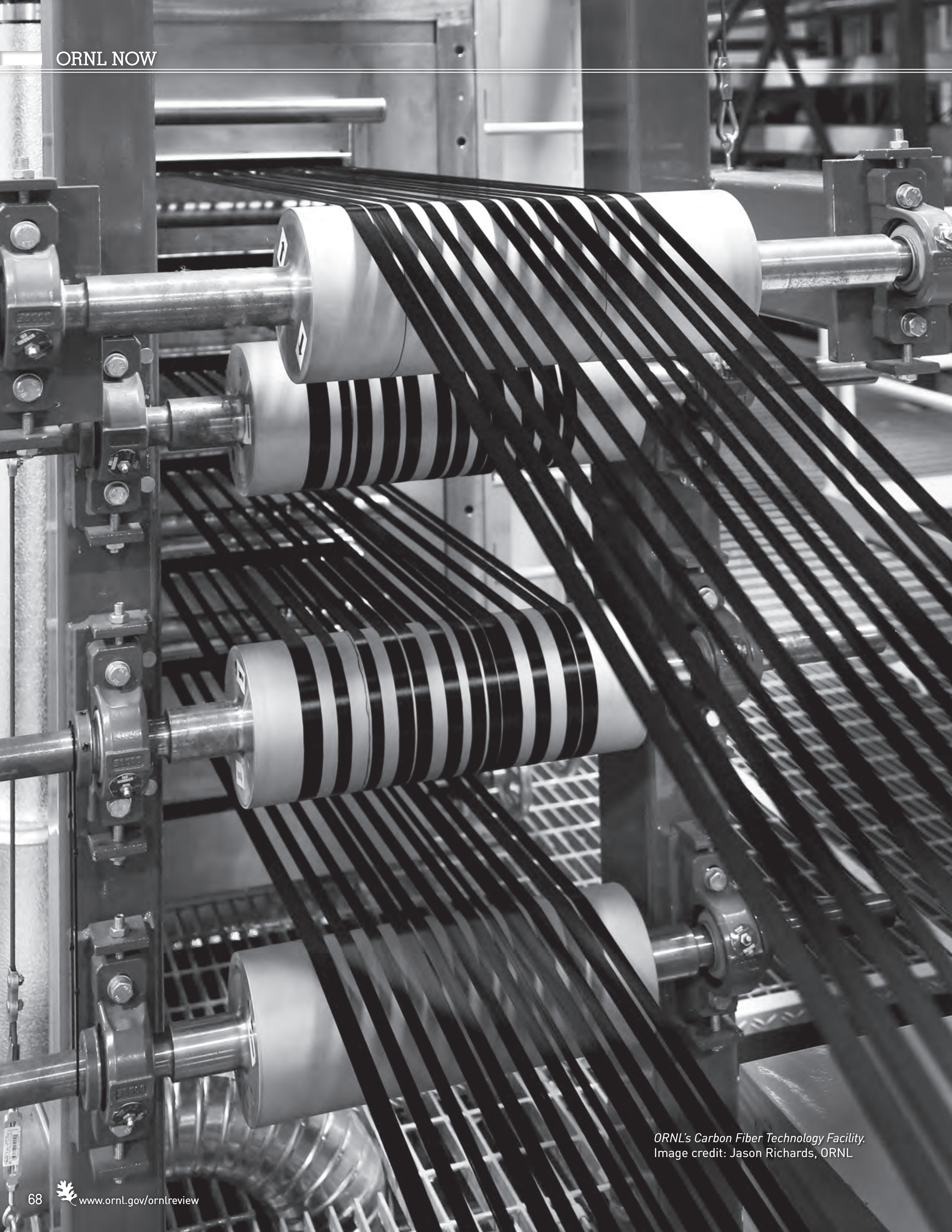


*INOR-8, a nickel-molybdenum-chromium-iron alloy that resists aging, embrittlement, and corrosion from exposure to hot fluoride salts was developed to contain fuel used in the Molten Salt Reactor Experiment.* Image credit: ORNL

In the 1970s and '80s, the lab developed steel alloys containing chrome and molybdenum that made effective pressure vessels. More recently, the lab has worked with DOE, industry and regulators to assess extending the operating lives of America's nuclear reactors.

Busby points to a combination of ORNL's skills and facilities for promoting the lab's preeminence in nuclear materials. The High Flux Isotope Reactor and ORNL's complex of hot cell and radiological facilities allow researchers to irradiate and analyze samples, while the lab's strength in modeling and simulation helps promote a deeper understanding.

"I think pulling all of those pieces together has been a real bonus to solving some of these problems, developing a deeper understanding and providing solutions."



*ORNL's Carbon Fiber Technology Facility.*
Image credit: Jason Richards, ORNL

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- The lab's Stable Isotope Production Facility, equipped with a gas centrifuge production cascade capable of producing kilogram quantities of stable isotopes, is expected to go into production by 2023. Enriched stable isotopes have many medical, R&D and national security uses including being fabricated into targets for the production of radioisotopes used to diagnose and treat cancers and other ailments.
- The lab is ramping up production of plutonium-238, which powers NASA deep space missions.

> *"When you think of carbon fiber cost drivers, there's capital, energy, and raw materials. Raw material is half the cost of the product, so alternative precursors make a very big impact."*
>
> — Carbon Fiber Technology Facility Director **Merlin Theodore**

"We are becoming well recognized for our ability to produce radioisotopes effectively," said Cecil Parks, director of ORNL's Nuclear Security and Isotope Technology Division. "What we want to do is use our science and technology here at the lab to do that in improved ways."

## The tech future is here

Nothing demonstrates the relationship between basic and applied research better than the development of new technology. ORNL scientists and engineers take the lab's expertise in materials research, neutron science and high-performance computing and create both the technologies and the materials that will dominate manufacturing into the next century.

"The legacy of Oak Ridge is turning science to manufacturing—taking fundamental scientific discovery and scaling it up to full-scale manufacturing. That's what the Manhattan Project was all about," said Lonnie Love, leader of ORNL's Manufacturing Systems Research Group. "Nowhere else is there this conglomeration of fundamental scientific tools and talent that, brought together, can really leapfrog the world in terms of additive manufacturing."

### Manufacturing layer by layer

Perhaps the most important manufacturing advances this century will be in 3D printing, known to professionals as additive manufacturing.

ORNL is at the forefront of this technology, demonstrating its prowess by printing cars, buildings, heavy machinery and even a submersible. The lab even earned a Guinness World Record for the world's largest solid 3D-printed item, a trim-and-drill tool for building aircraft.

ORNL's additive manufacturing team works with both metals and polymers. Along the way the team has improved the materials that go into these printed objects, making them stronger and more reliable. Looking forward, ORNL researchers are focusing on new materials tailor-made for 3D printing.

"In the past, most people would ask, for instance, 'Can you 3D print aluminum?'" Love said. "That's really not the right question to ask. The right question is, 'What properties do you need, and can we create materials and structures that are printable and achieve these properties?'"

As the work moves forward, researchers are developing methods to print objects with multiple materials, adding properties such as extra strength where they are needed most.

"We want to look at graded material structures rather than just a monolithic material," said Bill Peter, director of DOE's Manufacturing Demonstration Facility at ORNL. "I could, for instance, build most of a part with a low-carbon steel, but as I go along I could shift that chemistry and go to a higher-carbon steel or other material and grade the properties."

That approach would be useful, for instance, in extreme environments such as reactor vessels in nuclear or fossil-fuel power plants. In such environments, materials that are resistant to oxidation, radiation and high temperature could be strategically placed in exposed areas.

Materials have always been a challenge for additive manufacturing. Because the process involves melting and cooling metals or polymers, there are many opportunities for flaws in a finished product that affect its performance. In response, researchers rely on both neutron scattering and high-performance computing to ensure that materials perform properly.

"We're already using artificial intelligence in our additive manufacturing," noted Vincent Paquit from ORNL's Imaging, Signals and Machine Learning Group. "As you're building parts layer by layer, you're rich in terms of data. The challenge is, can you do real-time analysis of that data and repair defects *in situ* and ultimately control your whole process?"

### Ten times stronger than steel

Another focus of ORNL's manufacturing efforts is the production of low-cost carbon fiber. Carbon fiber is lightweight and as much as 10 times stronger than steel, making it ideal for industries where weight is an issue. The problem is that carbon fiber is also expensive, limiting its use.

A key potential use for carbon fiber is in electric vehicles, where reductions in weight translate directly into increased range for batteries.

"Weight is going to be more and more important," noted Craig Blue, director of ORNL's Energy Efficiency and Renewable Energy program. "With carbon fiber you have the opportunity to

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*ORNL created much of this excavator with 3D printing.* Image credit: Rachel Brooks, ORNL

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decrease the weight of the car chassis by 30 to 50 percent by going to carbon fiber composites."

ORNL's 42,000-square-foot Carbon Fiber Technology Facility is focusing both on carbon fiber precursors—the materials that are turned into carbon fiber—and the ovens and other processing equipment that turn those precursors into usable carbon fiber.

"When you think of carbon fiber cost drivers, there's capital, energy and raw materials," explained CFTF Director Merlin Theodore. "Raw material is half the cost of the product, so alternative precursors make a very big impact."

The traditional carbon fiber precursor is a resin called polyacrylonitrile. Alternatives include textiles—essentially the same materials used to produce carpeting. Carbon fiber researchers are also developing new oven technologies that save both time and space. The goal, Theodore said, is to bring the cost of carbon fiber—which is now around $8.50 a pound—down to $5 or below.

In 2016, ORNL demonstrated and made available for licensing a new production method that researchers estimated could reduce the cost of carbon fiber by as much as 50 percent and the energy used in its production by as much as 60 percent. Companies, including licensees of ORNL's carbon fiber production method, use the CFTF to refine and validate manufacturing processes.

"One of the main hesitations I see from industry is the cost," Theodore said. "If you get the cost down, I really do believe the use of carbon fiber will expand. You have automotive leading demand, then there's aerospace. With that cost point going that low, you may see some new areas emerging."

## Understanding superconductors

ORNL researchers are exploring a variety of materials that could be game changers, but maybe none has as much potential as superconductors—materials that conduct large amounts of electricity with no loss.

Superconductors hold enormous promise. Without resistance, a superconducting wire can carry current indefinitely without energy loss, making it an ideal transmission line. In addition, superconductors generate very strong magnetic fields, making them useful in lightweight, compact and efficient generators and magnets.

The primary challenge of superconductors is that they have to be kept very cold before they become superconducting. Even so-called high-temperature superconductors must be kept

*See ORNL IN THE 21ST CENTURY AND BEYOND, page 72*

# Neutrons and quantum materials

by Sean Simoneau
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*ORNL researcher Clarina dela Cruz at HFIR.* Image credit: Genevieve Martin, ORNL

Neutron scattering scientist Clarina dela Cruz uses the powerful tools at SNS and HFIR to investigate quantum materials, whose exotic physical properties arise from the quantum mechanical properties of their electrons.

Dela Cruz's research lies at the nexus of topology, quantum field theory and quantum information science, with a healthy amount of materials and computer science. She uses neutron scattering techniques to study the structural, electronic and magnetic properties and correlations in novel quantum materials such as unconventional superconductors, quantum magnets and multiferroic systems with switchable electric and magnetic functionalities.

"There is absolutely rich and novel physics yet to be explored in the field of quantum materials research," dela Cruz said. "In addition to the exciting science, quantum materials could have fundamental and far-reaching impacts on technology and are potentially transformative over a host of grand challenges for energy research."

In the future, dela Cruz's work will be integrated with that of other researchers, from theorists and computer scientists to physicists and materials experts. Their collaboration will enable researchers to build powerful quantum simulation tools and predict materials with novel quantum states that can be tuned for specific functionalities.

These novel materials can then be designed into smart materials, customized for practical real-world applications such as ultrasensitive sensors and faster, more energy efficient computers and next generation electronic devices.

*ORNL's Parans Paranthaman uses e-beam evaporation to make a superconducting wire.*
Image credit: Tom Cerniglio, ORNL

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below about minus 200°F, meaning they must be cooled with liquid nitrogen. In addition, existing superconducting wires are complex, requiring many layers of material to support a thin film layer of superconducting material that makes them both expensive and inflexible as wires.

Even so, some superconductors are being used in short cables to transmit electricity to condensed urban areas and in applications such as magnetic resonance imaging machines and magnetic levitation trains. ORNL researchers are working to better understand the workings of superconductors and the best arrangement of the atoms within these materials.

In the 1990s, an ORNL team led by Amit Goyal developed a high-temperature superconducting wire technology that was licensed for the commercial production of highly energy-efficient, copper-oxide based high-temperature superconducting wires. Following its development, ORNL demonstrated that the rolling-assisted, biaxially textured substrates technology—or

RABiTS—delivered 3,750 times more amperes per square centimeter than typical copper wire, conducting electricity at practically no resistance or loss.

The RABiTS development process was later used by Brookhaven National Laboratory to make an iron-based superconducting wire for carrying very high electrical currents through high magnetic fields.

The focus at this point is on superconducting materials containing iron or other earth-abundant elements.

"We want to understand the atomic-level interactions that are causing these superconducting transition temperatures," explained ORNL's Athena Sefat. "What is crucial to note is that it is fundamental knowledge that we are collecting: What causes the superconducting temperature?"

To deepen their understanding, researchers are making liberal use of ORNL's user facilities: exploring the magnetic basis of superconductors with neutron scattering at SNS, examining the nanostructures of crystals with microscopy and spectroscopy at CNMS, and hypothesizing new arrangements of atoms with computing resources at the Oak Ridge Leadership Computing Facility.

Fundamental though it is at this stage, this research is likely to lead to more useful and less expensive superconducting wires that can revolutionize the way we transmit and use electricity.

The creation of new materials is guided by predictive theory and supercomputer modeling on Titan and Summit. Materials analysis relies on neutron scattering at SNS and HFIR, which is able to probe magnetic properties at length scales ranging from single atoms to tens of nanometers—or roughly 1,000 times smaller than the width of a human hair.

And specialized microscopy equipment can take samples to near absolute zero—or just above negative 460 degrees Fahrenheit—which is necessary for many quantum materials to exhibit their exotic properties.

"The discovery of new technologies critical for daily life in the 21st century and beyond relies on mastering our understanding of the extraordinary properties and behaviors of quantum materials," said Ho Nyung Lee, ORNL manager of DOE's Basic Energy Sciences Materials Science and Engineering Program.

### Glass that sheds water

ORNL's Tolga Aytug and colleagues have developed a nanostructured antireflective glass surface that also sheds water.

Because it doesn't reflect light, the coating is especially useful for electronics displays. It also has the potential to make solar panels more efficient—both because of its antireflectivity and because beads of water roll off the superhydrophobic surface, carrying dirt and dust away with them and making the panels easier to clean.

> *"We want to understand the atomic-level interactions that are causing these superconducting transition temperatures. What is crucial to note is that it is fundamental knowledge that we are collecting: What causes the superconducting temperature?"*
>
> — ORNL chemist **Athena Sefat**

### The future of materials

Superconductors are an example of quantum materials—materials that have exotic properties due to the interaction of particles at the nanoscale.

Quantum materials are promising for next-generation information and energy technologies such as:

- ultrafast electronics for energy-efficient computing,
- ultrahigh-density data storage,
- the use of electron spin in electronics—known as spintronics—without power dissipation, and
- quantum computing.

ORNL researchers work to unveil new classes of these materials, such as 2D materials, unconventional superconductors and quantum magnets, creating new materials in forms such as thin films and nanostructures.

These efforts make use of ORNL's strengths.

"Antireflectivity means that you don't see yourself when you look at the window," Aytug said. "With solar panels, that reflection is a loss. Because light is not reflected back, more is coming through."

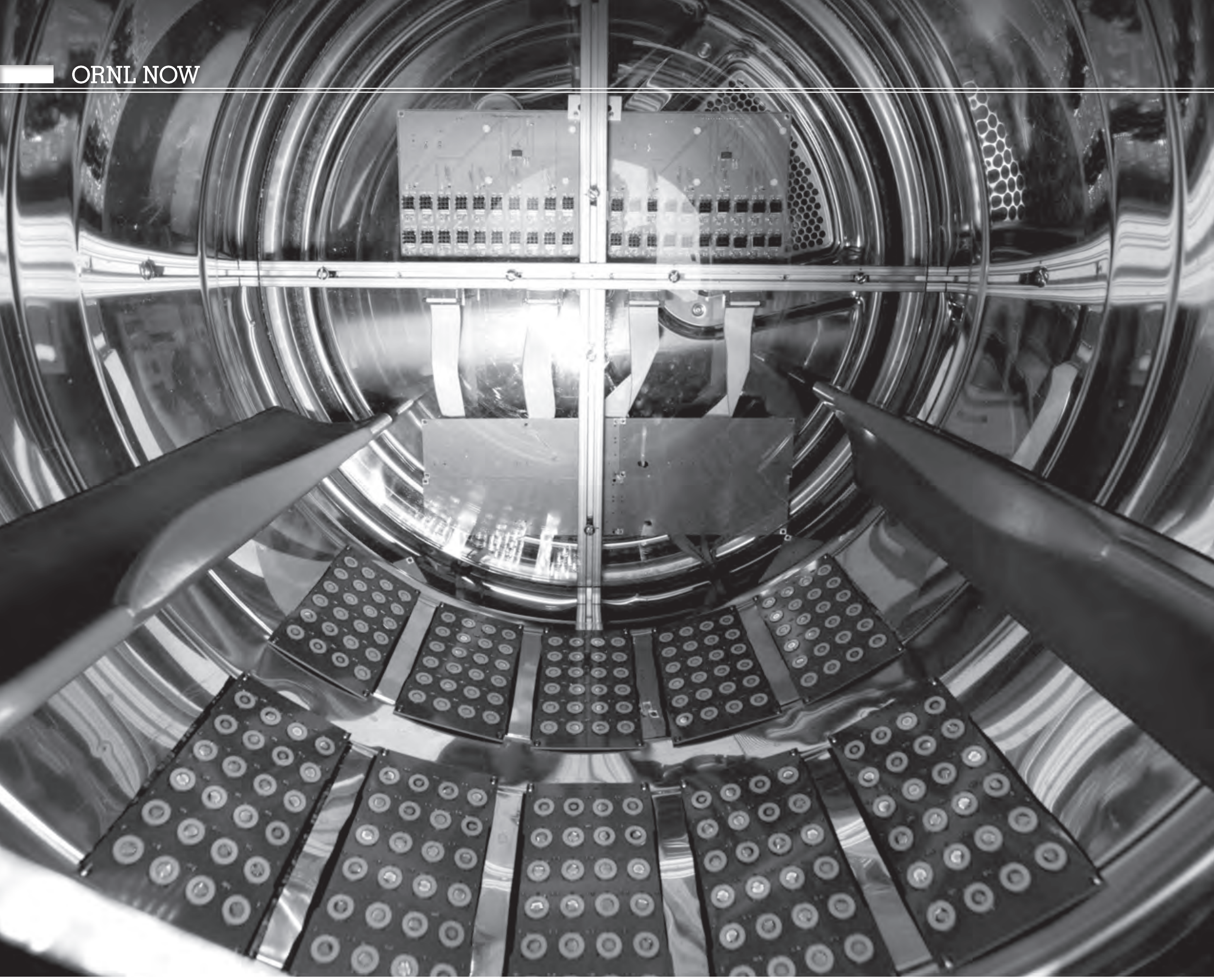
Samsung and Carlex Glass Co. have licensed the technology.

### More efficient home tech

Heating, air conditioning and appliances consume about 40 percent of energy in the United States, so advanced building technologies can provide an enormous opportunity for energy and cost savings. Heating, ventilating and air conditioning consume more than half of our utility bills.

ORNL researchers have more than 40 projects focused on advancing building technologies, including appliances and HVAC, explained Ayyoub Momen, a member of the lab's Building Equipment Research Group.

*See ORNL IN THE 21ST CENTURY AND BEYOND, page 74*



*An ultrasonic dryer at ORNL uses piezoelectric transducers to generate high-frequency mechanical vibration, mechanically extracting moisture from the fabric as cold mist.* Image credit: Carlos Jones, ORNL

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Refrigeration technology is poised for advancement. For instance, ORNL researchers are using the magnetocaloric effect—in which some alloys heat up in the presence of a magnet and cool down when the magnet is withdrawn—to develop refrigerators that eschew environmentally harmful refrigerants.

Other efforts include the exploration of refrigerants that are effective, environmentally benign and safe—a challenging trio of goals. Alternative refrigerants—propane, for one—tend to be flammable, so they can be used only in small amounts.

"We're doing research to understand how much of this flammable refrigerant can certain devices contain and still be safe," noted Brian Fricke, group leader in ORNL's Building Equipment Research Group. "A refrigerator in your kitchen or a window air conditioner would use very small amounts of propane, but if you're talking about a large refrigeration system in a supermarket, for example, there you've got thousands of pounds of refrigerant in the system, so obviously propane would not be a wise choice."

Clothes dryers are also a great candidate for innovative technologies. ORNL researchers have invented an ultrasonic dryer that removes water from clothing with vibrations rather than heat. They are also working on systems that use thermoelectric heat pump technology, another big advance.

Other projects include dishwashers that retrieve the heat from the hot water they use and vacuum insulation technologies that provide twice the protection in half the thickness of conventional insulation.

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# UT-ORNL partnerships benefit students

by Bill Cabage
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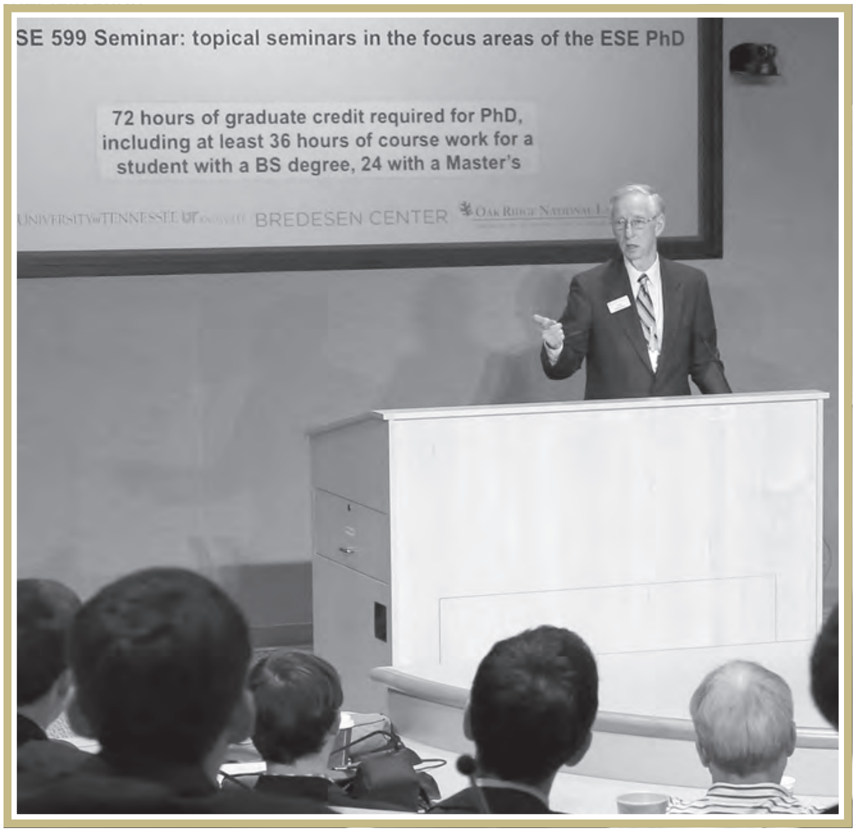
When ORNL climate researcher Melissa Allen was a graduate student at the University of Tennessee in 2011, her advisor, Joshua Fu, told her about the Bredesen Center for Interdisciplinary Research and Graduate Education, a new partnership between the university and ORNL offering a unique way to earn a Ph.D.

The Bredesen Center offers a wide range of opportunity in fields such as additive manufacturing, renewable energy, transportation and nuclear energy. The new Data Science and Engineering track includes advanced data sciences, advanced manufacturing, health and biological sciences, urban systems and national security.

Allen's interest in climate science was a natural fit, given ORNL's prowess in high-performance computing and climate modeling and simulation.

"I knew what I wanted to do, and I was able to develop my own Ph.D. curriculum as long as I met program requirements," she said. "I had interacted with ORNL scientists already and knew their capabilities, so that was a real advantage."




*Bredesen Center Director Lee Riedinger talking to students in 2014.* Image credit: Jason Richards, ORNL

The Bredesen Center's range of disciplines is as broad as the those of the university and national lab. The center has produced 57 doctorates from about 200 students, including 131 current doctoral students. The center offers those students a highly technical Ph.D. that leverages the lab and its resources, said Bredesen Center Director Lee Riedinger.

"What makes these degrees really unique is each graduate student has to spend time in entrepreneurship or policy," he said. "We've already seen a half dozen companies started up through the center. We're attracting a special breed of graduate student."

Allen, of the inaugural Bredesen Center class, is an example.

"The links between UT and ORNL and the resulting resources and capabilities are a real selling point," she said.


*ORNL's Damon Parks (left) and Javin Parson assist with the unpacking of a transport container for spent nuclear fuel rods.* Image credit: Carlos Jones, ORNL

# Skilled tradespeople keep ORNL running

by Leo Williams
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It takes more than world-class scientists and engineers to run an institution like ORNL. It also takes world-class welders, pipefitters, glassblowers, riggers and other tradespeople to keep the facilities running and sometimes to build specialized equipment that is unobtainable in any other way.

ORNL boasts 1,100 staff scientists and engineers working with a wide range of unique, expensive and highly demanding equipment, including two of the world's most advanced neutron scattering facilities, a range of advanced—and often highly customized—electron and atom probe microscopes, and the world's fastest supercomputer. Under the circumstances, the lab's mission support staff have an enormous job keeping ORNL running smoothly.


*ORNL's Brad Sexton (left) and Scott Elmore working at SNS in 2012.* Image credit: Jason Richards, ORNL

One team—which included machinists, welders, engineers and a boilermaker—fabricated components that will replace existing equipment at the High Flux Isotope Reactor that can shut down the reactor. Those new components were to be built by an outside firm, but ORNL's professionals stepped in when that outside firm was unable to meet the reactor's stringent specifications.

"The value of that is that our people were able to do something that an outside firm was unable to do," noted Ed Bodey of ORNL's Integrated Operations Support Division, "which was meet these really critical tolerances in these pieces that were fabricated for HFIR."

Another group has been nominated for an internal award at the lab for their support in installing prototype equipment that will coat fuel for pebble-bed high temperature gas-cooled reactors. That effort included more than 6,000 hours from the support team and allowed the project to meet a critical DOE milestone.

Still other tradespeople support projects such as the American contribution to the multinational ITER fusion reactor, located in Europe, and the SPRUCE climate experiment in Minnesota.

"It would be very hard to accomplish our mission without the help of our support staff," Bodey said.

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## Energy to keep it all running

ORNL nuclear scientists are working both to ensure the safety and longevity of the country's current power plants and to develop safer, less expensive new technologies to take over when current reactors are eventually mothballed.

Nuclear power provides about a fifth of the electricity used in the United States and almost two-thirds of our carbon-free electricity, yet nearly all of the country's nuclear plants will reach the end of their operating lives over the course of the next couple of decades.

> *"We're doing research to understand how much of this flammable refrigerant can certain devices contain and still be safe."*
>
> — ORNL Building Equipment Research Group leader **Brian Fricke**

To help them make the most of the time they have left, the ORNL-led Consortium for Advanced Simulation of Light Water Reactors developed the Virtual Environment for Reactor Applications, or VERA, a tool that uses Titan to perform high-fidelity simulations of operating reactors and to enable less powerful computers to tackle problems, too.

VERA modeled the first 18 years of operation at Unit 1 of the nearby Watts Bar Nuclear Plant, for example, and CASL partner Westinghouse used the tool to model the company's new AP1000 pressurized water reactor.

ORNL's computing expertise will also pave the way for a new generation of reactors. Current power plants use regular water both to cool the core and to moderate the reaction (that is, slow down fast-moving neutrons to sustain a nuclear chain reaction). Potential new reactors may fill those functions in various ways by, for instance, cooling the core with a gas such as helium or moderating the reaction with graphite.

ORNL is particularly involved in the development of reactors that are powered and cooled by molten salts—an appropriate role given that ORNL was home to the world's only molten salt reactors: the Aircraft Reactor Experiment in the 1950s and the Molten Salt Reactor Experiment in the 1960s. ORNL's Lou Qualls has been chosen by DOE's Office of Nuclear Energy as the national technical director for molten salt reactors.

One advantage of advanced new designs—including molten salt reactors—is that, unlike current reactors, they don't need to be kept under pressure. This makes them inherently safer and potentially lower cost than pressurized water reactors.

"They operate at atmospheric conditions," explained Ken Tobin, director of ORNL's Reactor and Nuclear Systems Division. "If you were to have a breach, once that salt gets down below 450 degrees or so, it solidifies, so you don't have to worry about radiation contamination into the atmosphere."

### Turning plants into fuel

The transportation industry will benefit from the work being done by ORNL biologists and colleagues from across the country. These researchers are using their knowledge of genetics, computational biology and other tools to develop next-generation biofuels that provide all the benefits of ethanol, without the drawbacks.

Advanced fuels, such as butanol and esters, are not derived from food crops such as corn, but rather from perennial plants such as poplar and switchgrass. The fuels themselves, such as isobutanol, are chemically much closer to gasoline than ethanol is, so they can be introduced into the fuel earlier in the production and distribution process.

According to ORNL's Jerry Tuskan, who leads the Center for Bioenergy Innovation, one of four DOE bioenergy research centers, this similarity means that advanced biofuels can be blended into gasoline in greater concentrations than ethanol, possibly making up as much as 30 percent of fuel.

Before they become feasible, however, the process must advance at each step along the way, he said. Plant yields must rise substantially, the amount of fuel per volume of bioreactor (known as the "titer") must be higher, and the microbes that convert the plants into fuel must become more robust and yield fuels at higher titers.

Finally, researchers must scale the process up from benchtop to industrial scale.

"We have produced these advanced fuels, so we know it's feasible," he said. "Our job, our focus, is to use modern genetics and genomics, metabolic engineering and computational biology to help us elevate the yield, titer and robustness."

## Keeping us safe

ORNL's grid-related research works to keep the lights on in the event of a natural disaster or human attack, from modeling the electrical grid in North America to locate potential vulnerabilities, to operating DOE's Eagle-I—Environment for Analysis of Geo-Located Energy Information—system, which tracks electricity disruptions across the country.

ORNL researchers have developed low-cost sensors that are plugged into outlets around the country to monitor conditions of the electrical grid such as voltage, frequency and current. They are also developing sensors that can be used to detect cyberattacks.

ORNL is also leading the way to develop a private communications and control system for the grid to move utilities and grid operators off the public internet. The research initiative, called DarkNet, will take advantage of unused fiber-optic cable to create a network separate from the public internet.

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# Microscopy and computing for futuristic materials

by Sean Simoneau
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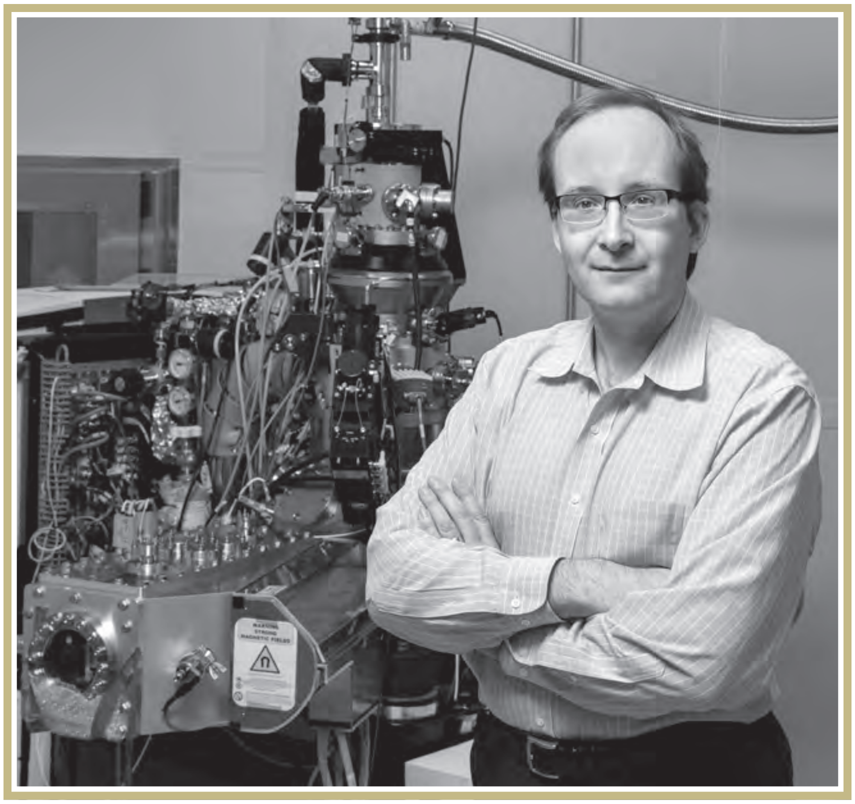
Integrating electron microscopy and atomic imaging with big data technologies is a monumental task, but the end result is a deeper, more powerful understanding and control over materials functionality at the atomic level.

That understanding is what attracted Sergei Kalinin, a researcher at the Center for Nanophase Materials Sciences.

The steady progress in microscopy in the last decade has "opened the floodgates of high-veracity structural information and has offered insights into physical and chemical functionalities on an atomic level," Kalinin said.

Working at ORNL, Kalinin saw the promise of high-performance computing to drive machine learning and artificial intelligence in materials research, making sense of the enormous amount of data captured by electron and probe microscopes. These methods not only generate high-resolution images but can also help researchers understand the underlying physics, which in turn will help computational researchers create higher-fidelity simulations.

The simulations go beyond imaging and can help researchers control and direct matter atom by atom with an atomically focused electron beam, creating atomic configurations optimized for specific physical and chemical properties.



*ORNL researcher Sergei Kalinin with a helium ion microscope at the lab's Center for Nanophase Materials Sciences.* Image credit: Carlos Jones, ORNL

The knowledge gained through this merger can be used to improve material functionalities, improve synthesis, and design and predict novel materials. The electron-beam-based atom-by-atom fabrication techniques developed by Kalinin and others at ORNL can even open pathways for applications in quantum computing, single-spin magnetoelectronics and atomic robotics.

"These two directions—materials fabrication and understanding—are closely intertwined," Kalinin said. "Only if we understand material on the atomic level will we know what we need to fabricate and how to do it."


*ORNL researchers—along with partners from Lawrence Livermore National Laboratory and Wisconsin-based Eck Industries—have developed cerium-containing aluminum alloys that are both easier to work with and more heat tolerant than previous products. In this photo, the molten alloy is being poured into a ladle that will then be used to fill a mold.* Image credit: Zachary Sims, ORNL

# Materials for the world

by Bill Cabage
cabagewh@ornl.gov

Jeremy Busby didn't always understand the power of technology transfer, where fundamental discoveries are nurtured to succeed in the marketplace.

Busby, who directs ORNL's Materials Science and Technology Division, is older and wiser now, and he's seen the process work.

Busby leads one of ORNL's largest and most storied divisions, with a portfolio that evolved from the materials challenges of the early Atomic Age. In those days, ORNL developed corrosion-resistant steels for nuclear reactors that became industry mainstays. Now, that expertise is applied to tough materials challenges ranging from energy to additive manufacturing to national security applications.

His division averages 70 to 80 invention disclosures and 30 to 40 patents annually. "Almost every week I get a notification that someone is interested in one of our patents," Busby says.

When the basic-to-applied model works, the payoff can be huge. ORNL's work with high-temperature materials in the 1990s evolved into a critical part of General Electric's LEAP jet engine.

*ORNL's Jeremy Busby with cast stainless steel.* Image credit: Jason Richards, ORNL

"They have incorporated that technology into ceramic parts in jet engines that allow higher temperatures and greater efficiency. They've presold $150 billion worth of aircraft engines largely based on collaborative research with us," he says.

Busby believes high-tech solutions to problems in energy and national security could make the biggest impacts in seemingly mundane infrastructure applications, such as water pipes.

"We have all the tools and experience. We do lots of work in fusion, fission, geothermal, fossil, energy storage, wind and solar. It's fun bringing those things together. A solution for one may also help solve others," Busby says.

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At those points where the two networks necessarily overlap, the system will use quantum encryption techniques to thwart unwanted intrusions.

Among the most potentially innovative approaches to power security will be the development of 3D-printed utility poles that can bend under stress. This research will leverage ORNL's expertise in grid, electricity, materials and additive manufacturing to produce the poles, which can keep both the poles and power lines from breaking, according to Sustainable Electricity Program director Tom King.

"Let's say you have two utility poles," he said. "If a tree falls on the line between them, typically that's going to snap the line or the distribution tower. But if these poles have some give at the base, once the trees are removed, it comes back up."

ORNL researchers also partner with the Chattanooga Electric Power Board to test new cybersecure sensors and instrumentation on the city's fiber-optic "smart grid"—an electric grid that uses digital technology to communicate between the utility provider and the customer.

The smart grid devices provide real-time data on the environment, such as solar irradiance, temperature, humidity, and wind; inputs such as vibrations, radio frequencies, coronal discharge, and thermal images from infrared cameras; as well as physical and cybersecurity situational awareness via measuring/monitoring parameters including cell phone signals, the presence of drones, sensor network cyberintrusion attempts, or physical intrusion.

### Keeping nukes out of the wrong hands

ORNL's nuclear, chemical, and materials science R&D capabilities strengthen the lab's ability to deliver on its nuclear security mission. The Nuclear Security and Isotope Technology Division researches, develops, and deploys technology that enhances nuclear nonproliferation and safeguards, reduces threats to nuclear material and facilities at risk, and expands the national capabilities in radiation detection and nuclear forensics.

ORNL's Nuclear Analytical Chemistry and Isotopics Laboratories Group—whose members are recognized as world experts in nuclear analytical measurements—help federal and international agencies address nuclear threats and materials security worldwide.

As a member of the International Atomic Energy Agency's Network of Analytical Laboratories, the group provides ultra-trace detection and measurement to analyze swipe samples, thereby ensuring that countries are living up to treaty obligations regarding uranium enrichment.

The swipes are collected on walls and surfaces of a nuclear facility. Because the process can analyze very low levels of nuclear material to a high degree of precision, it has proven to be an extremely powerful technique for detecting undeclared nuclear material and activities.

The ORNL group, led by Joe Giaquinto, also works closely with the Department of Homeland Security's Office of Countering Weapons of Mass Destruction, which is responsible for ensuring that nuclear materials are not smuggled into the country.

Working with other DOE laboratories, the ORNL scientists are leaders for the production of nuclear forensic reference materials. DHS labs use these materials in an investigation to validate analytical methods and provide traceability and defensibility for their forensic measurements.

In addition, the group trains international scientists to ensure they are competent at destructive analysis protocols used for nuclear security. This work includes the establishment in Beijing of analytical laboratories in China's Center of Excellence for nuclear security, which was funded through a collaborative agreement between the American and Chinese governments.

The facility is a world-class training platform in the protocols and methodologies required to control and account for nuclear materials in an operating nuclear facility. The ORNL group is developing destructive analysis training materials for the Chinese center to train scientists across Asia.

> *"With this long history of research using theoretical tools such as density functional theory, the interacting nuclear shell model, and more recently coupled-cluster theory with realistic nucleon-nucleon interactions, we have made big splashes in nuclear physics."*
>
> — ORNL Physical Sciences Associate Laboratory Director **David Dean**

## Looking at big questions

Nuclear physicists at ORNL couple theory with high-performance computing to understand how protons and neutrons combine to create the nucleus of an atom and, by extension, nuclei that formed the universe as we know it.

These efforts grow from a half-century legacy of work in theoretical nuclear physics dating back to the 1960s, according to David Dean, ORNL's associate laboratory director for Physical Sciences. Over that time, ORNL researchers have explored a variety of theoretical approaches to understand the nucleus.

"With this long history of research using theoretical tools such as density functional theory, the interacting nuclear shell model, and more recently coupled-cluster theory with real-

*See ORNL IN THE 21ST CENTURY AND BEYOND, page 84*

# Billion-dollar impacts from ORNL innovations

*ORNL Research Director Eugene Wigner, second from left, hands the first shipment of a reactor-produced radioisotope—carbon-14—to the director of the Barnard Free Skin and Cancer Hospital of St. Louis, Missouri, in 1946.* DOE photo by Ed Westcott

- >$1B
- Fueleconomy.gov: $1B in cost savings — $1B
- Ceramic matrix composites for gas turbines — $150B
- Lab-on-a-chip: Caliper acquired by PerkinElmer — $0.6B
- Cesium extraction: Basis for waste processing plant — $1.3B
- Reactor life extension: $20B cost avoidance — $20B
- Advanced alloys: Chrome-moly steel in widespread use
- Ion implantation: Integrated circuits and medical implants
- Cryopreservation (mouse embryos): Livestock reproduction
- Centrifuge technology: Basis for vaccine purification and US enrichment industry
- Instrumentation: Products and spinoffs from ORTEC and TENNELEC — >$1B
- Reactor technology: Concepts for light water, high temperature, and molten salt reactors
- PUREX: Basis for nuclear fuel reprocessing techniques used worldwide
- Radioisotopes: Multibillion dollar industry (>100 million procedures per year) — >$5B/year

1940s — Today

Image credit: Brett Hopwood, ORNL

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istic nucleon-nucleon interactions, we have made big splashes in nuclear physics," Dean said.

Throughout this history, researchers have relied on ORNL's expertise in high-performance computing, from punch-card computing in the early days to the lab's Summit system, currently the world's most powerful supercomputer. Most recently, with an eye toward future computing technologies, ORNL researchers were able for the first time to simulate a nucleus using a quantum computer.

*"Our theoretical understanding of what's going on has seen the light of day in observations."*

— ORNL Physical Sciences Associate Laboratory Director **David Dean**

ORNL astrophysicists also explore the ways in which stars manufacture new elements through nuclear fusion and other processes, and how they distribute those new elements through neutron star mergers and supernova explosions.

According to Dean, the lab's theoretical work in nuclear physics is getting a boost from the Laser Interferometer Gravitational-Wave Observatory—or LIGO—the world's largest gravitational wave observatory. LIGO recently observed the merger of two neutrons stars.

"Optical telescopes have seen from that same merger evidence that nuclei, such as gold, are being ejected," Dean said, "so our theoretical understanding of what's going on has seen the light of day in observations."

*Aerial view of ORNL.*
Image credit: Jason Richards, ORNL

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