LOS ALAMOS NATIONAL LABORATORY ◇ WINTER 2023

NATIONAL ★ SECURITY SCIENCE

THE ENERGY ISSUE

Fission forward: Atom-splitting experts forge ahead.

Harnessing the sun: Los Alamos continues the quest for fusion.

Building a geothermal future: Machine learning assists in mining the Earth's heat.

The molecule of the future: Hydrogen is key to energy storage solutions.

+PLUS:

Quantum dot technology may soon power your home	Computer modeling capabilities predict wind turbine success	Plutonium heat sources sustain spacecraft on Mars and beyond

PHOTOBOMB

▼

On June 12, 2023, the Responsive Development Experiment XL-2B successfully launched from White Sands Missile Range in southern New Mexico. The flight test was a collaboration between Albuquerque-based X-Bow Systems Inc., which designed the modular boost rocket, and Los Alamos National Laboratory, which designed the payload and collected data on the way the payload handled extreme conditions, including zero gravity, very high and low temperatures, and varying accelerations, velocities, and pressures.

“The future of flight testing is clearly commercial, and New Mexico is an ideal place for flight testing,” said Los Alamos program manager Steve Judd in a news release. “Our partnerships with companies like X-Bow allow us to move much faster at much lower cost, and each flight gives us greater confidence in our teams, our technologies, and our ability to be responsive in a rapidly changing world.” ★

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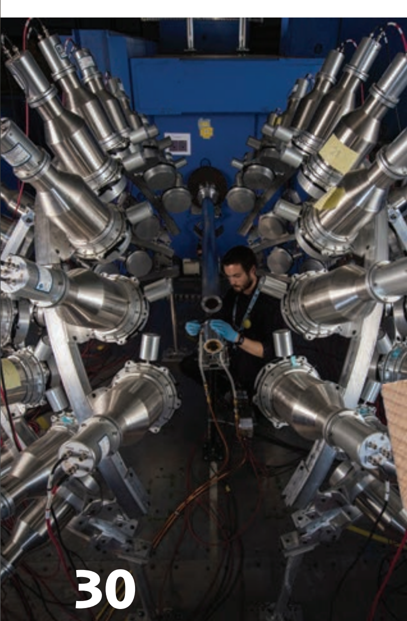

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IN THIS ISSUE

FEATURES

About the cover: Different size quantum dots absorb different wavelengths of light, which affects their color. To demonstrate how quantum dots can also guide light in certain directions, scientists placed glass tubes in vials of quantum dot solutions. The solutions directed the light up the tubes. To learn how quantum dots are being used for energy-saving technologies, see p. 10. ★

THE ENERGY ISSUE

Los Alamos National Laboratory efforts make a more sustainable future possible.

BY PAT FITCH
ASSOCIATE LABORATORY DIRECTOR FOR CHEMICAL, EARTH, AND LIFE SCIENCES

Every day, we rely on energy and likely take for granted the complex infrastructure behind the simple flip of a light switch. Power plants, electrical grids, and natural gas pipelines are more than modern conveniences—they are the bedrock of our society, which makes them desirable targets for our enemies. Although deliberate physical and digital attacks could be catastrophic, less tangible evolving threats, such as fossil fuel depletion and climate change, also put the health and safety of the United States and its citizens at risk. For many reasons, energy security is national security.

This issue of *National Security Science* sheds light on the efforts of Los Alamos National Laboratory to ensure that the United States has access to the expertise for maintaining our quality of life, improving our resilience, and protecting our planet for generations to come. We are actively exploring various types of energy research, including nuclear, hydrogen, biological, and geothermal.

This past December and again this August, the National Ignition Facility, based at Lawrence Livermore National Laboratory, had major research breakthroughs toward solar-inspired, clean fusion energy production. Despite not being in the spotlight, Los Alamos has made significant contributions to the nation's fusion efforts dating back to the early 20th century (see p. 32). The Laboratory's National High Magnetic Field Laboratory (MagLab) continues to make strides toward high-temperature superconductors, which get us closer to creating commercial fusion energy (see p. 8).

Building on decades of innovation, Los Alamos is also investing in the hydrogen economy through collaborations with industry, academia, and government. Read more about the Lab's efforts to develop hydrogen fuel cells on p. 52.

Reducing greenhouse gases is essential to mitigating climate change. We are seeing more and more electric vehicles on the road, which is fantastic. However, some fuels and chemicals will remain carbon-based and need alternate routes to production—for example, sustainable jet fuel produced from leftover biomass (see p. 16). We need an improved understanding of both carbon in the environment and in engineered systems, such as options in biological manufacturing. Los Alamos contributes research and design in both of these areas and is aggressively pursuing solutions in our own operations (see p. 5).

Nearly every challenge facing our society becomes simpler to address when abundant, low-cost energy is available. In this issue, you will discover the ways that Los Alamos National Laboratory helps provide the energy needed to drive our national security, economy, and society. ★

■ An artist's rendering shows the various types of energy research underway at Los Alamos National Laboratory.

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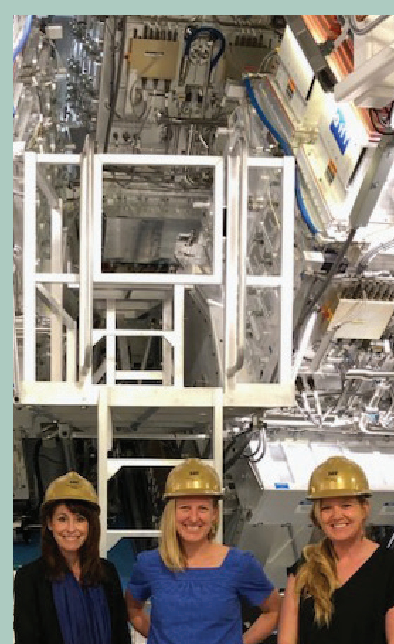
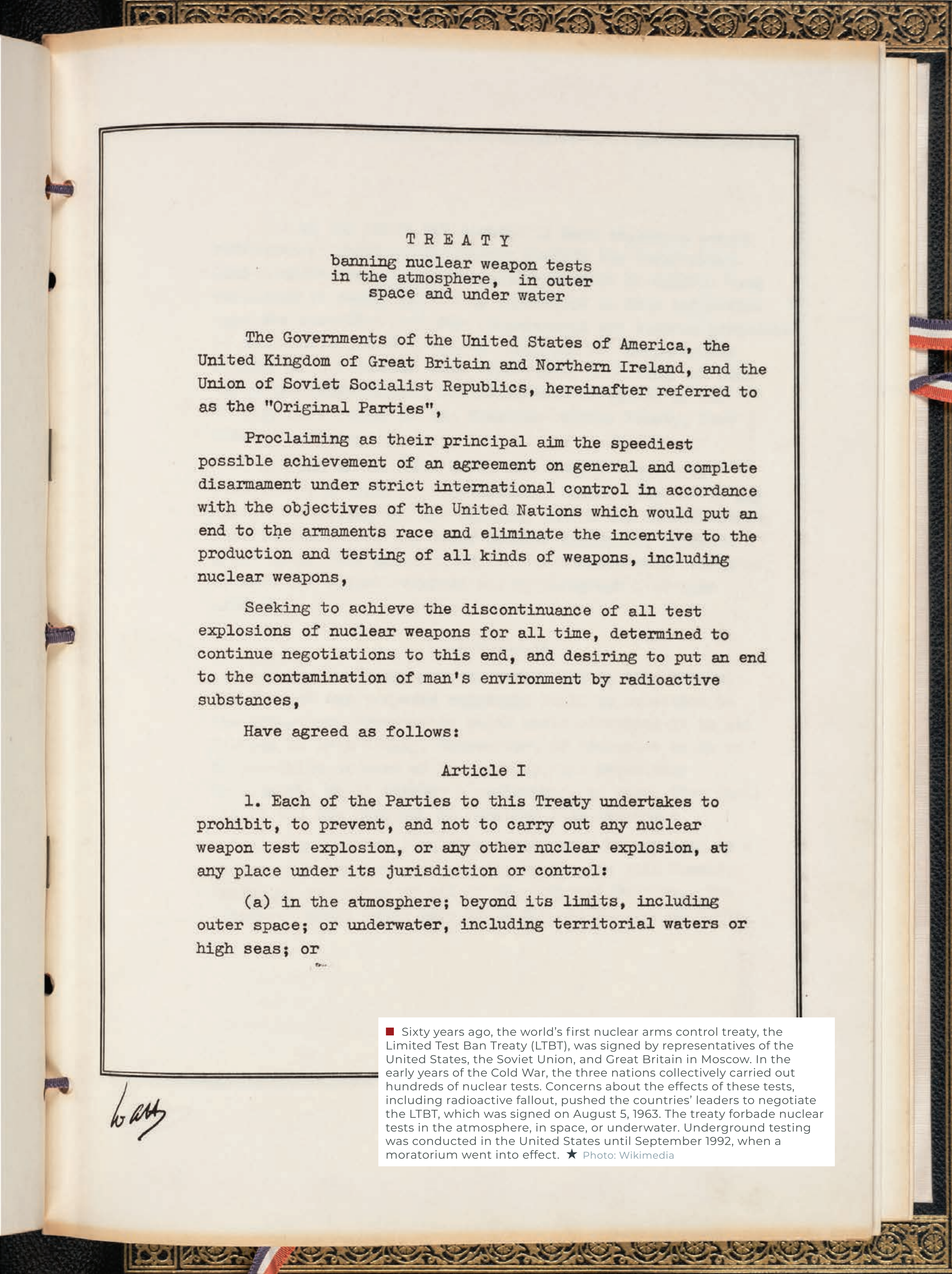
NSS STAFF SPOTLIGHT



In May 2023, *NSS* writer Jill Gibson, editor Whitney Spivey, and art director Brenda Fleming toured Lawrence Livermore National Laboratory, including the National Ignition Facility (pictured), which is used for inertial confinement fusion research. Learn more about fusion on p. 32. ★



TREATY

banning nuclear weapon tests in the atmosphere, in outer space and under water

The Governments of the United States of America, the United Kingdom of Great Britain and Northern Ireland, and the Union of Soviet Socialist Republics, hereinafter referred to as the "Original Parties",

Proclaiming as their principal aim the speediest possible achievement of an agreement on general and complete disarmament under strict international control in accordance with the objectives of the United Nations which would put an end to the armaments race and eliminate the incentive to the production and testing of all kinds of weapons, including nuclear weapons,

Seeking to achieve the discontinuance of all test explosions of nuclear weapons for all time, determined to continue negotiations to this end, and desiring to put an end to the contamination of man's environment by radioactive substances,

Have agreed as follows:

Article I

1. Each of the Parties to this Treaty undertakes to prohibit, to prevent, and not to carry out any nuclear weapon test explosion, or any other nuclear explosion, at any place under its jurisdiction or control:

(a) in the atmosphere; beyond its limits, including outer space; or underwater, including territorial waters or high seas; or

Sixty years ago, the world's first nuclear arms control treaty, the Limited Test Ban Treaty (LTBT), was signed by representatives of the United States, the Soviet Union, and Great Britain in Moscow. In the early years of the Cold War, the three nations collectively carried out hundreds of nuclear tests. Concerns about the effects of these tests, including radioactive fallout, pushed the countries' leaders to negotiate the LTBT, which was signed on August 5, 1963. The treaty forbade nuclear tests in the atmosphere, in space, or underwater. Underground testing was conducted in the United States until September 1992, when a moratorium went into effect. ★ Photo: Wikimedia

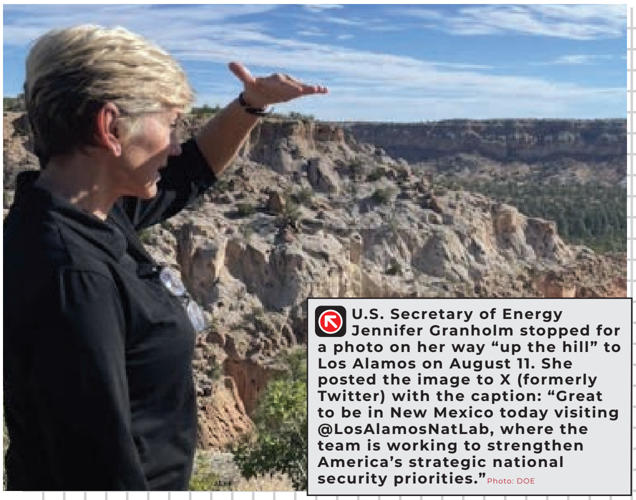
INFOGRAPHIC

THE INTERSECTION

Science and culture converge in northern New Mexico—and beyond.

SCIENCE

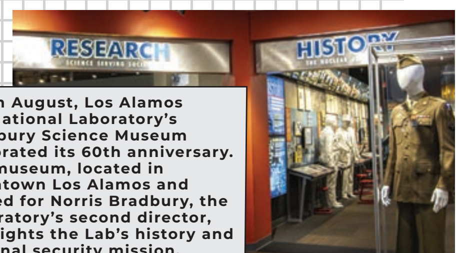
CULTURE



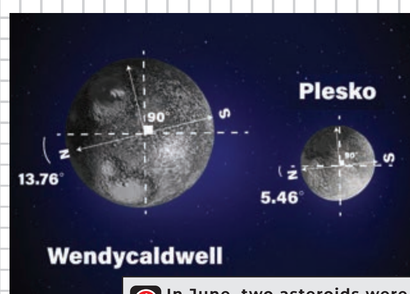
U.S. Secretary of Energy Jennifer Granholm stopped for a photo on her way "up the hill" to Los Alamos on August 11. She posted the image to X (formerly Twitter) with the caption: "Great to be in New Mexico today visiting @LosAlamosNatLab, where the team is working to strengthen America's strategic national security priorities." Photo: DOE

November is Native American Heritage Month. Many of the Laboratory's Native American staff have relatives who served during World War II as part of the Manhattan Project or as Navajo Code Talkers—the group of Native American soldiers who used simple words and phrases from their tribal language to baffle Japanese code-breakers and spur Allied victory in the Pacific theater. Pictured here, in the summer of 1990, the Laboratory hosted an event to honor the surviving members of the Navajo Code Talkers.

In downtown Los Alamos, actors Cillian Murphy and Matt Damon stand with statues of J. Robert Oppenheimer and General Leslie Groves, who the actors portrayed, respectively, in the recent motion picture *Oppenheimer*, directed by Christopher Nolan. Did Nolan get it right? "There are some details [in the movie] that aren't completely true to the historical record, but the broader arc of the story actually nailed it, and most of the changes that were introduced I can understand," says Los Alamos Director Thom Mason. "I'm at peace with the inaccuracies." Photo: Los Alamos Historical Society



In August, Los Alamos National Laboratory's Bradbury Science Museum celebrated its 60th anniversary. The museum, located in downtown Los Alamos and named for Norris Bradbury, the Laboratory's second director, highlights the Lab's history and national security mission.



In June, two asteroids were named after Los Alamos planetary defense scientists Cathy Plesko and Wendy Caldwell. The Working Group for Small Bodies Nomenclature published the names on behalf of the International Astronomical Union, dubbing asteroid 32105 "Plesko" and asteroid 32110 "Wendycaldwell." Both were discovered in 2000.

Each October, families from across Los Alamos enjoy Hugh Roper's nuclear Halloween display. Roper, of the Lab's Multimedia Production group, creates mock-radioactive decor, including gloveboxes that dispense "toxic waste" candy and interactive games that involve transporting "hazardous" materials. "Caution: Radioactive Pruittonium" reads a sign in front of the Roper house, which is located on Pruitt Avenue. Photo: Hugh Roper

■ Clockwise from top left: Electric bicycles, solar-powered vehicle charging stations, and plans for a hydrogen bus are among the ways the Laboratory is working to reduce its carbon footprint.

A NET-ZERO NATIONAL LAB

Los Alamos is working to reduce, and eventually eliminate, its carbon footprint.

BY J. WESTON PHIPPEN

Los Alamos National Laboratory's 40-square-mile campus in northern New Mexico consumes about 450,000 megawatt-hours of energy annually. That's on par with a 43,000-home city. Why? The Lab must power mission-critical infrastructure, such as supercomputers and experimental facilities, and also cool, heat, and light the offices where more than 17,000 employees work.

The Lab's carbon footprint includes energy purchased from power plants that consume fossil fuels, as well as a much smaller footprint generated on site. Due in part to recent federal green energy directives, in early 2022, the Lab began phase one of a three-step plan to reduce its carbon emissions by 50 percent by 2030. By 2050, the Lab hopes to reach net-zero emissions.

"We have some unique facilities and engineering requirements here at Los Alamos," says Jesse Freedman, a net-zero emissions analyst with the Lab's Sustainability team. "We have nuclear facilities, high security facilities, and environmental considerations, so it's always a little more challenging for us to undertake improvement projects."

The path to zero emissions began with a recommendation to leverage the Lab's own research. Los Alamos has developed technologies in myriad energy sources, so why not incorporate some into its own power generation? Freedman and his team will explore the potential of algal biofuels, carbon capture and sequestration, hydrogen power, and how other carbon-cutting research can be used at Los Alamos.

Another early action the Sustainability team took was to reduce the power already being used by Lab facilities. The team implemented automated building operation systems, a networked software that models the most efficient use of power. If, for example, the weather outside is cool and a building requires less air conditioning, the system can automatically respond to these outside conditions, ensuring the most efficient use of energy.

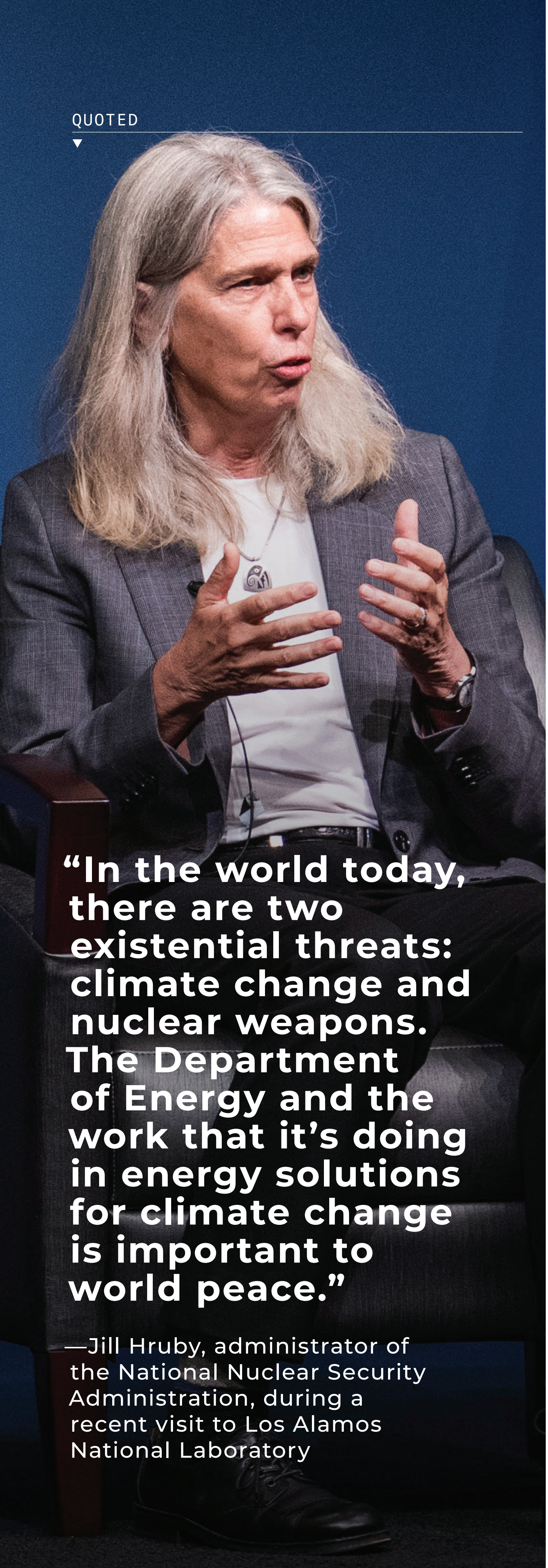
Going forward, the biggest change will come from where the Lab sources its power. For several years, Los Alamos has been working to finalize contracts with local energy suppliers that will increase, and eventually replace, all Lab energy consumption with carbon-pollution-free electricity.

"Together with Los Alamos County, we're exploring local and regional options for clean energy that benefit the Laboratory, support our critical mission work, and help the county reach its own carbon goals," says Utilities and Infrastructure Division Leader Monica Witt, who in her previous role as sustainability manager, reduced energy use at the Lab by 8 percent and water use by 20 percent.

The Lab is also exploring sustainable ways for employees to commute to work, as well as travel around the Lab's vast campus. In May 2023, the Lab launched its first express bus pilot program from an off-site parking lot approximately 20 miles away. Because more than 60 percent of employees commute to work from outside of Los Alamos County, there are plans to expand the pilot bus service to another remote lot about 70 miles away. As part of this program, the Lab will receive a hydrogen fuel cell bus in 2024 to help transport employees around campus and nearby areas.

For shorter distances, the Lab is already experimenting with an electric bike pilot program.

"Electric bikes will alleviate a tiny portion of emissions, but they're very visible," Freedman says. "They are one way of telling employees that we're thinking about net-zero seriously, and we want everyone to get excited about this mission." ★



MORE THAN A GRAIN OF SALT

A new computing project helps make molten salt reactors a viable technology.

BY JAKE BARTMAN

Currently, every commercial nuclear reactor in the United States uses water as a coolant. Over the decades, however, researchers have designed reactors that use other substances instead. Oak Ridge National Laboratory's Molten Salt Reactor Experiment (MSRE), which operated from 1965 to 1969, used salt as a coolant. In reactors like the MSRE, salt becomes molten (liquified by heat) as the nuclear material mixed with the salt fissions. The mixture then circulates to a heat exchanger, which can harness the fission heat to power a turbine and generate electricity.

Although MSRE succeeded in showing that molten salt reactors can work, the experiment also demonstrated some of the challenges that such reactors face. Most notably, the hot, salty, radioactive conditions inside the reactors can cause the metal that the reactors are made of to crack or corrode.

No molten salt reactor has been built in the United States since the MSRE. However, in recent years, the Department of Energy (DOE) has begun again to research molten salt reactors, which, among other advantages, have the potential to be safer and more efficient than a typical light-water reactor.

Today, researchers at Los Alamos National Laboratory are helping to develop metals that can withstand the punishing atmosphere inside a molten salt reactor. One Los Alamos-led project, which is a part of DOE's Scientific Discovery through Advanced Computing (SciDAC) program, is drawing together researchers from across disciplines and institutions—including Idaho, Lawrence Berkeley, and Sandia national laboratories, and Carnegie Mellon University—to achieve this goal.

Los Alamos' Laurent Capolungo, who leads the project, says that experts in electrochemistry, applied mathematics, nuclear physics, and materials science are all contributing. "I don't think I've ever seen a project that is as multidisciplinary as this one," he says.

Capolungo's team aims to develop a modeling framework that can predict the simultaneous effects of salt and radiation on nickel-based alloys, and understand how well such alloys will withstand these effects over decades of use. Achieving this goal would allow for the creation of metals that can be deployed in molten salt reactors without the need for years-long tests, facilitating the kind of rapid deployment necessary if the United States is to achieve the Biden administration goal of a carbon-pollution-free power sector by 2035.

According to Capolungo, Los Alamos is the right institution to lead the project because of its expertise in the multiphysics modeling that is central to the project's research. The project

■ Research at Los Alamos may help make molten salt reactors, which use liquid salt as a coolant, into a viable technology.

relies on computer codes developed at Los Alamos and builds off the Los Alamos Reduced Order Model for advanced nonlinear equations (LAROMance), which Capolungo helped develop. Like the SciDAC project, LAROMance used computing to explore the response of metals to extreme environments.

In the first of the project's five years of funding, researchers are refining key computer codes and building a roadmap for the future. They're also fostering interdisciplinary dialogue to better understand the obstacles that the project faces.

"Without SciDAC, what we're doing would be science fiction, not science," Capolungo says. "We're developing a new modeling framework that will plant the seeds for the next 20 years of research." ★

For more on fission, see p. 22.

■ Nobel laureate Glenn Seaborg, who chaired the Atomic Energy Commission from 1961 to 1971, visited the Molten Salt Reactor Experiment in 1965.

LISTEN

NATIONAL ★ SECURITY SCIENCE PODCAST

The *National Security Science* podcast is a spin-off of *National Security Science* magazine. Listen to stories from Los Alamos National Laboratory's Weapons Programs—stories that show how innovative science and engineering are key to keeping America safe. Check out the latest episode to hear parts of a 1964 lecture by the Laboratory's first director, physicist J. Robert Oppenheimer.

ENERGY

SUSTAINING SUPERCONDUCTORS

The Los Alamos Pulsed Field Facility's powerful magnets are essential for the development of superconductors with energy applications.

BY IAN LAIRD

The National High Magnetic Field Laboratory (NHMFL) spans three locations: the University of Florida in Gainesville, Florida; Florida State University in Tallahassee, Florida; and Los Alamos National Laboratory in Los Alamos, New Mexico.

Each site has a magnetic field specialty, and Los Alamos is home to the Pulsed Field Facility (locally called "the MagLab"), where strong magnetic fields can be generated for up to a few seconds following a pulse of electric current. This differs from the Tallahassee and Gainesville facilities, which generate weaker magnetic fields continuously. The magnets at Los Alamos are some of the most powerful in the world, and the strongest magnet at Los Alamos is capable of reaching 100 tesla (for comparison, a refrigerator magnet is about 0.005 tesla, and the Earth's magnetic field is about 0.00005 tesla).

As part of the NHMFL, the MagLab is a user facility that is open to researchers from across the world. Hundreds of scientists use

Originally acquired to help with fusion research at Los Alamos, the generator pictured here is now used to power experiments conducted at the MagLab. The MagLab is home to some of the most powerful magnets in the world, with one magnet generating a record 100 tesla non-destructive magnetic field in 2012.

the facility annually, and included in that group are many Los Alamos scientists. Their experiments cover a range of programmatic and exploratory areas, including research with potential implications for the energy sector.

For the past two decades, the MagLab has been particularly useful for the study of superconductors, which are materials that typically expel magnetic fields and have no electrical resistance. High-temperature superconductors—superconductors that are capable of operating at just above -200 degrees Celsius—are key to creating commercial fusion energy because their exceptionally powerful magnetic fields can quickly and efficiently confine plasmas.

The Achilles heel of superconductors are magnetic vortices, which appear inside type II superconductors that are subjected to forces from electrical currents. These electrical forces cause the vortices to move, and the movement of these vortices generates dissipation, preventing the superconductor from doing its job.

However, the vortices can be anchored at "pinning centers," which are essentially material defects inside the superconductor. This anchoring process prevents energy dissipation, allowing the superconductor to stay in a superconducting state at higher currents.

"Any superconductor that is useful for power applications is a type II superconductor," says Los Alamos scientist Boris Maiorov, who has worked at Los Alamos for more than 20 years. "Back in the early 2000s, we found that columns were created when we added barium zirconate [to superconductors]; these columns are really good pinning centers that allow the superconductor to generate and withstand much higher magnetic fields."

While introducing defects through the addition of materials is now standard in superconductor production, adding too many defects can kill a superconductor. In a fusion reactor, for example, a superconductor is bombarded with neutrons, which produces defects. Determining how many defects a superconductor can sustain and how they react at high magnetic fields is now a focus of research at the MagLab.

"In the beginning, those defects are going to help you," Maiorov says. "Then the question becomes: how many is too many?" To answer this question, Maiorov and other researchers are leveraging the Lab's extensive plutonium expertise. Maiorov and his colleagues can identify properties and behaviors of plutonium that are applicable to superconductors, and then use that information to predict how a superconductor might behave. "For example," he says, "we're studying the self-irradiation of plutonium as a function of time and temperature, and we can use what we learn to try and model how superconductors might respond to the radiation of a fusion reactor"—an attractive outcome in more ways than one. ★

Los Alamos has been at the forefront of quantum dot research for decades, producing these tiny nanocrystals and researching their behavior.

BIG ENERGY FROM TINY CRYSTALS

Quantum dot technology developed at Los Alamos may soon power your home.

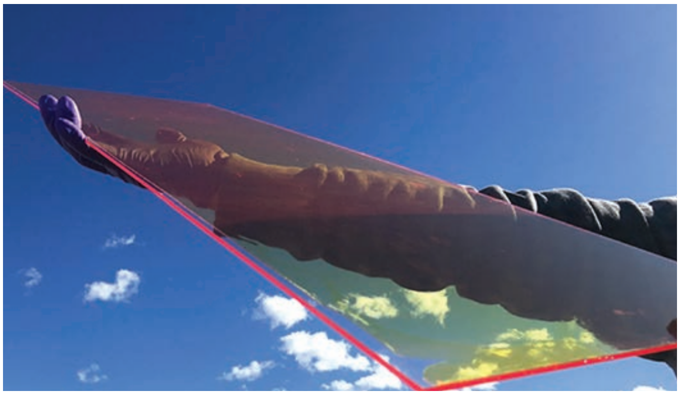
BY J. WESTON PHIPPEN

The width of a human hair is about 100,000 nanometers (a nanometer is one-billionth of a meter). A single bacterium is just 1,000 nanometers wide. And a quantum dot is a mere few nanometers across. These tiny crystals, however, might one day provide big energy.

For nearly 30 years, Los Alamos National Laboratory has helped to pioneer quantum dot research, raising it from a purely theoretical, even science fiction-esque idea, to a technology that is already in use around the country.

“When we started this work, our understanding of quantum dots was very minimal and there were a lot of challenges,” says Victor Klimov, leader of the Nanotechnology and Advanced Spectroscopy team in the Lab’s Chemistry division. “Today we have many patents and papers on quantum dot technologies; we have helped the world understand the power of these nanocrystals.”

Scientists at the Lab create quantum dots through colloidal synthesis, during which precursor materials are reacted in a chemical solution. “It’s pretty much like cooking at a moderate temperature, about 200 to 300 degrees Celsius,” Klimov says. “You do this and the materials—such as cadmium selenide—nucleate into tiny crystals. Depending on the temperature and time, we can control how large they grow.”

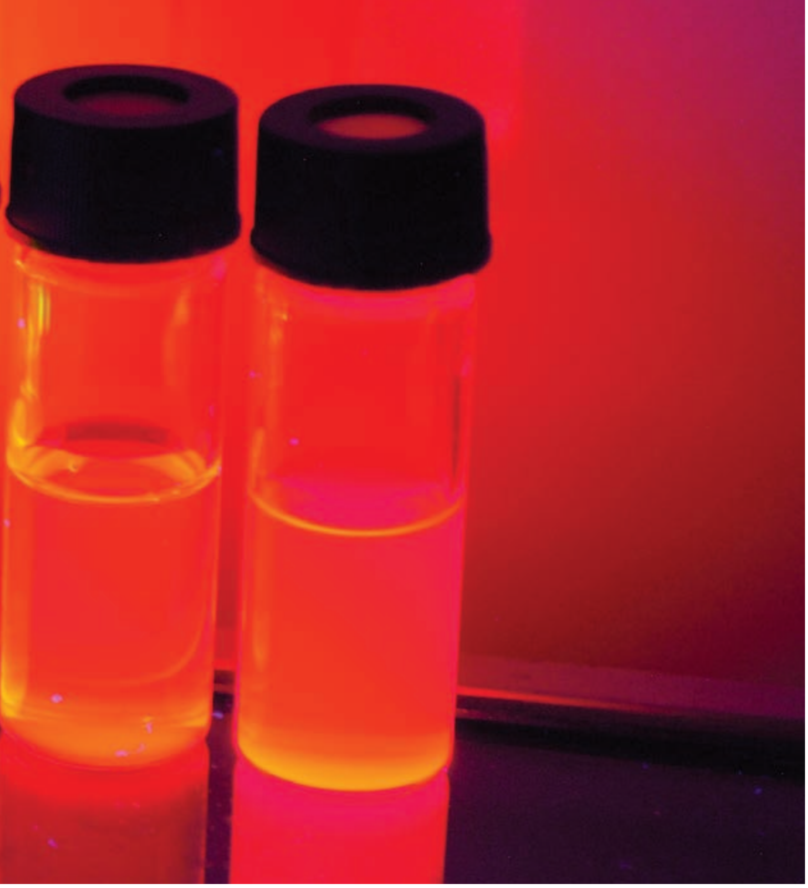


This quantum dot luminescent solar concentrator directs absorbed light from the face of the glass toward the narrow edges, where the light can then be converted into electricity by solar cells.

The resulting nanocrystals share many properties with atoms, including the ability to absorb or emit energy and light. The wavelength of light a quantum dot grabs, or generates, depends on its size, and because scientists have full control over this sizing, developers can create quantum dots that react with the entire spectrum of light, from the infrared to visible and further ultraviolet ranges.

Quantum dots are already used in televisions, where blue light from a display panel excites the nanocrystals and they glow red or green, depending on their size, to provide the clearest picture available.

A similar effect can be used to harness solar energy, and the Lab has dedicated much of its focus to this research. Quantum dots can enable so-called luminescent solar concentrators, which harvest sunlight for photovoltaic panels. Because quantum dots



are so small, they can be manufactured into a thin roll of film, akin to the tint used on car windows—except that this tint creates energy. This technology is already being used on windows in homes and buildings, and it helps supplement traditional sources of electricity.

"Present-day photovoltaic panels, most of which rely on crystalline silicon to convert solar energy into electricity, top out at an efficiency around 25 percent," Klimov says. "But with quantum dots, we can potentially exceed this limit by employing carrier multiplication."

A typical photovoltaic solar panel absorbs one photon of light and releases one electron, which becomes energy. But with advances developed at the Lab, including carrier multiplication and incorporating magnetic manganese ions, quantum dot solar panels generate two or more electrons for each photon absorbed.

Klimov's team is also researching how quantum dots can be used in energy-demanding chemistries such as ammonia production, which currently accounts for more than 2 percent of global energy use (ammonia is used for everything from plastic production to fertilizer). In this particular application, Klimov's team uses quantum dots to generate not light but "free electrons" through the process of photoemission. The current method of producing ammonia requires laser pulses to generate these free electrons, but Klimov and his team are working to achieve this reaction with nothing more than quantum dots and solar energy.

"When I first came to Los Alamos from Russia in 1995, I brought with me a handful of fragments of semiconductor-doped colored glass—the predecessors of modern quantum dot samples," Klimov says. "Since then, Los Alamos has built a world-class quantum dot program that brings together efforts in synthesis, spectroscopy, theory, and devices. Many more exciting applications of these fascinating structures are under development in areas spanning from solar energy and radiation detection to novel lasers and quantum information." ★

WATCH ▼

OPPENHEIMER

Science · Mission · Legacy

In September 2023, the Laboratory's National Security Research Center (NSRC) released a three-part documentary. *Oppenheimer: Science, Mission, Legacy* incorporates rare photos, documents, and footage from the NSRC's unclassified collections and details the Manhattan Project's creation, as well as the Laboratory's current mission.

ANY WAY THE WIND BLOWS

Los Alamos scientists develop computer modeling capabilities to predict wind turbine success.

BY JILL GIBSON

Los Alamos National Laboratory research and development engineer Matt Nelson wouldn't say his job is a breeze, but he does spend a great deal of time considering which way the wind blows. That's because Nelson's work focuses on predicting the viability of small wind turbines so that individuals, businesses, and communities can make informed decisions about where such turbines will work to serve on-site energy needs.

Nelson is part of a project team led by the National Renewable Energy Laboratory (NREL). "We have developed tools that help people predict the potential for small-scale wind projects," Nelson says. Using a computer modeling program called Quick Urban & Industrial Complex (QUIC) integrated into NREL's Tools for Assessing Performance (TAP) framework, Nelson can determine whether any obstructions, such as buildings or trees, will slow wind before it reaches a turbine. "By repurposing code originally developed for counterterrorism, we have created an affordable tool for the wind industry that can run in a few minutes on a laptop," he says. "There are definite challenges for the wind industry, and often you are dependent on whatever Mother Nature gives you. We are trying to prevent bad information and bad decisions to make wind energy more predictable and affordable."

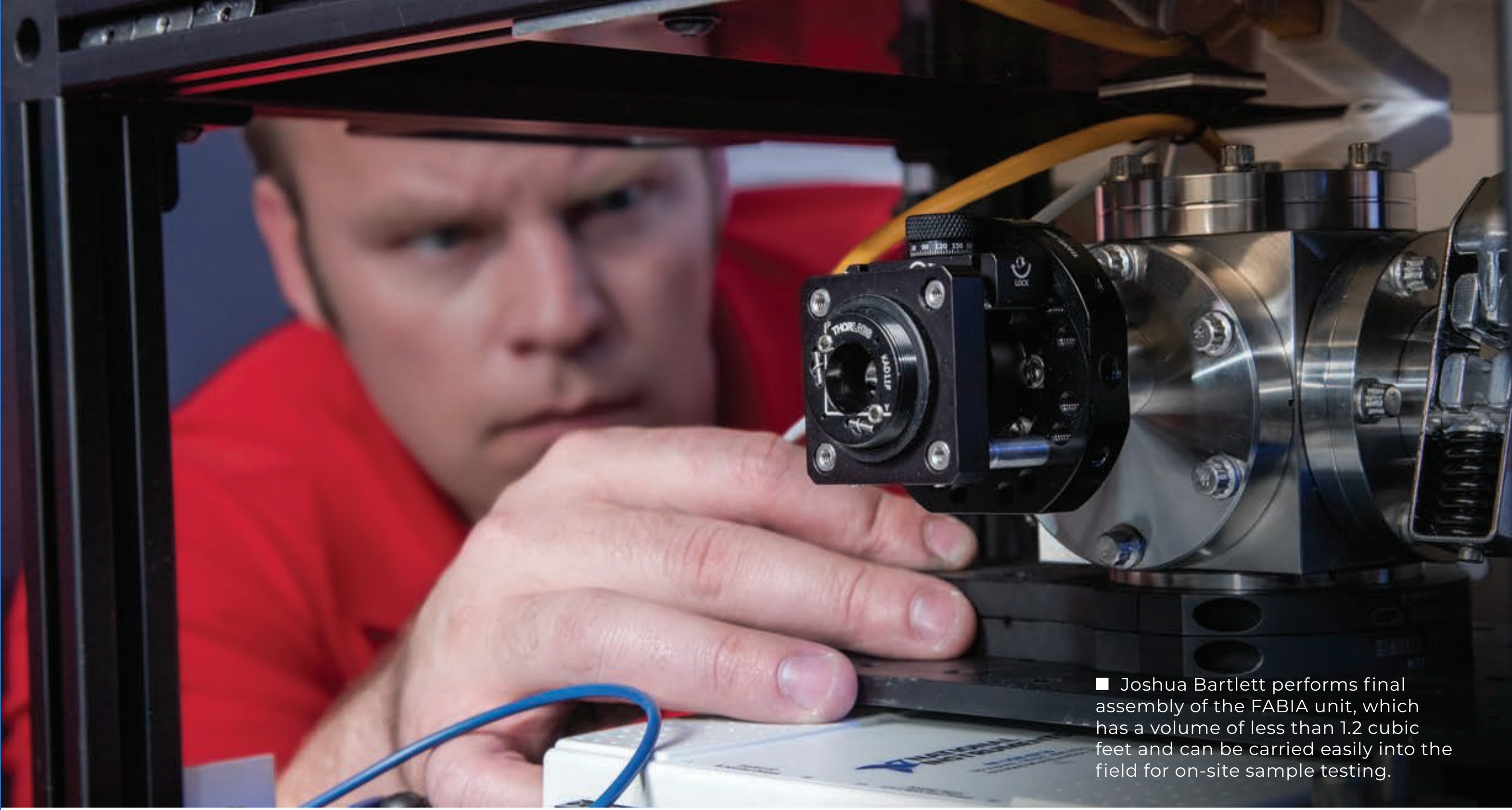
Nelson notes that TAP is used for "distributed wind" projects, which are typically small in size, number of turbines, and budget. Distributed wind turbines are usually located close to where the energy is used and can be situated alone or grouped to meet larger energy needs. Individuals and companies considering small wind turbines rarely have the funds to construct meteorological towers to measure wind speeds. That's where TAP comes in.

"We're using machine learning to train our fast-running models based on a suite of high-fidelity simulations and validating it with field experiments," notes Nelson. "When it comes to wind modeling, there are lots of variables and many parameters that must be addressed to include varying speeds, directions, and thermal conditions."

Nelson points out that the Lab has drawn on its computational and atmospheric science expertise, supercomputing capabilities, and ongoing work with wind flow and contaminant dispersal to develop what will become an online portal that will provide the wind industry with much-needed data. "Our work in national security has helped develop new tools for energy security," says Nelson, adding that "energy security ensures national security, too."

"If we can find an economically viable way to harness the wind, it's a piece of solving the energy puzzle that we shouldn't blow off." ★

■ Los Alamos research helps predict whether wind turbines, such as this one located close to a building, can be effective despite possible obstructions. Photo: Dreamstime



■ Joshua Bartlett performs final assembly of the FABIA unit, which has a volume of less than 1.2 cubic feet and can be carried easily into the field for on-site sample testing.

ENRICHING TO A POINT

A novel portable device provides real-time results for uranium enrichment assessment.

BY LISA KISNER

Although most of the world's nuclear reactors rely on uranium, natural uranium cannot be used directly in a reactor because its concentration of fissile uranium-235 is too low. Natural uranium is composed of three isotopes: uranium-235, -238, and -234. The concentration of uranium-235 must be increased, or enriched, for reactor use. If that enrichment is continued to reach concentration levels common in nuclear weapons, it threatens nuclear nonproliferation efforts.

That's where the International Atomic Energy Agency (IAEA) comes in.

The Treaty on the Non-Proliferation of Nuclear Weapons—signed by 191 nations since 1968—stipulates that the IAEA can inspect enrichment plants of signatory nations to ensure that uranium is being enriched only for energy production. The most common method used to analyze samples is thermal ionization mass spectrometry, which requires large equipment at dedicated facilities. Not only are results slow to come by, but difficult-to-dispose waste is also produced.

To streamline inspections, Los Alamos National Laboratory scientist Alonso Castro led a team that designed, built, and tested the Fieldable Atomic Beam Isotopic Analyzer (FABIA). FABIA measures the isotopic content of uranium, plutonium, and other actinides with high sensitivity, resolution, and speed. Bulk samples can be collected throughout the nuclear reactor fuel cycle to determine the purity and composition of materials.

FABIA weighs about as much as a suitcase (around 40 pounds) and can be carried or wheeled directly to inspection sites. Results can tell inspectors in fewer than 10 minutes whether uranium has been enriched beyond reactor-grade levels. This capability also aids in the disposition and reprocessing of spent fuel. The knowledge from such quick analyses lowers the cost of energy production and increases safety at nuclear plants.

According to Castro, "FABIA makes the world a better place by aiding in verifying that nations comply with their commitments under nonproliferation treaties."

Additional benefits include that a sample does not require preprocessing or separation, nor does it produce chemical waste. FABIA also provides flexible analysis: Simply by swapping the diode laser, the instrument can be customized to analyze most solid elements in the periodic table.

FABIA's benefits extend to other global security applications, too. For example, if a mysterious nuclear device is detonated, FABIA could help scientists quickly and accurately understand the origin, processing history, and composition of the nuclear material before detonation, as well as the overall fission efficiency of the device.

In addition, FABIA can determine the purity of individual isotopes used in the field of medicine. Because medical isotopes have short lifetimes, it is imperative to rapidly analyze them right at the point of production.

To develop a device with so many applications, Los Alamos needed to draw from a diverse set of skills. "We assembled a team of scientists from a variety of fields: atomic physics, spectroscopy, actinide chemistry," says Castro. "Talent from those fields can be readily applied to nuclear nonproliferation, and it was very exciting to witness such a diverse team working together toward a common goal." ★

■ Los Alamos scientists (from left) David Fobes, Russell Bent, and Harsha Nagarajan were part of a team that developed PowerModelsONM. The technology allows users to design and model networks of microgrids that are more versatile and resilient than most modern power grids.

ENERGY

MICROGRID MODELING

Los Alamos scientists develop breakthrough software for power grid analysis.

BY IAN LAIRD

Nearly every aspect of modern society relies on large and complex power grids to deliver energy. Major disruption to these grids could have significant effects, including loss of human life and economic instability. Climate change is exacerbating the situation by making extreme weather events more powerful and frequent.

"Natural disasters and interference from bad actors on power grid infrastructure are becoming more and more prevalent," says Russell Bent, a scientist at Los Alamos National Laboratory who uses artificial intelligence and operations research to optimize infrastructure networks. "There are constantly news articles about threats like hurricanes, wildfires, and earthquakes impacting the power grid."

One way to improve grid resiliency is by installing microgrids. Microgrids are localized energy grids that contain their own power-generating systems and load storage capabilities. They can operate independently from the main power grid, reducing dependence on central power systems and decreasing the effects of localized, outage-inducing extreme events. The United States currently has 4 gigawatts of microgrid capacity, and 20 percent of that capacity has been added in the past five years.

"But the computational tools to analyze the impacts and potential advanced usage of these microgrids are still lagging," says Los Alamos scientist David Fobes.

Fobes and Bent are part of the development team for PowerModelsONM, a modeling software that allows users to analyze the design, validation, and installation of grid systems. The software is a collaboration among Los Alamos, the National Renewable Energy Laboratory, Sandia National Laboratories, and the National Rural Electric Co-op Association. It was funded by the Microgrid Research and Development Program in the Department of Energy's Office of Electricity and recently won a 2023 R&D 100 award.

"Previous technology has largely focused on the expansion-planning aspect or decision support around adding microgrids under typical operating conditions," Fobes says. "In contrast, PowerModelsONM considers the operational strategies themselves to produce the best actions to take during extreme events or even to improve grid operations under normal conditions."

One of the key capabilities of PowerModelsONM is the ability to model networked microgrids. Microgrids can be networked together so that excess capacity on one microgrid can support emergency backup and jumpstart efforts for another microgrid following an outage. Prior to PowerModelsONM, no software was capable of analyzing the benefits of networking microgrids together. By introducing this capability, users can generate quantifiable data on the financial benefits and resiliency benefits of networked microgrids.

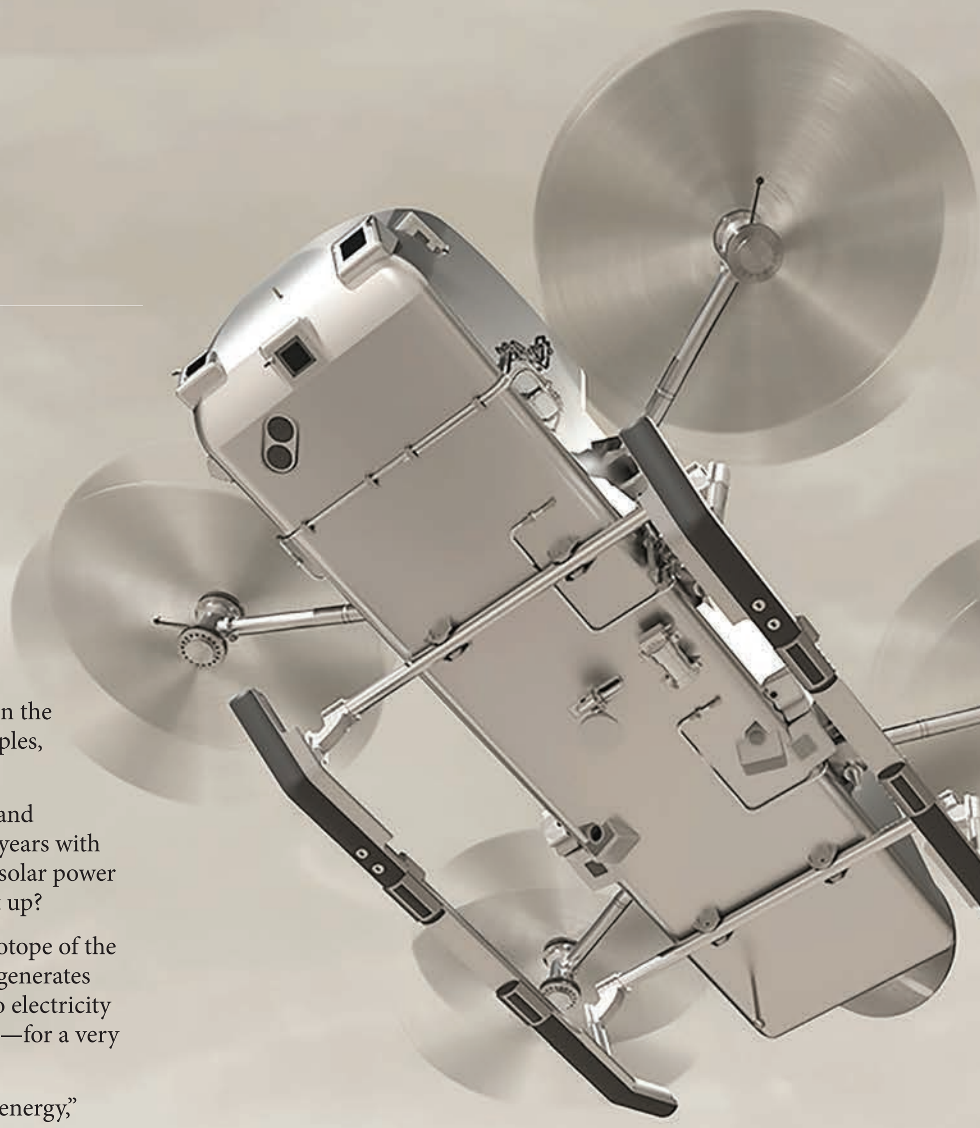
PowerModelsONM was also designed to work with existing technologies, including Hardware-in-the-Loop, a small-scale testing system that allows researchers to simulate how grids might respond in various circumstances. The seamless integration between such platforms allows stakeholders to validate grids to ensure customers will be as safe as possible during an emergency.

"Combined with our rigorous validation and verification," Fobes explains, "operators can confidently test and simulate restoration plans without risk to the electric grid." ★

POWERED BY PLUTONIUM

Los Alamos makes radioisotope power systems for Mars and beyond.

BY MAUREEN LUNN



■ Powered by plutonium heat sources developed at Los Alamos, Dragonfly will explore Saturn's moon, Titan. The moon's dense, calm atmosphere and low gravity are ideal for flying. Image: NASA/Johns Hopkins APL

At this very moment, two rovers—Curiosity and Perseverance—are exploring the surface of Mars. Their mission is to gather data to help scientists understand the potential for life on the Red Planet. The rovers capture images, take samples, record sounds, and chronicle the weather.

Curiosity has been exploring Mars for 12 years, and Perseverance has been on the move for nearly 3 years with potentially a decade more to go, but neither use solar power nor have a refueling source. How do they keep it up?

The rovers are powered by plutonium-238, an isotope of the radioactive element plutonium. Plutonium-238 generates heat as it decays. This heat, which is converted to electricity by a generator, can power a device in deep space—for a very long time.

"Something like the Mars rover requires a lot of energy," says Dave Kolman, the program director for Power Systems Programs and Integration at Los Alamos National Laboratory, where plutonium heat sources are manufactured. "The cold temperatures and long distance to the sun require a reliable power source that has to be radioisotope power."

In addition to powering the Mars rovers, plutonium heat sources manufactured at the Laboratory's Plutonium Facility have powered the Galileo mission to Jupiter (1989–2003), the Cassini mission to Saturn (1997–2017), and others. In 2027, plutonium-238 will power the Dragonfly mission to Saturn's largest moon, Titan.

"We've pressed and made almost every heat source for NASA in the past 50 years right here at Los Alamos," says product engineer Nicholas Wozniak. "When it comes to heat sources, we're the only place that can do this."

The Laboratory produces approximately 10 to 15 heat sources annually. On paper, the process is simple: plutonium-238 is either pulled from existing inventory or arrives fresh from Oak Ridge National Laboratory; turned into an oxide (powder); pressed into small pellets; encapsulated; and sent to Idaho National Laboratory, where the encapsulated pellets are stored until they're placed on spacecraft and blasted into the cosmos.

In reality, manufacturing heat sources is a long and complicated process due to the complexity of plutonium. Handling the radioactive element requires highly trained workers and special equipment, such as a hot press, which is a hybrid furnace and hydraulic press that heats plutonium-238 to extremely high temperatures while compressing it into the right shape and density.

The Laboratory is also continually improving its heat sources. The plutonium pellets that will power the Dragonfly mission, for example, will be smaller and lighter than those on the Curiosity rover. They'll also be used to keep parts of the rotorcraft lander from freezing. "The waste heat from the power system is a key aspect of our thermal design," explains Zibi Turtle, the principal investigator of the Dragonfly mission and a scientist at the Johns Hopkins Applied Physics Laboratory. "The surface of Titan is very cold, but we can keep the interior of the lander warm and cozy using the heat from plutonium-238 pellets manufactured at Los Alamos." ★

ENERGY

▪ Sara Pacheco works with a bioreactor, the system responsible for using algae to fix carbon into molecules that are then modified by the chemistry team to produce sustainable aviation fuel.

GREEN JET FUELS TAKE OFF

Researchers aim to decarbonize the aviation industry.

BY IAN LAIRD

We've all heard of electric cars and semitrucks that are powered by hydrogen fuel cells, but what about airplanes?

"The problem with aviation is that if you want to move to a new technology like hydrogen, it's going to take a long time," says Paolo Patelli, a scientist in the Information Systems and Modeling group at Los Alamos National Laboratory. "Designing an airplane is complicated, and there are a lot of risk factors to consider compared to designing a truck."

While more sustainable aircraft are designed and tested—which could take decades—Patelli says sustainable aviation fuel (SAF) is a good nearer-term solution. SAF is made from renewable biomass and waste resources, and according to the Department of Energy, has "the potential to deliver the performance of petroleum-based jet fuel but with a fraction of its carbon footprint, giving airlines solid footing for decoupling greenhouse gas emissions from flight."

However, aviation fuel—of any type—is more complex than automobile fuels. Aviation fuel must be able to withstand extreme environmental conditions, including fluctuations in temperature and air pressure.

When it comes to SAF, researchers at Los Alamos are optimistic and involved in several projects that are exploring the future of sustainable aviation fuel.

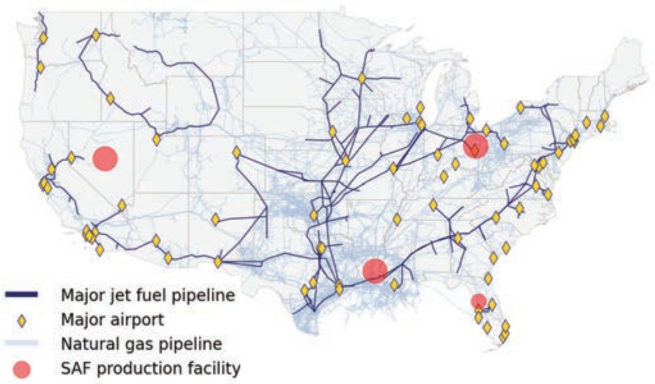
One project, which includes Patelli and fellow scientist Chloe Zhou, involved collecting data on where potential biofeedstock (things like plant oils and algae that are used in SAF production) is located and where demand for SAF will be highest. Then, the team derived an algorithm to connect supply with demand and model two production pathways.

The first pathway is a centralized model of vertically integrated production. That means one plant would be responsible for all production steps. The second pathway is a two-step process where biofeedstock would be converted into methane, transported using gas pipelines, and then chemically transformed into SAF by many smaller, decentralized SAF production facilities.

"We will need to produce SAF in high quantities if we want to meet decarbonization goals," Patelli says. "That's why decentralized production might be beneficial. Those plants are smaller projects, smaller investments that are much easier to bootstrap."

Currently, commercial-scale efforts to produce SAF are few and far between because aviation companies don't have any incentive to switch fuels. This is where a second Lab project comes in.

A team led by Babetta Marrone of the Bioscience division received funding for a three-year Laboratory Directed Research and Development project called Versatile Synthesis Platforms for Advanced Biomanufacturing (VESPA). VESPA focuses on



A map produced by Paolo Patelli and his team shows what a decentralized biofuel manufacturing and transportation network could look like.

developing a SAF production process that is both economically and environmentally sensible. The team will explore three different areas. First, a techno-economic analysis will evaluate the economic viability of production processes.

"It's really important to use the economic analysis to guide the biological and chemical research," says Bill Kubic, a research and development engineer who helps lead the analysis. "Understanding things like cost can direct research toward the processes that are economically appropriate and more competitive in the market."

Although Kubic admits production of SAF might initially be more expensive than traditional jet fuel, he believes SAF could eventually become competitive with petroleum prices. This would mean a shift away from a decentralized production model to a centralized model where economies of scale could be leveraged to make the process more economical.

Once Kubic has completed his analysis, scientists Raul Gonzalez and Xiaokun (Claire) Yang will step in. Gonzalez and Yang will work on two parallel tracks for the biological and chemical processes with the aim of merging the two processes in the most efficient manner possible.

The biology hinges on photosynthetic organisms called cyanobacteria, which are fast-growing microbes that capture, use, and transform carbon dioxide molecules from the atmosphere. Cyanobacteria can be engineered to produce isoprene, ethylene, and polyhydroxalkanoates—three carbon-rich molecules that can be chemically modified to become jet fuel compounds. The biologically produced molecules can also be converted to valuable co-products, such as plastics, thus helping to offset the jet fuel production costs.

After the initial genetic transformation is complete, the team will determine the percentage of fixed carbon that turns into the desired molecule. "Once we have done that, we just begin an iterative process called design, build, test, learn," Gonzalez says. "Whatever we learn at the end, we will use to try and improve our product yields."

The team will continue this process until it produces a percentage of intermediate molecules that is considered economically competitive with petroleum. The available carbon within a cyanobacterium's cell is used for a variety of metabolic processes, and new engineered reactions may not perform efficiently.

The target amount for each project will be dictated by Kubic's analysis, but Gonzalez estimates they will need to achieve at least 20 percent of the total fixed carbon going into target molecules.

Meanwhile, Yang's team will be focused on chemically converting the key bio-derived intermediates, such as isoprene, to SAF molecules. SAF is a complex mixture of non-oxygenated hydrocarbons with 8 to 14 carbon atoms and properties defined by strict fuel standards. Selective chain-extension reactions are key chemistry operations that have been established and expanded upon by Yang's team to synthesize SAF-range molecules with application potential from the bio-derived intermediates.

"Controlling carbon chain lengths is a major challenge," Yang says. "You are coupling multiple active species together, but you also need to cut off the reaction before the chain overextends."

Each of the different carbon compounds performs a different function in jet fuel and synergistically determines the fuel's properties like heating value, viscosity, freezing point, and more. Therefore, it is crucial that Yang's team creates a blend of compounds that meets the properties and specifications of jet fuel.

"Once we produce the jet fuel range compounds, then there are a series of in-house property tests we conduct to ensure the mixture meets the property specifications of jet fuel," Yang says. "The percentage of our products to blend in current airplane engines can then be determined after blending tests. Our ultimate goal is to achieve 100 percent renewable fuels blending."

Throughout the project, Yang and Gonzalez will work together to integrate the two processes so that the biology team's products are efficiently fed into the chemical reactions. From there, it is a matter of evaluating how scaling up to commercial-scale production would work.

"One of the problems here at the Lab is we can develop all of these materials and processes, but we are doing so at bench-scale," Kubic says.

Members of the team believe reaching full commercial-scale production could take between 8 and 10 years.

"It's difficult, but I think we're on the right track," Gonzalez says. "The multidisciplinary nature of the Lab helps. Bringing together people with different areas of expertise is how we're going to solve this." ★

From left: Raul Gonzalez, Anjana Talapatra, Bill Kubic, Babetta Marrone, Shounak Banerjee, Claire Yang, and Paolo Patelli form the VESPA team.

QUOTED

"I often call DOE the solutions department, and of course the labs are where all those solutions begin. We've got a huge role in solving this climate problem."

—U.S. Department of Energy (DOE) Secretary Jennifer Granholm during a recent visit to Los Alamos National Laboratory

■ Los Alamos scientists use a drone to help locate abandoned oil and gas wells. Researchers suspect there may be as many as 2 million orphaned wells across the United States.

ENVIRONMENT

LOOKING FOR WHAT'S LOST

A Los Alamos scientist leads a consortium that locates orphaned wells.

BY JILL GIBSON

Abandoned and forgotten—that's the plight of hundreds of thousands of oil and gas wells in the United States, which are known as orphaned wells. Based on information from most oil- and gas-producing states, the Interstate Oil and Gas Compact Commission (IOGCC) estimates the number of undocumented orphaned wells to be between 310,000 and 800,000, though the true number is likely higher. Some researchers suspect that as many as 2 million undocumented orphaned wells exist across the United States.

Many orphaned wells date back to the 1850s—long before any environmental regulations were in place. Companies drilled wells and then went bankrupt, leaving many of their wells undocumented, leaking methane, and contaminating groundwater. These orphaned wells continue to pollute

backyards, parks, and other public spaces; emit toxic chemicals; and harm wildlife.

Such wells are located all over the country, including highly populated parts of New York and Pennsylvania, and even downtown Los Angeles. In most cases, nothing on the land surface indicates a well lies below the ground. In desert areas, such as the Four Corners, orphaned wells can sometimes be identified by sight, but in places like the East Coast, many well sites are overgrown and cannot be identified without special techniques, which is where America's national laboratories can help.

In January 2023, the United States Department of the Interior was allocated $4.7 billion to address the orphaned well problem. This led to the Department of Energy (DOE) receiving $40 million to advise on best practices for locating the wells. DOE, in collaboration with IOGCC, created a research consortium made up of Los Alamos, Lawrence Livermore, Sandia, and Lawrence Berkeley national laboratories and the National Energy Technology Laboratory.

Hari Viswanathan, a scientist in the Energy and Natural Resources Security group at Los Alamos, leads the consortium. "Finding these wells is technically challenging," Viswanathan says. "There is not one silver bullet that allows you to find them. We have to use multiple signatures and find cost- and time-effective strategies for collecting information and sorting through distracting or false data."

Viswanathan says the five-lab consortium is taking a divide-and-conquer strategy. "The consortium's job is to figure out the most efficient way to find these things." One approach involves using fixed-wing drones, which carry multiple signature detectors to locate wells. Another strategy involves training artificial intelligence to extract information from handwritten historical records from the original drilling of the wells.

"Before we formed this consortium, people were using methane sensors, magnetometers, and aerial photography, but they were not working together," Viswanathan says. "With this consortium we can combine resources." Along with locating the wells, the group will determine which ones need mitigation. Not every abandoned well is leaking, and some are better off left alone, Viswanathan says.

Viswanathan says he is passionate about this project. "You can make large inroads on eliminating pollution and addressing the climate issue and have an impact," he says. "We will come up with best practices on how to identify these orphaned wells and characterize their environmental risk so the issue can be fixed." ★

HOW TO TRACK AN ARTIFICIAL METEOR

OSIRIS-REx, NASA's asteroid-sampling mission, provides Laboratory researchers with a unique research opportunity.

BY JAKE BARTMAN

Scientists study meteors to learn about interplanetary space and to better understand impact risks, among other reasons. Unfortunately, meteors are unpredictable, liable to enter the Earth's atmosphere with little warning. That makes it difficult for researchers to test the kinds of sensing equipment that could help the scientific community understand the behavior of meteors and objects returning to Earth from space.

On September 24, 2023, however, researchers from Los Alamos and Sandia national laboratories had advance warning of the arrival of a meteor, albeit an artificial one: the sample return capsule of the National Aeronautics and Space Administration's (NASA's) OSIRIS-REx spacecraft.

NASA launched OSIRIS-REx in 2016. The spacecraft, whose name is an acronym for Origins, Spectral Interpretation, Resource Identification, and Security—Regolith Explorer, was tasked with traveling to the 4.5-billion-year-old asteroid Bennu and collecting about a coffee cup's worth of dust and rocks from the asteroid's surface. This sample is expected to provide researchers with invaluable insight into the earliest days of the universe.

Onboard OSIRIS-REx, the sample was packaged in a steel container, which was in turn sealed inside a conical return capsule the size of a small air conditioner. When OSIRIS-REx passed by Earth on September 24, the spacecraft released the sample return capsule for a vertiginous plunge back to the planet. After falling some 150 miles, the capsule deployed a parachute and touched down safely in the U.S. Department of Defense's Utah Test and Training Range.

Before landing in the Utah desert, though, the capsule reached speeds of nearly 28,000 miles per hour. Those speeds made the capsule the second-fastest artificial object ever to travel through Earth's atmosphere (the fastest was the sample return capsule that came back to Earth in 2006 as a part of NASA's Stardust mission, clocking in at some 28,860 miles per hour).

As the OSIRIS-REx return capsule streaked through the atmosphere, heated to temperatures greater than 5,300 degrees Fahrenheit, the capsule generated sound and gravity waves. When the capsule passed near the town of Eureka, Nevada, researchers from Los Alamos and Sandia—the latter of which led the interlaboratory collaboration—used advanced sensing equipment to detect those waves.

From left, Colorado State University student Elisa McGhee and Los Alamos National Laboratory researchers Luke Beardslee, Loic Viens, and Chris Carr take a break from unspooling optical fiber in Newark Valley, Nevada. This fiber was used as a continuous seismoacoustic sensor to monitor the arrival of the OSIRIS-REx spacecraft's sample return capsule.

A team led by Los Alamos' Chris Carr, who also directed the Laboratory's involvement in OSIRIS-REx generally, positioned itself beneath the capsule's trajectory and used distributed acoustic sensing (DAS) technology to monitor the capsule's return. DAS involves deploying a network of fiber-optic cables to detect seismic or acoustic signals. In the case of the OSIRIS-REx capsule, DAS sensors were deployed over more than 7 miles.

According to the Laboratory's Carly Donahue, who oversaw the deployment of DAS during the capsule return, interest in DAS has been "exploding" in recent years as the technology is increasingly deployed for seismic, pipeline, and traffic monitoring, among other applications.

"There are many unknowns about DAS," Donahue says. "This is the first time that DAS sensors have been used to record an artificial meteoroid, and we were thrilled to see the signal clearly over kilometers of fiber. This expands our knowledge of the signal frequencies and pathways that DAS is capable of acquiring."

Another Los Alamos team, this one led by physicist Bob Haaser, was also positioned beneath the capsule's flight path. Haaser's team used ground-based GPS receivers to measure the way that sound and gravity waves made by the capsule spread upward into the ionosphere (a part of the atmosphere that extends from 50 to 600 miles above the Earth's surface).

Finally, a team led by geophysicist Phil Blom was positioned some distance away from the flight path, using instruments called microbarometers to measure infrasonic sound waves—that is, sound waves whose frequency lies below the range of human hearing—emitted by the capsule.

"We're building a more complete model of how infrasound is generated by sources," Blom says. "The capsule return gave us a chance to test those models."

Researchers from Sandia, meanwhile, deployed infrasound and seismic equipment on the ground and on weather balloons to monitor the capsule's return.

OSIRIS-REx provided a unique opportunity to test these varied sensing technologies. Unlike other objects that travel through the atmosphere to Earth, researchers knew ahead of time the sample return capsule's size, velocity, and entry angle. Knowing these details provided a kind of "ground truth" that researchers could use to verify sensor measurements.

The combination of all instrumentation deployed by scientists from Sandia and Los Alamos made the OSIRIS-REx sample capsule's return better monitored than any comparable event. "We had orders of magnitude more instruments for this project than for any other capsule return," Carr says. "There were more components under the capsule's trajectory alone than there were in total for the Stardust mission."

That degree of preparation ensured that researchers from both labs were able to make the most of a unique research opportunity.

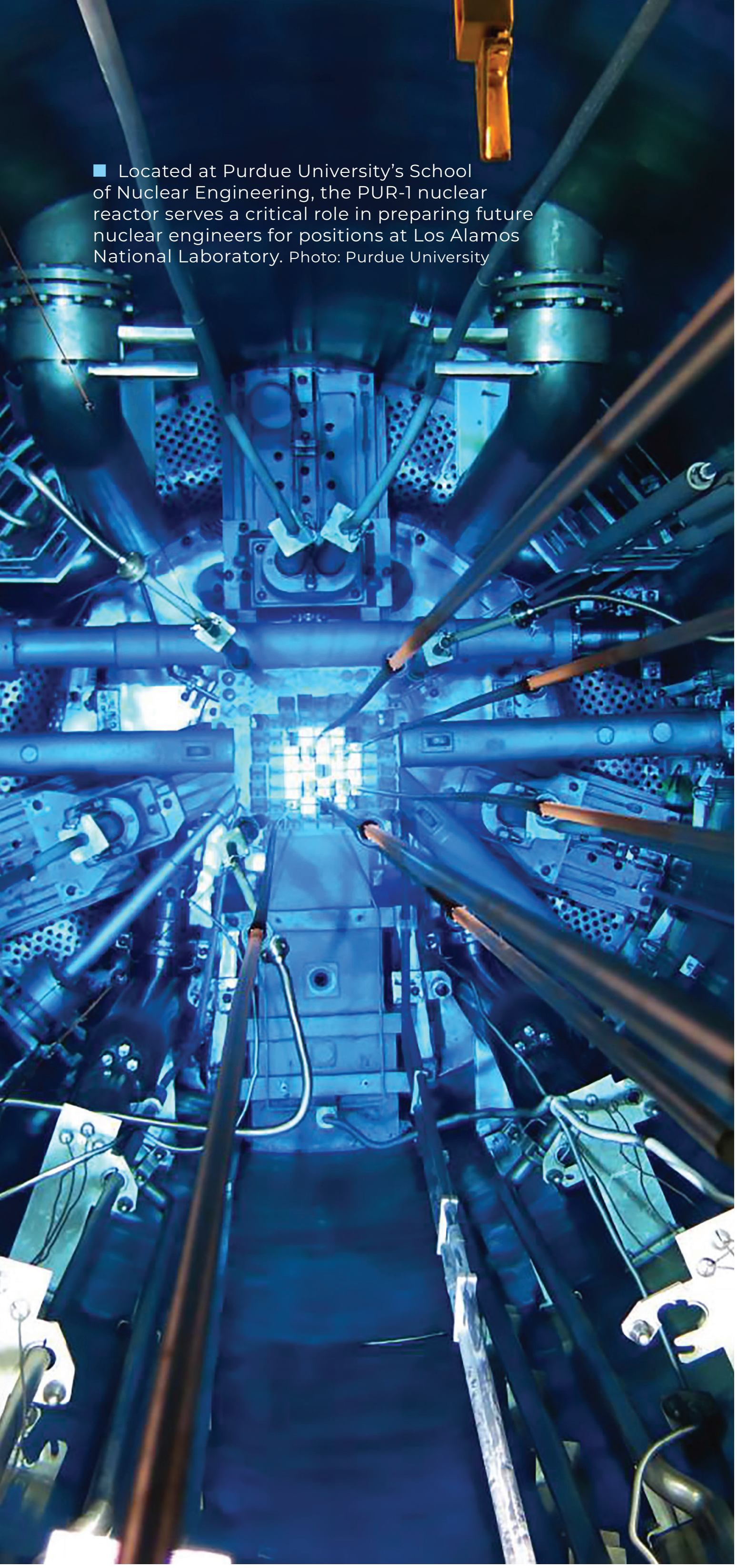
"It's like lightning: you never know when it's going to strike," Haaser says. "But this time we knew when and where it was going to strike." ★


FISSION

FORWARD

Los Alamos has been a leader in fission research since the 1940s. Today, the Laboratory's atom-splitting experts forge ahead in pursuit of clean energy.

BY JILL GIBSON



■ Located at Purdue University's School of Nuclear Engineering, the PUR-1 nuclear reactor serves a critical role in preparing future nuclear engineers for positions at Los Alamos National Laboratory. Photo: Purdue University

Wearing a T-shirt emblazoned with the words "fission is my mission," Dasari V. Rao, the director of Los Alamos National Laboratory's Civilian Nuclear Program, is optimistic about the future of nuclear energy. Rao says recent advances in nuclear fission reactor technology, both at the Lab and across the globe, are paving the way for a solution to climate concerns.

Research on nuclear fission is not new to Los Alamos. In fact, it dates back to the Manhattan Project, the United States' secret mission to split the atom, harness its power, and build the world's first atomic bombs. Today, scientists at Los Alamos are delving into the next generation of nuclear fission breakthroughs. Researchers are uncovering new ways to use the process discovered more than 80 years ago to meet the nation's energy needs.

Current work at the Lab involves research into the development of new fuels and materials for both existing and newly developed nuclear reactors. Another key area involves the design of small modular reactors and microreactors. These concepts offer the possibility of portable, easy-to-produce reactors that can meet a variety of energy needs—including the possibility of fueling deep-space exploration or powering human habitats on the moon or Mars.

"The Lab's ability to make new types of reactor fuel and work with industry to build efficient reactor designs will lead to success," Rao says. "Nuclear power is essential for producing affordable clean energy."

What is nuclear fission?

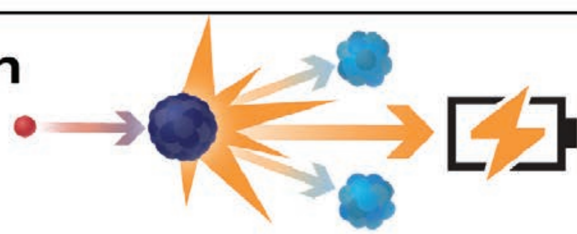
Fission takes place when a neutron slams into a larger atom, splitting the larger atom into two smaller atoms. Additional neutrons are also released during the collision, which initiates a chain reaction of splitting atoms—or fissions. When each atom splits, a tremendous amount of energy is released.

Nuclear reactors contain and control the nuclear fission process while releasing heat at a controlled rate. Nuclear power plants transform the energy that the reactors release into electricity. Currently, all commercial nuclear reactors (called light-water or conventional reactors) built in the United States use uranium dioxide as fuel with water as a moderator that helps slow down the

ENERGY 101

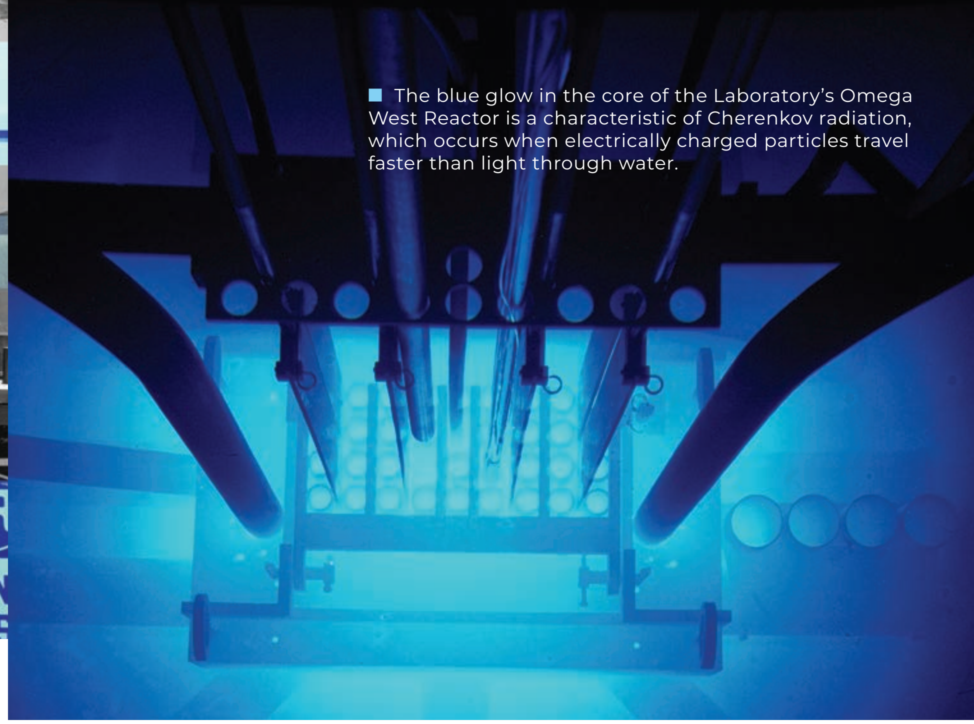
Nuclear fission

Fission takes place when a neutron slams into a larger atom, splitting the larger atom into two smaller atoms. When the atom splits, a tremendous amount of energy is released.



Nuclear

Completed in 1956, the Omega West Reactor was initially used to support the Lab's weapons work. The reactor operated until 1992.



The blue glow in the core of the Laboratory's Omega West Reactor is a characteristic of Cherenkov radiation, which occurs when electrically charged particles travel faster than light through water.

neutrons produced by fission. The fission creates heat, and the power plant uses that heat to turn water into steam, which then turns a turbine to produce electricity. The reactor core (where the fissions take place) must be kept cool or the nuclear fuel will overheat and melt. Water is used as a coolant.

Built in 1942 at the University of Chicago, the first fission reactor, called Chicago Pile-1, generated the first self-sustaining fission reaction. Shortly thereafter, nuclear reactors constructed during the Manhattan Project were used to produce the uranium and plutonium that would eventually go into the Fat Man and Little Boy atomic bombs. At the same time, scientists were exploring the energy applications of nuclear fission. After World War II, in 1951, an experimental reactor in Idaho generated the first electricity from nuclear energy. In 1954, the United States used the same approach to launch the first nuclear-powered submarine, and the U.S. Navy continues to operate a nuclear-powered submarine program today.

In 1955, the Atomic Energy Commission announced a program to develop nuclear power plants. During the 1960s and '70s, more than 100 commercial reactors went into operation in the United States.

The decades of decline

Although the nuclear industry started off strong in the United States, that growth soon plateaued. The U.S. Energy Information Administration (EIA) reports that nuclear reactors were responsible for only 19–20 percent of the total annual U.S. electricity generation from 1990 through 2021. As of August 1, 2023, the United States had 93 operating commercial nuclear reactors at 54 nuclear power plants in 28 states. The newest reactors, which are in Georgia, began operation in July 2023, but most reactors are older, with an average age of 42 years. The oldest commercial reactor, located in New York, began operation in December 1969.

What slowed the growth of the industry? Scientists admit that nuclear energy has always suffered from an image issue. "With fission reactors, the big problem we have had is the tie-in with nuclear weapons, which leads to negative perceptions," Rao says.

Safety concerns are also part of the problem. Rao explains that three high profile nuclear reactor accidents have colored public opinion. "The incidents at Three Mile Island [the 1979 partial meltdown in Pennsylvania], Chernobyl [the 1986 incident in the Soviet Union caused by flawed reactor design and operator errors], and Fukushima Daiichi [the 2011 meltdown in Japan that occurred when a tsunami disabled cooling ability] caused a lot of panic."

These incidents led to increased regulatory oversight, which slowed the industry's growth but also prompted scientists to improve reactor technology and fuel. Rao notes that "we have solved many of the safety issues that caused concern in the past."

Hand in hand with problems related to public perception of nuclear reactor safety are worries about nuclear waste. Nuclear reactors produce no greenhouse gases;

> "This is the next generation of nuclear energy and one of the best solutions for climate issues."
> —Josh White

From 1959 to 1971, Los Alamos National Laboratory conducted the Ultra-High Temperature Reactor Experiment to research ways to lower the cost of nuclear power. In this photo, technicians examine the fuel system of the reactor.

however, they do create radioactive waste. This waste is primarily from used nuclear fuel, which is a solid both going into the reactor and coming out. When the used fuel is removed from the reactor, it is cooled in steel-lined concrete pools of water and then stored in dry, sealed casks made of steel, concrete, or other protective shielding. Casks are currently stored at individual reactor sites.

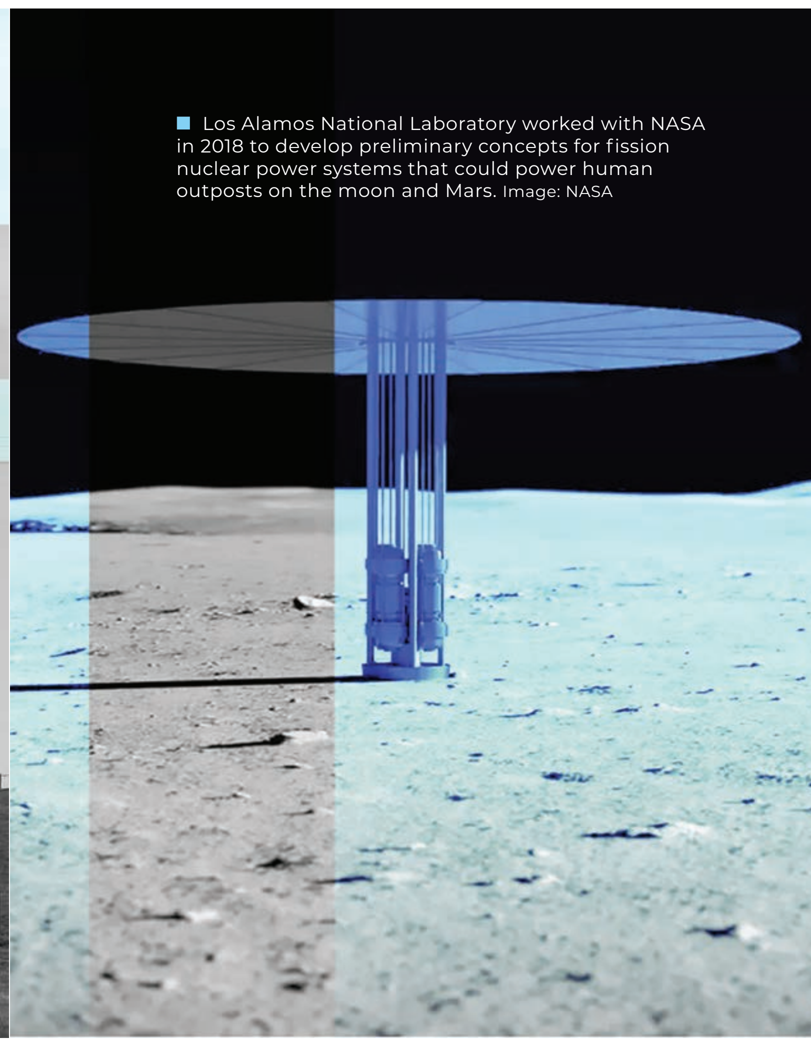
Time and money have also been roadblocks to embracing nuclear energy. Constructing massive nuclear reactor-fueled power plants is expensive and time consuming. The newest reactors built in Georgia ran $17 billion over budget and were completed 7 years behind schedule, according to ABC News. "What company is willing to invest $10 to $20 billion, wait up to 10 years to turn on the plant and then wait for 20 years to recover that money?" Rao asks. Many new nuclear energy inventions are targeting ways to solve that problem, he adds.

> "I expect that microreactors will be pretty big game changers going forward."
> —Dasari V. Rao

The future of fuels

One of the ways Los Alamos scientists are making light-water reactors safer and more efficient is by developing accident-tolerant fuels. "We're developing fuels with higher thermal conductivity to eliminate problems if a plant loses its cooling ability, which is what happened in the Fukushima incident," says Scarlett Widgeon Paisner, a research and development scientist at Los Alamos. "Developing composites using existing fuels—such as uranium dioxide—and researching high-density fuels are ways we can enhance both safety and efficiency of the reactors." Paisner points out that new fuels require extensive testing and must adhere to rigorous government regulations. "We have to know exactly how each fuel behaves under every condition possible, both normal and off-normal conditions."

Los Alamos scientists aim to make light-water reactors (such as the one pictured here) safer and more efficient by developing accident-tolerant fuels. Photo: Dreamstime



Los Alamos National Laboratory worked with NASA in 2018 to develop preliminary concepts for fission nuclear power systems that could power human outposts on the moon and Mars. Image: NASA

Along with boosting safety, the new fuels have the added benefit of increasing reactor efficiency, which adds to commercial viability, according to Rao. “By using more advanced fuels, you can make more power from the same amount of fuel—denser and better fuels that are safer and have real financial merits,” he says.

The development of new fuels is also impacting the actual design, structure, and size of reactors. “We are doing research on high-density fuels that don’t require as much enrichment, which means the reactor can be scaled down,” says Josh White, a senior scientist in the Lab’s Materials Science and Technology division. “Decreasing the amount of uranium needed in the reactor makes the reactors smaller and easier to build.”

One new fuel type under development is high-assay, low-enriched uranium (HALEU), which contains an increased concentration of uranium-235 (the fissile uranium isotope) to improve reactor performance, reduce refueling needs, and decrease waste volume. HALEU would allow researchers to design new types of reactors that can operate for decades without refueling and that produce less waste.

“Los Alamos National Laboratory is one of the few places in the country that can make that fuel,” says White, noting that HALEU is not commercially available in the United States. This is a problem because demonstration (prototype) reactors require hundreds of kilograms of fuel to achieve proof of performance.

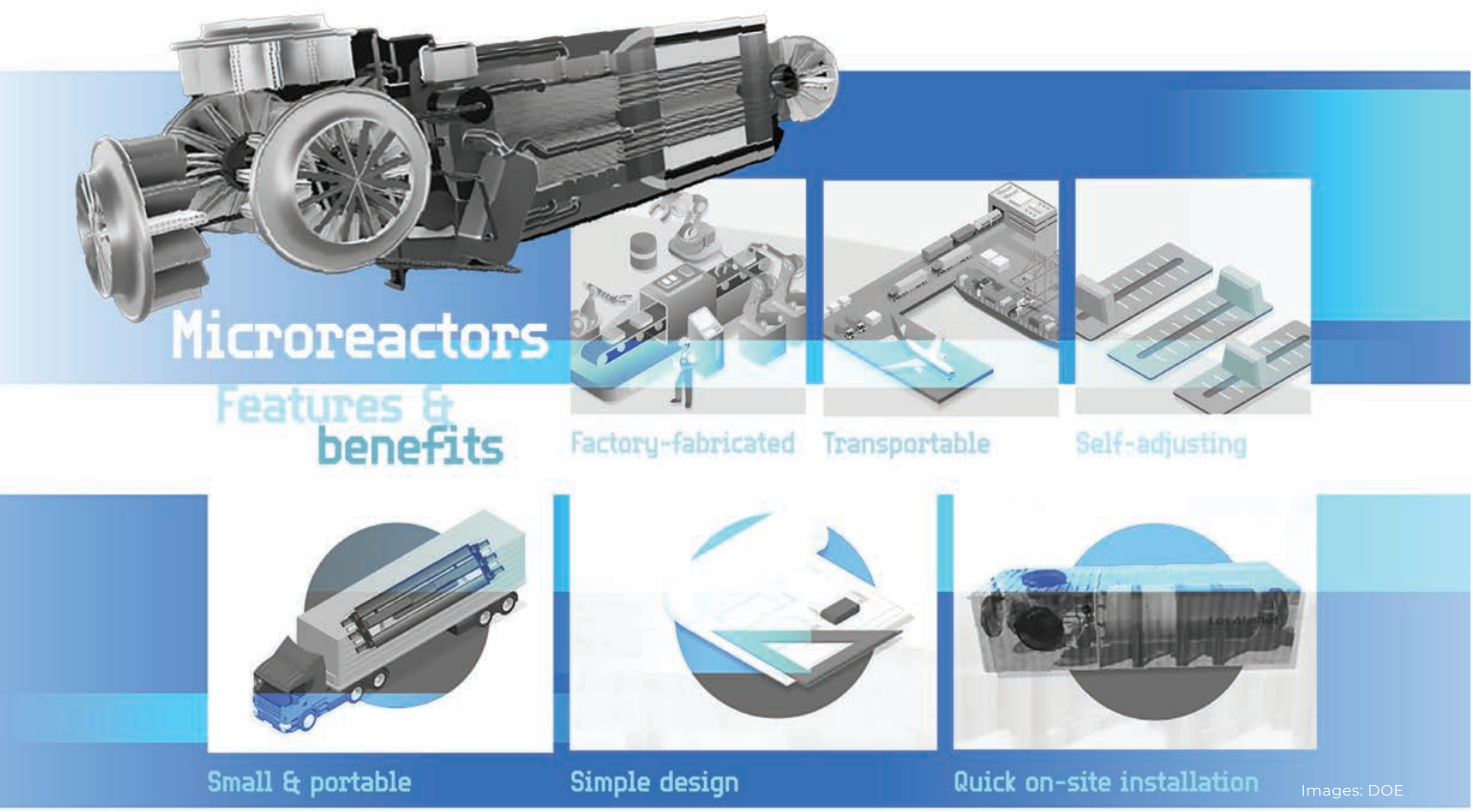
To bridge the gap, the Low-Enriched Fuel Fabrication Facility (LEFFF) is being built at Los Alamos and is expected to be fully operational by 2025. LEFFF will start by fabricating HALEU for Kairos Power, a private company with a New Mexico facility that is making nuclear fuel pellets for a demonstration reactor under construction in Tennessee.

LEFFF will make a variety of different types of fuels, working with one customer at a time. “We will be a national tool to facilitate the maturation of fuels,” says LEFFF team leader Tim Coons. “LEFFF will serve as a launching pad for these advanced reactor companies to move to the commercial stage of reactor development.”

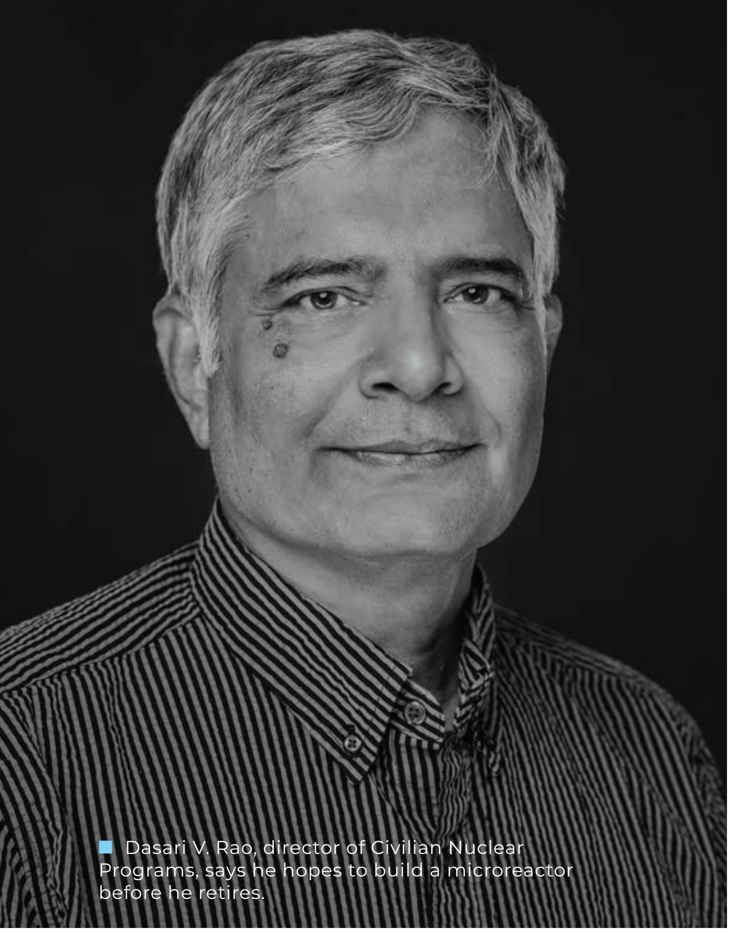
When fully operational, the LEFFF team will use automation and advanced technology to focus on quality, performance, safety, and cost of whatever type of fuel the new reactor designs require. “This facility is the catalyst to promote the next generation of advanced fuels coupled with advanced nuclear reactors,” Coons says. “If we are successful, you are going to start to see nuclear reactors used commercially throughout the United States.”

The spotlight on size

So, what will these advanced reactors look like? When it comes to nuclear reactors, bigger isn’t necessarily better. Los Alamos scientists are working with industry partners to develop small modular reactors and microreactors—diminutive, easy-to-produce, portable sources of nuclear energy.



Images: DOE



Dasari V. Rao, director of Civilian Nuclear Programs, says he hopes to build a microreactor before he retires.

> "Our goal is to develop reactors that can be fully factory manufactured and deployed fast."
> —Dasari V. Rao

"Our goal is to develop reactors that can be fully factory manufactured and deployed fast," Rao says. These reactors can fit on a plane, train, or truck for quick and easy delivery to remote areas, such as isolated military bases or communities hit by natural disasters. Need more power? Add multiple reactors. They can be used in groups to produce low-carbon energy and can operate as part of the electric grid, independently from the electric grid, or as part of a microgrid, a self-sufficient energy system that can be connected or disconnected from the larger power grid.

Microreactors can produce between 0.1 and 20 megawatts of energy, whereas the smallest operating U.S. nuclear power plant produces 581 megawatts. To put that in perspective, a microreactor generating 10 megawatts of energy could produce around 10 years or more of electricity for more than 5,000 homes, 24 hours a day, 7 days a week.

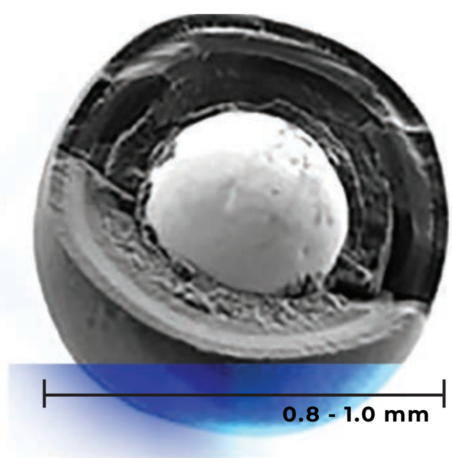
Microreactors are self-contained within a single portable unit. Scientists say these tiny power generators are expected to operate for years without refueling or waste removal. "They are basically for places that are hard to get power to, such as mine sites," White says. "Or, you could put one up in the Arctic for 10 to 30 years and leave it alone."

Rao says the key to success is standardizing production of reactor components to speed up fabrication time and cut down on costs. He describes the technology as still in the growing stages and notes he is cautiously optimistic about the future. "I expect that microreactors will be pretty big game changers going forward," he says. "But we need to be able to deploy them, have them operate somewhat autonomously, and have regulators feel comfortable about that."

The materials matter

Another area Los Alamos scientists are working on is the development and testing of new materials for moderators and reactor construction. Moderators are any material placed in the reactor core to slow down neutrons and create more fissions. By experimenting with different types of moderators, Lab researchers are finding ways to make reactors safer. "The benefit of solid moderators is if the temperature gets too hot, the reactor will passively shut down without an operator," White says. "Safety is dramatically enhanced without requiring the human part of the equation. It's not possible for the reactors to fail. They are inherently engineered not to fail."

One of the moderators Los Alamos scientists are developing is yttrium hydride—a rare earth metal and hydrogen mixture. "This moderator allows us to make smaller, more efficient microreactors that produce fewer waste products," says Los Alamos nuclear engineer Holly Trellue.



Tristructural isotropic (TRISO)-coated particle fuel is a key part of many advanced reactor designs.

Other materials research focuses on methods used for cooling, such as replacing water cooling with molten salt (see p. 6), and advanced materials to meet the unique demands of the smaller reactor designs.

"To be able to produce power efficiently in a microreactor," Trellue explains, "we would like to be able to operate at as high a temperature as possible, so we are experimenting with different structural materials, advanced fabrication methods, and new approaches to shielding."

She points out that one of Los Alamos' key contributions to reactor advancements is the development of heat pipes that use passive cooling to make the reactors safer and more portable. "Los Alamos is the expert on heat pipe technology," she says. "As a Lab we have always had great ideas, state-of-the-art facilities, and expertise to contribute to advanced reactor systems."

The next step for nuclear

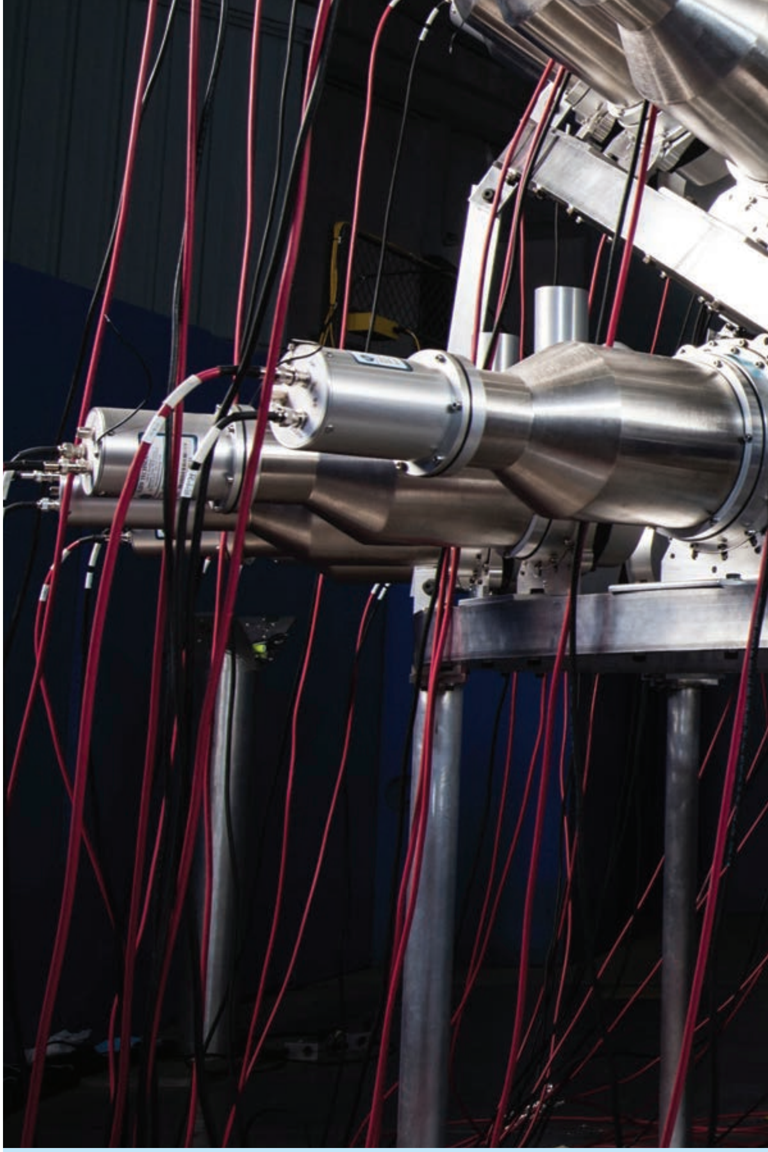
If it seems as though Los Alamos researchers are reaching high with their new reactor ideas, they are—including all the way to outer space. The Lab has supported research on nuclear propulsion technology and the possibility of using reactors to power human outposts on the Earth's moon and Mars. In 2018, the Laboratory—in conjunction with National Aeronautics and Space Administration and the Department of Energy—tested a system named KRUSTY (short for kilopower reactor using Stirling technology).

Development of new technology and collaborations to support both space and terrestrial applications will continue at the Lab. Trellue says she has many reasons to feel excited about this work, including "developing clean energy sources, helping remote communities meet their energy needs, and being part of the nuclear growth of this country."

Coons shares that commitment to continued nuclear research. "It's an incredibly exciting time to be a part of this. I think nuclear is the future," he says. "The demonstration reactors are part of reaching that—showing people these reactors are viable and safe."

White agrees. "These are not your grandfather's or great-grandfather's reactors," he says. "This is the next generation of nuclear energy and one of the best solutions for climate issues."

As for Rao, he's ready for action. "I want to build a microreactor before I retire. A really small, completely mobile reactor," he says. "We have the ability to do that here at Los Alamos." ★



THE CHI-NU PHYSICS EXPERIMENT

New data sheds light on the fission of actinide isotopes.

BY BRIAN KEENAN

The Chi-Nu project, a years-long experiment by researchers at Los Alamos and Lawrence Livermore national laboratories that measures the energy spectrum of neutrons emitted from neutron-induced fission, recently concluded the most detailed and extensive measurement and uncertainty analysis of three major actinide isotopes: uranium-238, uranium-235, and plutonium-239.

Actinides are the 15 elements, all radioactive, with atomic numbers from 89 to 103. These elements, and the chain reactions they can undergo, are important for nuclear weapons and energy reactors. When a nucleus undergoes fission, or splits, several neutrons are released, potentially inducing fission in neighboring nuclei to create a chain reaction. The probability of subsequent reactions in the chain depends on the energy of the fission neutrons.

"Nuclear fission and related nuclear chain reactions were only discovered a little more than 80 years ago, and

■ Jaime Gomez (left) and Keegan Kelly set up the Chi-Nu experiment, calibrating detector distances and installing gas lines for the fission-counting target (center).

"Nuclear fission and related nuclear chain reactions were only discovered a little more than 80 years ago, and experimenters are still working to provide the full picture of fission processes for the major actinides."

—Keegan Kelly

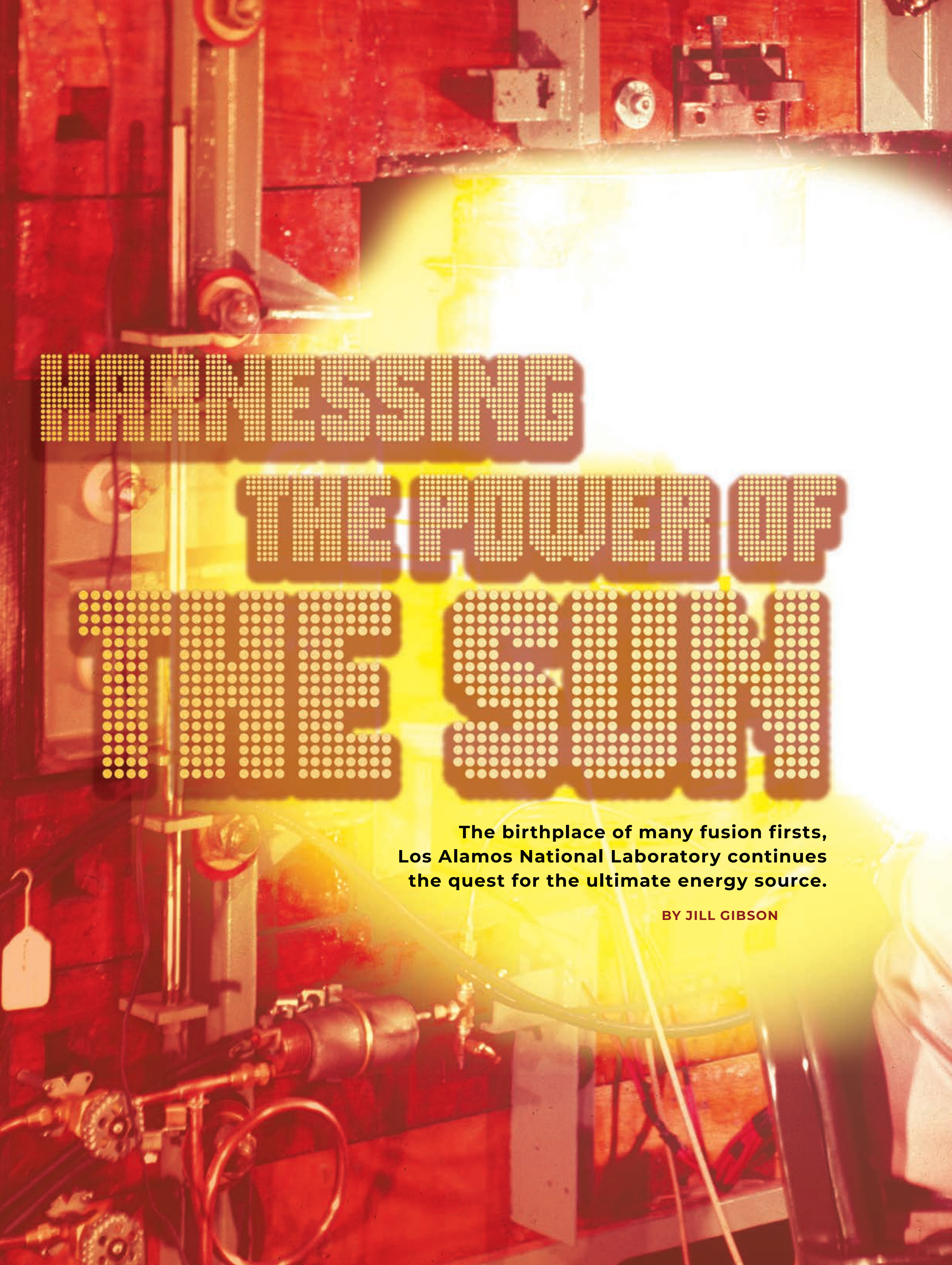
experimenters are still working to provide the full picture of fission processes for the major actinides," says Los Alamos physicist Keegan Kelly. "Throughout the course of this project, we have observed clear signatures of fission processes that in many cases were never observed in any previous experiment."

The Chi-Nu team's final study, conducted on the isotope uranium-238, was recently published in *Physical Review C*. The experiment measured uranium-238's prompt fission neutron spectrum: the energy of the neutron inducing the fission and the potentially wide-ranging energy distribution (the spectrum) of the neutrons released as a result. Chi-Nu focuses on "fast-neutron-induced" fission, with incident neutron energies in millions of electron volts, where there have typically been very few measurements.

The study was conducted at the Weapons Neutron Research facility at the Los Alamos Neutron Science Center (LANSCE), where a proton beam hit a tungsten target, generating neutrons that traveled along a flight path. When those neutrons hit a sample of uranium-238, fission events occurred and were measured along with the emitted fission neutrons.

Together with similar measurements of uranium-235 and plutonium-239, the results from the Chi-Nu experiment are now, in many cases, the dominant source of experimental data guiding modern efforts to evaluate the prompt fission neutron spectrum. The data inform nuclear models, Monte Carlo calculations, reactor performance calculations, and more.

Although the Chi-Nu experiment is complete, researchers are now applying the skills and methodologies they've acquired to study other isotopes and reactions. They are currently focused on the fission of plutonium-240 and uranium-233—two more snapshots in the full mosaic of actinide isotopes—as well as neutron scattering reactions. ★



HARNESSING THE POWER OF THE SUN

The birthplace of many fusion firsts, Los Alamos National Laboratory continues the quest for the ultimate energy source.

BY JILL GIBSON

■ In the 1950s, Los Alamos scientist James Tuck designed, built, and tested the first toroidal magnetic fusion pinch machine, named the Perhapsatron.

FOR DECADES, in the mountains of northern New Mexico, scientists at Los Alamos National Laboratory have pursued fusion energy, hoping to create in their experimental facilities the same clean, inexhaustible energy source that's found inside the sun and stars. Despite recent breakthroughs, the goal remains elusive.

"For more than 60 years, there has been a worldwide quest to solve incredibly complex physics challenges and achieve controlled, peaceful fusion, which would transform our world's energy needs," says Mark Chadwick, interim deputy director for Science, Technology, and Engineering at Los Alamos. "It's only in the realm of possibility because of the findings that took place at Los Alamos decades ago."

In December 2022 and July 2023, Lawrence Livermore National Laboratory, with support from Los Alamos and other institutions, took a step forward in the journey. Scientists at Livermore's National Ignition Facility (NIF) achieved what is called "fusion ignition"—when the energy from a controlled fusion reaction produces more power than it consumes. "Simply put, this is one of the most impressive scientific feats in the 21st century," U.S. Secretary of Energy Jennifer Granholm said during a news conference. She called the laboratory-based fusion ignition a milestone that "moves us one significant step closer" to having zero-carbon fusion energy "powering our society."

The NIF achievements are accompanied by other global fusion breakthroughs. In late 2021, the United Kingdom's Joint European Torus (JET) produced the world's greatest amount of fusion energy generated in a single experiment: 59 megajoules. In April 2023, China's Experimental Advanced Superconducting Tokamak (EAST) set a record by generating and sustaining an extremely hot, highly confined plasma for nearly seven minutes—a crucial step for creating fusion energy. Across the world, the quest continues for this ultimate energy source.

If fusion energy could be produced on a large scale, it would be unlimited and inexpensive, plus it wouldn't generate pollution. Unlike fossil fuels, fusion does not release carbon dioxide into the atmosphere. Also, fusion generates significantly less waste than nuclear fission reactions and poses no risk of nuclear meltdown. These qualities have inspired scientists to continue to look for ways to initiate and control fusion, despite the many challenges along the way.

SO, WHAT EXACTLY IS FUSION?

Let's circle back to the sun, the giant natural fusion reactor. In the sun's core, immense gravity compresses rapidly moving atoms, causing them to mash together, or fuse, at high speeds and high temperatures, which, in turn, releases tremendous amounts of energy.

Most fusion experiments here on Earth use two kinds of hydrogen molecules: deuterium and tritium. Deuterium is found in sea water, and tritium can be generated from the element lithium, which is extracted from the ground. Deuterium and tritium are both positively charged and repel one another. Fusion researchers aim to keep the deuterium and tritium together (confine them under pressure) and create enough heat that the molecules collide and fuse, forming an electrically charged gas known as a plasma—the fourth state of matter. A successful fusion reaction creates what is called a burning plasma that emits great amounts of energy.

When comparing the amount of energy fusion reactions produce to fission reactions, which split atoms rather than combining them, fusion fuel is more potent and can generate four times as much energy by weight. Theoretically, fusion energy can be achieved using an extremely small amount of fuel. According to experts, a thimble of fusion fuel can potentially generate as much energy as 20 tons of coal. Einstein's famous equation, energy equals mass times the speed of light squared, reveals that a small amount of mass can be converted into a large amount of energy. That's the concept behind making fusion work.

LOS ALAMOS' CONTRIBUTIONS TO THE QUEST

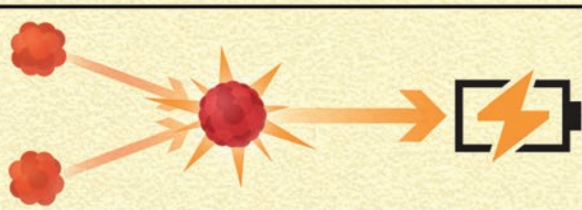
The journey to create fusion in the laboratory has been fraught with setbacks—and also significant milestones. NIF's recent ignition achievements reflect decades of fusion research, much of which has taken place at Los Alamos.

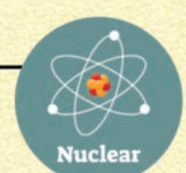
"Los Alamos has an extensive fusion research legacy," says John Kline, director of Fusion Energy Sciences at the Laboratory. Many of the first breakthroughs took place in the 1940s during Project Y of the Manhattan Project (what would later become Los Alamos National Laboratory). The scientists working to build the first

ENERGY 101

Nuclear fusion

Nuclear fusion occurs when two atomic nuclei combine to form a new nucleus, releasing massive amounts of energy. This is the same type of reaction that happens in the sun.





Los Alamos scientists used a fission reaction to trigger a fusion reaction during Operation Greenhouse George, a 1951 nuclear test that resulted in the first terrestrial production of fusion energy.

atomic bombs suggested creating a new, extremely powerful type of nuclear weapon—a thermonuclear weapon—by using a fission reaction to trigger a fusion reaction. In 1951, Los Alamos scientists proved this concept during Operation Greenhouse George, a nuclear test that resulted in the first terrestrial production of fusion energy.

"We produced more fusion than anyone could dream of," Chadwick says of Greenhouse George. In 1952, scientists tested Ivy Mike, the world's first thermonuclear device (essentially an undeliverable weapon, due to its massive size). Like Greenhouse George, Ivy Mike was detonated in the Enewetak Atoll in the Pacific Ocean.

In 1954, the B17 and B24 thermonuclear bombs, carried aboard the Convair B-36 Peacemaker aircraft, entered the U.S. nuclear stockpile. Fusion weapons have been part of America's nuclear deterrent ever since.

While researchers were exploring ways to apply fusion to national security issues, they also delved into fusion energy experiments. In 1951, Los Alamos scientist James Tuck started the Lab's fusion energy program by building a device he whimsically dubbed "the Perhapsatron." This machine led to the development of the "pinch concept" to confine plasma and achieve fusion conditions. In the late 1960s and '70s, Los Alamos built a set of fusion machines called the Scylla series (see p. 69), which also employed a related magnetic confinement "pinch" concept.

Another significant development in the Lab's fusion energy history focused on using high-energy carbon dioxide laser systems to create fusion conditions. The last of these devices, named Antares, was commissioned in 1975 and terminated in 1985.

Although fusion energy research continues today at Los Alamos, much of the current fusion-focused work concentrates on national security applications. Ever since the 1992 moratorium on full-scale nuclear weapons testing, the United States has relied on nonnuclear and subcritical experiments coupled with advanced computer modeling and simulations to evaluate the health and extend the lifetimes of America's nuclear

"Los Alamos has an extensive fusion research legacy."

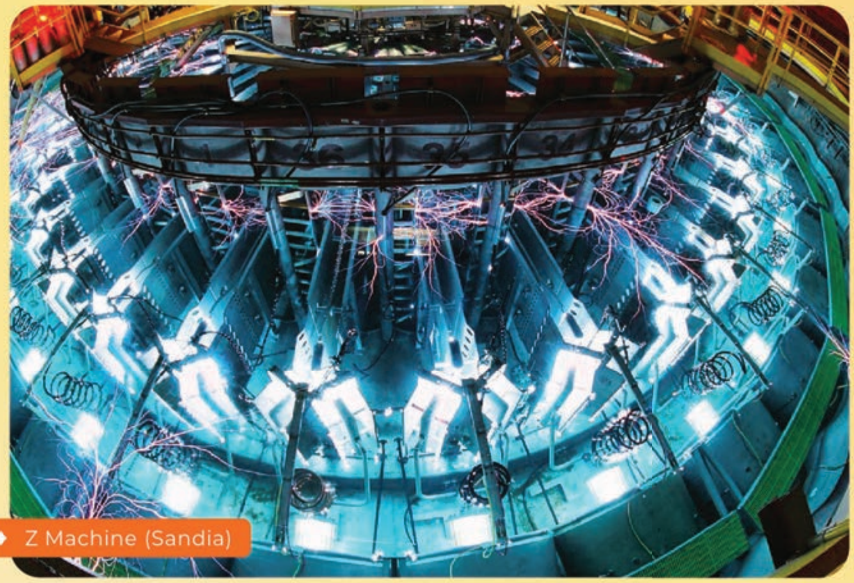
—John Kline

FUSION DEVICES

◆ NIF (Livermore)

Photo: LLNL

A **laser fusion device** fires laser beams into a centimeter-tall cylinder containing a deuterium-tritium target. The cylinder implodes, compressing the target and heating the deuterium-tritium fuel, which results in a fusion reaction. Lawrence Livermore's National Ignition Facility (NIF) is a laser fusion device.



◆ Z Machine (Sandia)

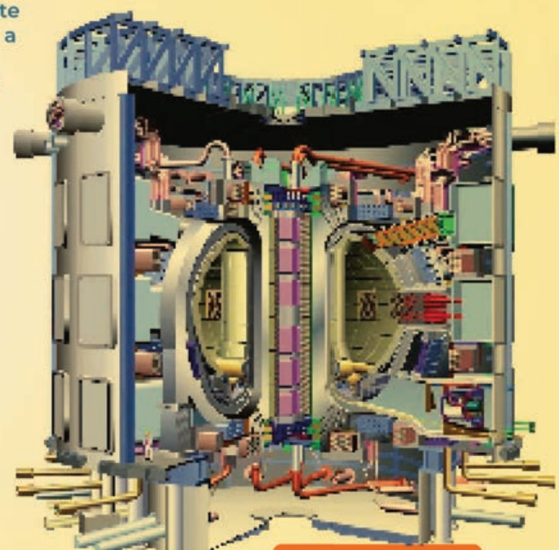
Photo: Sandia

A **Z-pinch fusion device** employs a Z pinch (zeta pinch), a type of plasma confinement system that uses an electric current to generate a magnetic field that compresses a plasma. The Z Machine at Sandia National Laboratories is a Z-pinch fusion device.

Photo: Wikipedia.org

◆ Wendelstein 7-X fusion reactor (Germany)

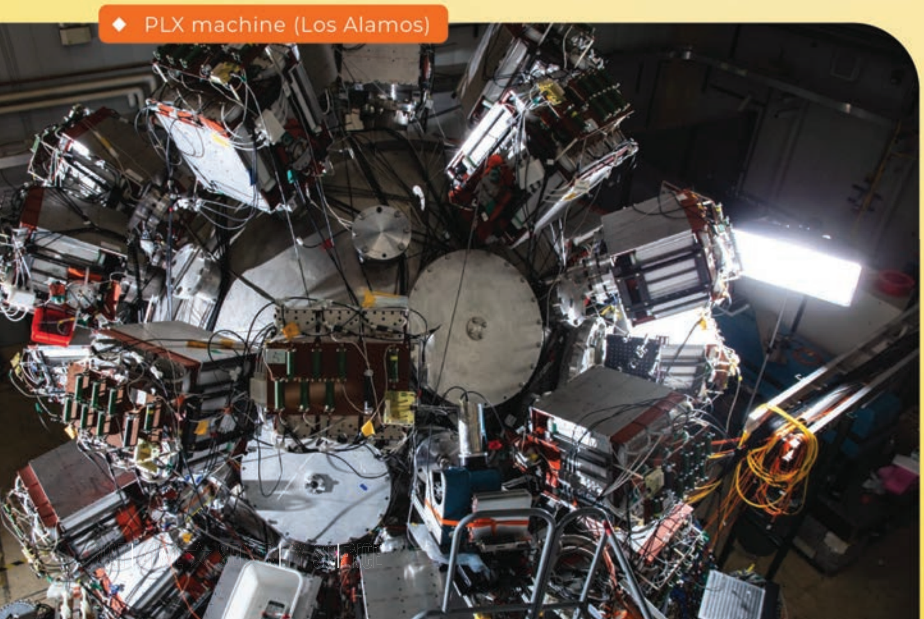
A **stellarator** confines a plasma using extremely strong electromagnets to generate twisting magnetic fields around the *outside* of a doughnut-shaped device (also called a torus). The Wendelstein 7-X in Germany is a stellarator.



◆ ITER (France)

Photo: ITER

A **tokamak** confines a plasma using magnetic fields *inside* a torus. Currently, a cooperative project involving multiple nations called ITER is aimed at constructing the world's largest tokamak in southern France.



◆ PLX machine (Los Alamos)

The **Plasma Liner Experiment** at Los Alamos National Laboratory combines aspects of both magnetic confinement and inertial confinement fusion approaches. The machine fires supersonic jets of ionized gas aimed in a spherical shape to compress and heat a plasma.

weapons. This approach is called stockpile stewardship. Through fusion experiments, such as those at NIF, scientists have been able to create certain conditions needed to collect data for running computer simulations to evaluate America's nuclear stockpile.

"At Los Alamos, we are actively engaged in all aspects of fusion research," says Charlie Nakhleh, associate Laboratory director for Weapons Physics. "Understanding fusion reactions and achieving ignition at NIF are important components of stockpile stewardship."

The pursuit of fusion has also led to multiple breakthroughs in materials research, weapons technology, and the overall understanding of basic science and physics. "Fusion is a 'grand challenge' scientific problem that tests our codes, our people, our facilities, and our integrated capabilities," Kline says.

Creating extreme conditions inside the laboratory also enhances research in other areas, according to Patrick Knapp, who leads the Pulsed Power Inertial Confinement Fusion and High Energy Density physics programs at Los Alamos. "We can use this capability to study all sorts of really exciting things like planetary formation, nuclear physics, atomic physics, solar physics, the list goes on and on," he says. "We as a Laboratory are just starting to learn how to exploit this capability to answer important and exciting questions, and the possibilities are almost limitless."

ONE GOAL, MULTIPLE APPROACHES

So, how do scientists replicate the power of the sun inside a laboratory? The bottom line is finding a way to duplicate the intense heat, pressure, and confinement needed to maintain a fusion reaction long enough to produce energy. Scientists have experimented with two basic ways to do this: Inertial confinement fusion (ICF) and magnetic confinement fusion (MCF). Other approaches combine both inertial and magnetic concepts. At Los Alamos, scientists support research at other national laboratories and conduct their own fusion energy experiments.

INERTIAL CONFINEMENT FUSION

The basic idea behind ICF is to direct a large amount of energy at a tiny fuel target the size of a grain of rice. Scientists have experimented with a variety of ways to deliver that energy. Short pulses of electron beams, ion beams, and protons, as well as lasers have been used to generate the initial energy that sparks a fusion reaction.

NIF uses lasers as its initial energy source. The machine takes energy from a giant capacitor bank and transforms it into 192 pulsed laser beams focused onto a tiny target capsule that contains deuterium and tritium—aka the fusion fuel. The deuterium and tritium are forced together at enormous pressure and temperature. The result is a burning plasma, which is a critical step toward self-sustaining fusion energy.

> **Fusion is a huge, multinational problem with the potential to revolutionize global energy security and climate change."**
>
> —Victoria Hypes-Mayfield

That's also what happened in December 2022 when NIF achieved ignition, an achievement that required the combined efforts of scientists from throughout the nuclear enterprise. Kevin Meaney, a Los Alamos plasma physics scientist, helped confirm the success of that experiment. His diagnostics measured how the fusion reaction progressed over time in the burning plasma. "Our measurements confirmed we are stepping into a new regime. The plasma is burning. It's propagating. Being able to say that with confidence is thanks to Los Alamos diagnostics," he says.

Nakhleh calls the ignition breakthrough "truly a national achievement. Los Alamos has been involved in the research on inertial confinement fusion for decades and has contributed to recent experiments and diagnostics on NIF in a significant and important way."

Another approach to ICF is taking place at Sandia National Laboratories using a device called the Z Machine, named after the technique of using a Z pinch (zeta pinch) to compress plasma and create energy leading to a fusion reaction. Los Alamos scientists work with Sandia scientists to conduct experiments with the Z Machine.

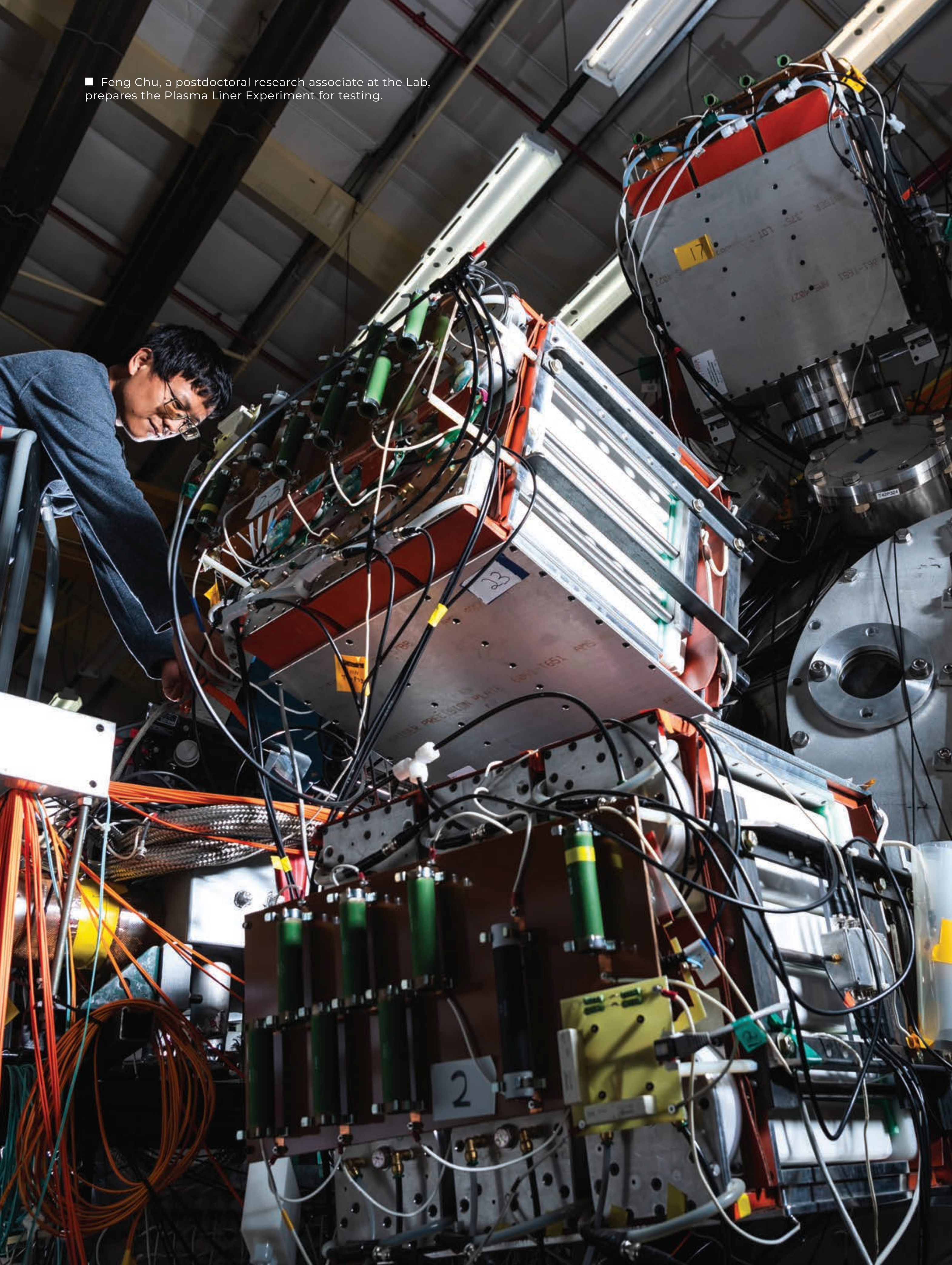
"Getting data relies on large experimental facilities," Meaney says. "These are the only facilities in the world that can make these conditions."

Knapp says he is grateful to be able to conduct experiments with both the Z Machine and at NIF, but he is already looking toward the future. "The facilities we use today to study inertial confinement fusion are a long way off from facilities that will be needed for power generation," Knapp says. "We need to learn how to operate much bigger facilities at much higher frequency—multiple times a second compared to once a day. These are huge challenges, but they are exciting ones."

MAGNETIC CONFINEMENT FUSION

Magnetic confinement fusion uses magnetic fields to confine fusion fuel in the form of a plasma. Stellarators and tokamaks are two types of machines that use magnetic coils to contain plasma.

Glen Wurden, a longtime Los Alamos plasma physicist, frequently travels to Germany to conduct experiments on a stellarator device called the The Wendelstein 7-X



■ Feng Chu, a postdoctoral research associate at the Lab, prepares the Plasma Liner Experiment for testing.

fusion reactor. "We have been able to maintain a burning plasma for up to 30 minutes," Wurden says, noting these international experiments advance many aspects of plasma physics.

Tokamaks are doughnut-shaped machines that use magnetic fields to confine plasmas. This is the approach used by ITER, a multinational fusion research and engineering project underway in France. Originally an acronym for "International Thermonuclear Experimental Reactor," project leaders now emphasize that "ITER" is Latin for "the way." The United States is one of seven countries partnering on ITER. Since the initiation of

> **Today, fusion looks more realistic than it did a decade ago. Every achievement is a stepping stone to answer questions and achieve a higher level of confidence."**
>
> —Kevin Meaney

the project, Laboratory scientists have participated in numerous efforts to support ITER's development, including designing a system that will process and deliver deuterium and tritium to the facility, which is scheduled to begin operations in 2035.

THE PLASMA LINER EXPERIMENT AND OTHER COMBINED APPROACHES

Some experiments combine aspects of both magnetic and inertial confinement. Sandia has developed a technique called magnetized liner inertial fusion, or MagLIF, that uses an extremely high-current pulse to create a Z-pinch magnetic field that crushes a preheated fuel-filled cylinder. These tests are being carried out using the Z Machine.

At Los Alamos, the Plasma Liner Experiment (PLX) uses plasma guns arranged in a sphere to fire ionized gas to compress and heat a pre-injected fusion fuel target plasma. Funded by the Department of Energy's Advanced Research Projects Agency-Energy program, researchers are using the device to study plasma compression and heating. They will then compare their results with computer simulations to determine the viability of this approach.

■ Samuel Langendorf, the Los Alamos scientist leading the Plasma Liner Experiment, and Feng Chu, a postdoctoral research associate at the Lab, review diagnostic data in the PLX control room.

"PLX is an innovative alternative concept that is still in the early stages," explains Samuel Langendorf, the Los Alamos physicist leading the project. He says the PLX approach could eliminate the need to rely on the solid fusion targets that get destroyed in other fusion devices, thus providing a more practical approach to fusion power. "With a plasma target you can envision how you can create an economical reactor."

Although the Los Alamos PLX project will wrap up in 2024, Langendorf hopes that private industry will invest in similar programs.

SUPPORTING RESEARCH AND DEVELOPMENT

Research on other fusion energy concepts and the technology that supports them is ongoing. "The pursuit of one thing leads to another thing," Kline says. "Los Alamos works on key diagnostics, deuterium and tritium reaction history, neutron imaging, fusion rate as a function of time, and other diagnostics," he says.

Because fusion reactors must be built from materials that can withstand high temperatures, irradiation, and stress, materials research and development is also needed. Lab scientists recently developed a new tungsten-based alloy that performs well in extreme environments. This alloy and similar materials bring researchers closer to their goal of building power plants that use fusion reactions to generate electricity.

"The new alloy has shown superior radiation tolerance and extraordinary potential," says Osman El-Atwani, a former Los Alamos scientist instrumental in this research. Experiments conducted at Los Alamos' Ion Beams Materials Laboratory have tested the alloy for irradiation resistance to ensure it can withstand the neutron damage that occurs in reactors.

"These newly developed tungsten-based high-entropy alloys are an important step to tame the harsh conditions faced by materials in fusion devices," says Yongqiang Wang, a scientist who leads the Lab's Radiation Science experimental team.

El-Atwani agrees, noting that "the development of this alloy, and the agreement between modeling and experimentation that it represents, points the way toward the development of further useful alloys, an essential step in making fusion power generation more robust, cost effective, economically predictable, and attractive to investors."

Saryu Fensin, a team leader at the Lab's Center for Integrated Nanotechnologies, adds that Los Alamos is uniquely positioned for this work. "We have expertise in studying materials under dynamic and temperature extremes—key to our core mission. We can now use that expertise in processing, characterization, irradiation, and mechanical testing to help the fusion community."

Los Alamos scientists are also researching tritium—a radioactive isotope of hydrogen and one of the fuels required for many fusion designs. Tritium does not occur naturally. Currently, it is produced in the Tennessee Valley Authority's Watts Bar Nuclear Plant and processed at the Savannah River Site in South Carolina. Understanding tritium behavior will play a crucial role in the success of fusion energy.

Researcher Victoria Hypes-Mayfield notes that there are a limited number of people who have the experience to design systems in line with tritium best practices. "Los Alamos has the knowledge to provide this expertise to the fusion community at large," she says.

Exploration of other ways to use hydrogen in place of tritium is also underway, which would make some experiments safer and more economically feasible. "Reducing the amount of tritium held in a fusion power plant is a key consideration for bringing fusion devices to the grid," says Hypes-Mayfield, who notes that "fusion is a huge, multinational problem with the potential to revolutionize global energy security and climate change. To be a part of the solution to such a wide-reaching problem is an awesome opportunity."

NEXT STEPS

What's next? Bigger, better machines are necessary to conduct new types of experiments that would yield new data to advance our understanding of fusion.

UNCOVERING BURIED BREAKTHROUGHS

Previously unrecognized research from 1938 paved the way for fusion energy.

BY JILL GIBSON

It was an unexpected discovery. Mark Chadwick, interim deputy director for Science, Technology, and Engineering at Los Alamos National Laboratory, was listening to oral interviews from the Lab's archives. "It was a Friday afternoon, and I had the audio tape going in the background while working on other things," Chadwick recalls. But he started paying attention when the audio revealed that in the late 1930s, scientists had made a significant discovery about fusion—a breakthrough that Chadwick was unfamiliar with. Now Chadwick was on the trail of a mystery. Had he found an important piece of research buried in the archives?

Chadwick and his colleague, physicist Mark Paris, began digging into the issue, trying to identify exactly what the early researchers had discovered and learn why their breakthrough had gotten lost. "The thing that's strange is that vast literature exists on the history of early fusion research. And nowhere is this research ever mentioned," Chadwick says. "At first, I thought it was a mistake."

As Chadwick explains, in the 1920s and '30s, scientists predicted that fusing two nuclei of deuterium (a hydrogen isotope) would generate a fusion reaction. More than

In 1951, Art Ruhlig worked for the Naval Research Laboratory and supported Los Alamos' Operation Greenhouse nuclear test series in the Pacific. He led a diagnostic group responsible for amplifiers and transmission lines. "It seems appropriate," Mark Chadwick says, "that having been the first to observe DT fusion in 1938, Ruhlig was part of the team that first observed an ignited burning fusion plasma in the first thermonuclear test explosion." That test was Operation Greenhouse-George, pictured here.

a decade later, researchers would discover that another radioactive isotope of hydrogen, called tritium, fuses more readily with deuterium. Tritium also fuses with deuterium at a lower temperature, which generates a much higher energy release than a deuterium-deuterium reaction. This practice of using deuterium-tritium (DT) reactions is credited to physicist Emil Konopinski (who was at Los Alamos during the Manhattan Project), but the archived interview Chadwick had found suggested the concept had originated far earlier. Had another scientist made this breakthrough?

At first, Chadwick told Paris that the speaker simply must have misremembered, but Paris wouldn't accept that explanation. "Mark Paris kept coming back to me saying, 'No, I'm not happy with that.' So, I kicked him out of my office," Chadwick recalls.

"He didn't kick me out. He was very nice," Paris says. Nevertheless, Paris did leave Chadwick's office and headed back to the archives to continue his search.

Paris admits he became somewhat obsessed with uncovering more information. "I would steal an hour or two in the evenings, or even in the middle of the day, because it was just burning on my mind."

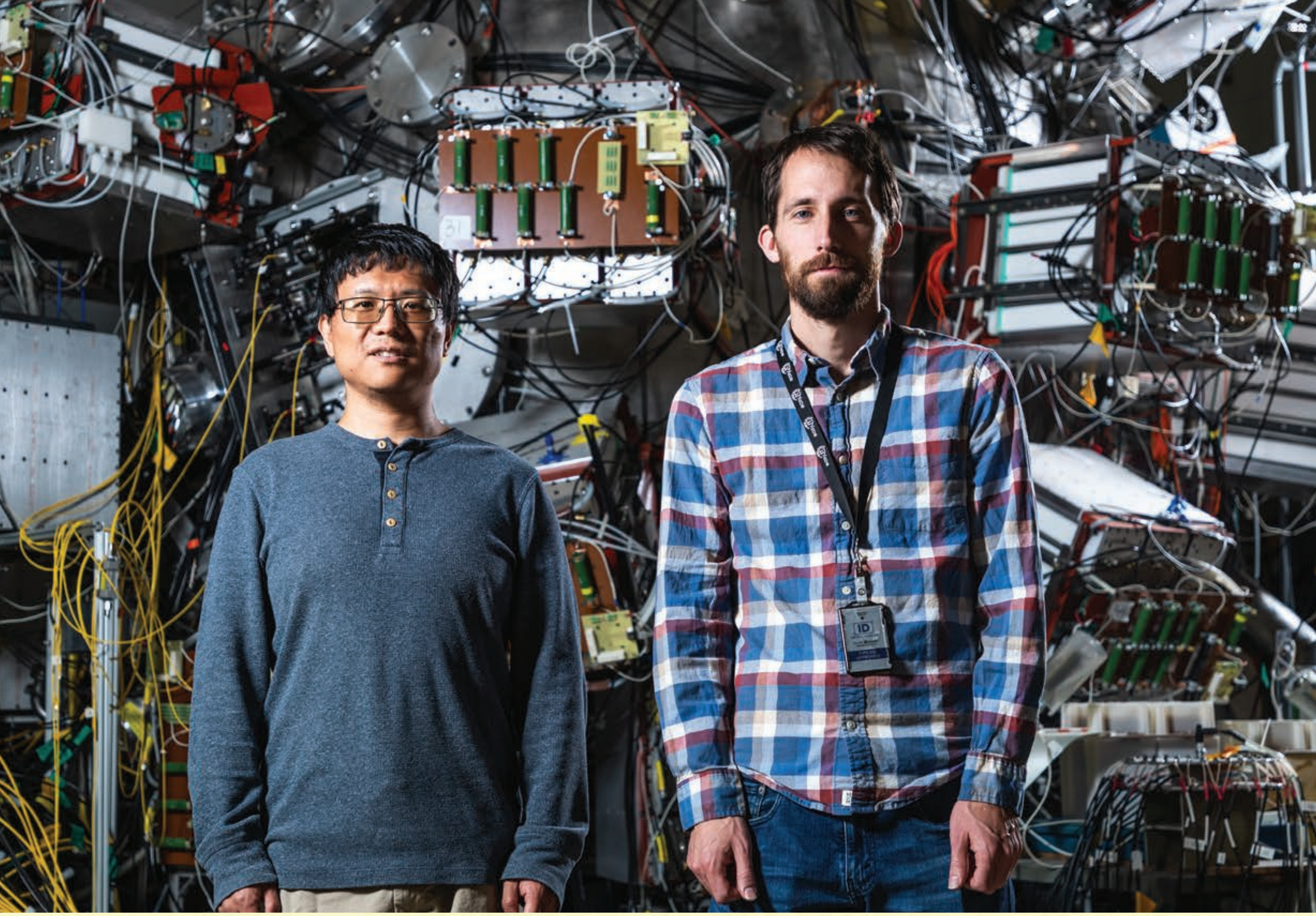
Finally, Paris found what he was looking for. "I just kept poking around, trying to discover where and when this DT fusion reaction was first measured in the laboratory, going down various rabbit holes. I came across a very short 1938 letter in the *Physical Review* by a virtually unknown fellow in nuclear physics named Art Ruhlig." The letter focused on a completely different topic but, in the final paragraph, Ruhlig referenced a study he had read about the DT reaction. Based on this research, Ruhlig predicted that the DT reaction "was a lot faster than anything else that scientists knew about," Paris says.

Chadwick called Ruhlig's letter "the key paper that seems to have been hiding in plain sight but was strangely neglected." Paris and Chadwick also discovered documentation that suggests Konopinski and physicist Hans Bethe mentioned Ruhlig's DT fusion work to physicist Edward Teller, who applied the findings when spearheading the development of the hydrogen bomb.

Today, the DT reaction is also the key to all fusion energy research. "I would say peaceful fusion energy would probably not have been possible without this breakthrough," Chadwick says.

Chadwick says the discovery of this early DT research underlies the important role Los Alamos has always played in measuring and tracking fusion reaction data. The databases assessing the probability of fusion reactions (called cross sections) are used by fusion simulation codes across the world. "Los Alamos defines the field, and we're in an authoritative position to be commenting on this," he says.

That's why Chadwick and Paris say they are eager to share the discovery of Ruhlig's long-forgotten findings. "Why didn't this guy make more of it? Why didn't he scream out to his colleagues that he'd been unfairly neglected?" Chadwick wonders. "Up until now, the most important discovery of the first-ever observation of this most important reaction that's central for humans' peaceful quest for fusion energy has never been commented on." ★



“I think fusion energy could transform the world in ways that are hard to imagine,” says Samuel Langendorf (right). “If you had access to clean, unlimited energy, you could really do some pretty wondrous things for the human species.”

“Right now, Los Alamos is partnering with Sandia to advocate for funding a next generation pulsed power facility that would be capable of demonstrating ignition and energy gain,” Knapp says. “This helps the nation diversify its technological paths to achieving necessary conditions in the laboratory for stockpile stewardship, and it also helps develop alternate paths that industry could benefit from. Pulsed power drivers are much more efficient at coupling energy to targets than lasers are. For a power plant, efficiency really matters, so understanding if it is possible to use this technology for fusion yield really benefits both missions.”

Meanwhile at NIF, scientists are outlining upgrades needed to generate more energy as well as update the aging device, which has been in operation since 2009.

As the national laboratories focus on expanding and upgrading their machines, they are also building new partnerships with private industry. “I am really excited about the prospects of collaborating with some of the private fusion companies that are out there,” Knapp says. “Given the pace at which these companies can innovate, we in the labs are likely to learn as much from them as they are from us.”

THE FUTURE OF FUSION

As fusion research continues, scientists are exploring many areas where they can apply breakthroughs. For example, “fusion can be very useful for other purposes, such as fusion rocket engines for planetary defense,” Wurden says. When it comes to clean energy, however, he believes “that fusion energy for commercially competitive electricity is a long way off.”

Just how long is a long way off? Kline smiles, saying that scientists once claimed a working commercial fusion reactor was just 30 years away, but now “we’ve made significant progress. Now it’s only 20 years away,” he quips.

Despite the difficulty, scientists agree that fusion energy is no longer a question of if but rather when. “We are on a much more concrete path,” Meaney says. “Today, fusion looks more realistic than it did a decade ago. Every achievement is a stepping stone to answer questions and achieve a higher level of confidence.”

Kline agrees. “Energy is life,” he says. “Everybody needs electricity. Whether we solve the problem today or in 70 years, it’s still going to be of value.” ★

Mark Chadwick

A DISCOVERY THAT RESONATES

"The Bretscher state" honors the Los Alamos physicist who identified the fusion state that formed the building blocks of life.

BY JILL GIBSON

Los Alamos National Laboratory physicists are paying tribute to a Manhattan Project scientist who discovered a significant effect that occurs during a certain type of nuclear fusion. The unique type of resonance that arises during deuterium-tritium (DT) fusion contributed to the beginning of life on Earth.

You see, something special happens when deuterium and tritium—both isotopes of hydrogen—get together, or fuse. Fusing deuterium (an atomic nucleus that consists of a proton and a neutron) and tritium (a proton and two neutrons) forms, for a very short time, a relatively stable arrangement of two protons and three neutrons called a compound system.

After an extremely short interval (think fractions of fractions of fractions of a second), the system falls apart to produce a neutron and a helium nucleus, also called an alpha particle. This reaction produces energy. In fact, it produces a huge amount of energy.

Now, sometimes, not always (you have to get lucky), these types of energy-producing reactions happen really quickly, with extremely high reaction rates. This "luck" is due to an effect called "resonance."

Resonance is familiar in the everyday world—think of a soprano breaking a wine glass by hitting and sustaining the perfect ear-piercing note. When the frequency of the note is just right, the energy in the sound waves is absorbed by the wine glass, causing the glass to vibrate. If the soprano sustains the high-pitched musical note for too long—crash! The vibrations of the glass will get too big, and the wine glass will shatter.

Resonance also operates in the submicroscopic world of hydrogen nuclei. When deuterium and tritium come together and react, they form a system that resonates with its own natural frequencies. This resonance greatly increases the intensity of the DT interaction, which leads to greatly increased production of neutrons and alpha particles. In fact, the reaction is about 100 times faster than it would be without the resonance. The resonance enhancement of the reaction means more energy can be created more easily. That's why deuterium and tritium are so often used to fuel fusion energy experiments.

Physicists now understand that nuclear resonance was a factor in the Big Bang—the DT reaction that created the universe. "That DT reaction and the unique resonance of fusing nuclei that took place during the Big Bang created most of the helium in our universe," says Mark Chadwick, interim deputy director for Science, Technology, and Engineering at Los Alamos. Helium, enhanced by the unique DT resonance, became the source for about a quarter of the carbon and other heavier elements in the human body. "Without this resonance, not only would fusion energy be beyond reach, but the universe itself might look very different, perhaps unable to support life," Chadwick says. "Basically, about one fourth of the human body is made up of the products of DT fusion."

Although DT resonance has been essential to life for nearly 14 billion years, it wasn't recognized as such until 1945. That year, Egon Bretscher, a Manhattan Project physicist working at Los Alamos, was the first person to identify and measure the particular DT resonance essential to the formation of helium.

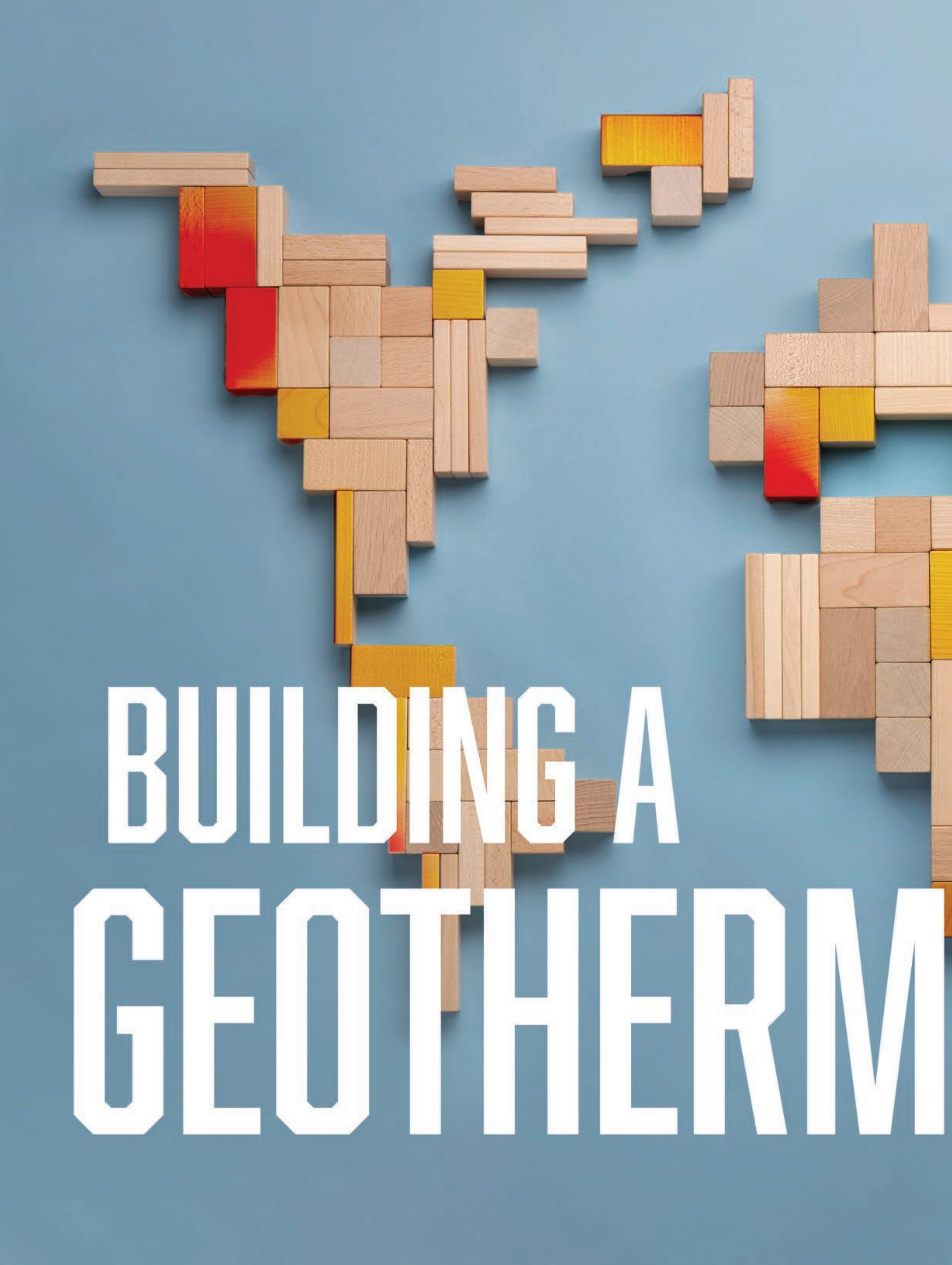
"This resonant enhancement was a game changer, opening up the potential for nuclear fusion technologies," Chadwick says.

Despite the significance of this discovery, Chadwick says Bretscher did not receive recognition for his discovery. So, in honor of Bretscher's role in identifying, characterizing, and measuring the DT reaction resonance, Chadwick and his colleague Mark Paris have proposed naming the resonant state created during the DT reaction after the Manhattan Project scientist. "We propose that the nuclear science community refer to it as the 'Bretscher state,'" Chadwick says, adding that he hopes that others in nuclear astrophysics adopt the term. "Naming this state after him acknowledges his work and Los Alamos National Laboratory's rich history in nuclear physics."

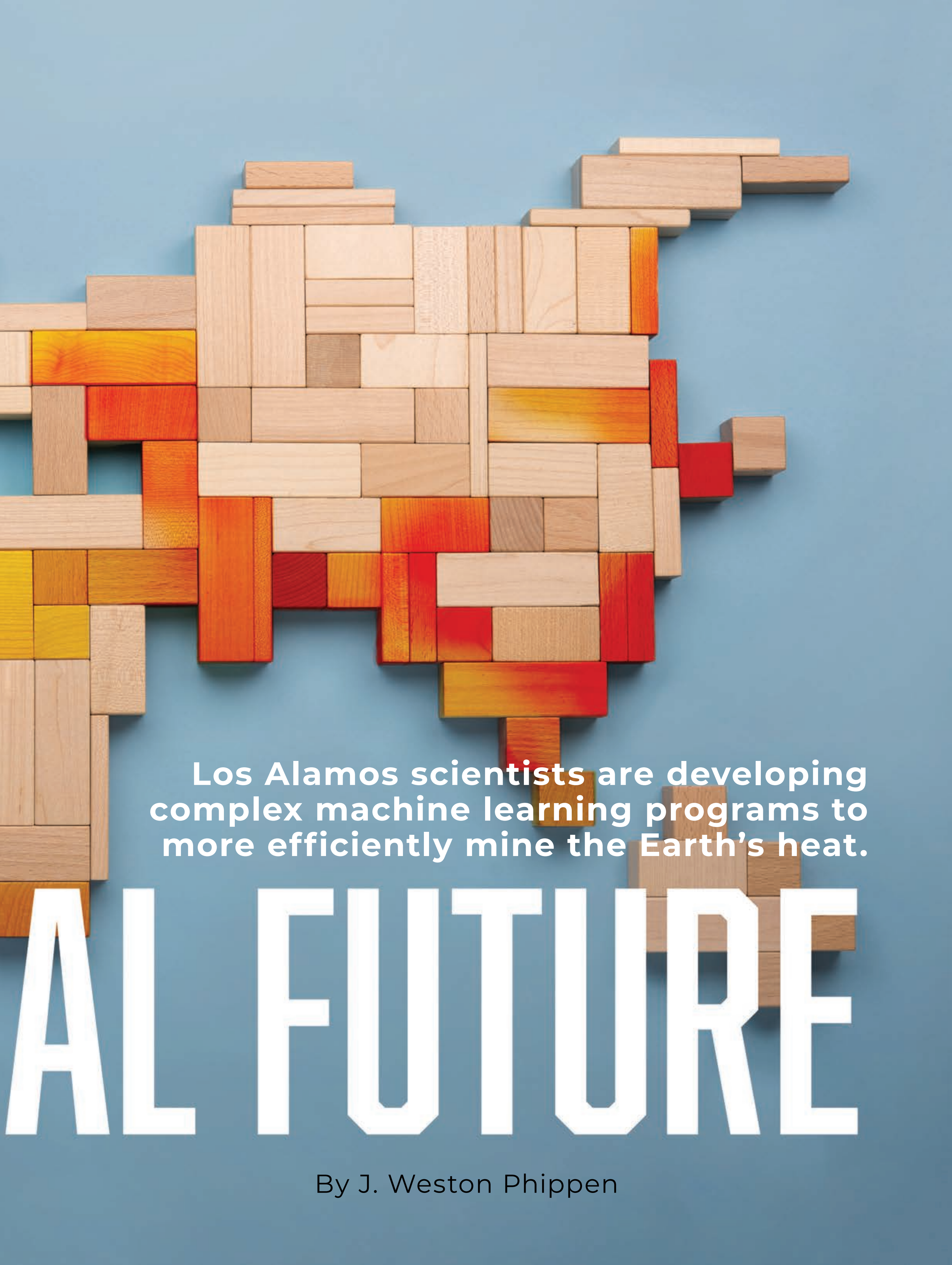
To learn more, read Chadwick's paper, "Big Bang fusion 13.8 billion years ago and its importance today," in the August 2023 edition of the American Nuclear Society's *Nuclear News*. ★

Mark Paris contributed to this article.

Egon Bretscher's Manhattan Project badge photo.



BUILDING A GEOTHERM



Los Alamos scientists are developing complex machine learning programs to more efficiently mine the Earth's heat.

AL FUTURE

By J. Weston Phippen

Geothermal sites at The Geysers, in California, take advantage of geothermal systems with naturally occurring sources of heat, water, and steam. But there are few such "ideal" sites in the United States. Photo: NCPA

"As the United States begins to develop geothermal sites that are lower in temperature, and there are many of these across the nation, knowing how to effectively extract heat from these sites becomes very important."

—Hari Viswanathan

The temperature of rock increases about 1 degree Fahrenheit for every 77 feet below the Earth's surface. Dig far enough, and this naturally occurring hot rock, if put in contact with water, will produce steam. This steam can be converted to energy, usually in the form of electricity.

The United States is the world's top producer of electricity from geothermal sources, and yet this electricity accounts for only 0.4 percent of the country's energy—enough to power about 2.7 million homes annually.

Most of the nation's geothermal energy comes from California, where sites like The Geysers, the Imperial Valley Geothermal Project, and the Coso Geothermal Field all take advantage of existing, natural reservoirs of hot water deep underground. Engineers pipe the steam created inside the reservoirs to the surface, where the steam turns turbines and creates electricity. These sites are ideal because all the necessary ingredients for energy creation are present: hot rock, water, and steam. The problem is that most of these sites have already been exploited.

Hari Viswanathan, a hydrogeologist in the Energy and Natural Resources Security group at Los Alamos National Laboratory, says the current state of geothermal energy is not unlike the early days of the fossil fuel industry. "The industry first tapped all the most readily available sources of oil and gas, and it wasn't until after several technological advances—like fracking and horizontal drilling—that the more difficult sites could be developed. That's basically where the geothermal industry is at."

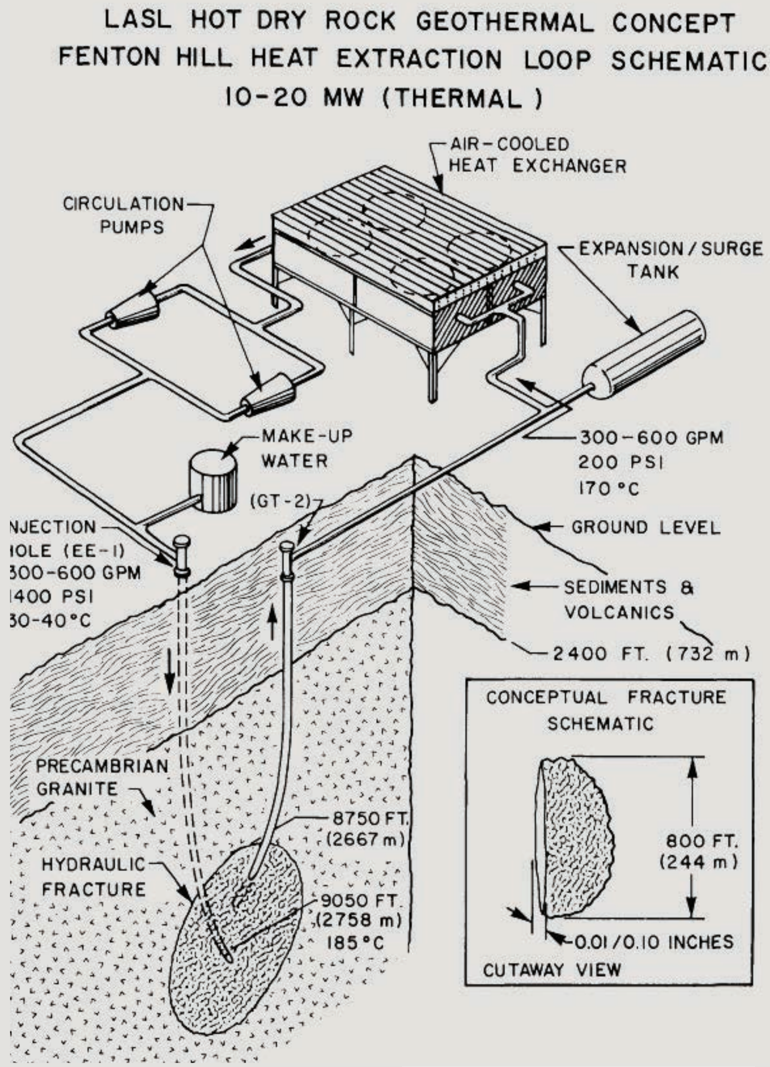
In 2022, the Biden administration announced a goal of powering at least 40 million homes with geothermal energy by 2050. But reaching that goal will require technological advancements, especially in machine learning. This is where research conducted at Los Alamos can help.

A past and present pioneer

Los Alamos has played an important role in advancing geothermal energy since the 1970s, when a ragtag bunch of scientists decided to find out if they could mine heat from the very hot, very impervious rock that's found ubiquitously at various depths below the Earth's surface. The challenge was reaching it (by drilling), engineering (through hydraulic fracturing) reservoirs within it, filling those reservoirs with water that heats up, bringing the hot water back to the surface, and converting it to steam to create energy. The Laboratory's Hot Dry Rock Program, which operated just west of Los Alamos until 1995, proved all of the above was possible.

Despite the success of the Los Alamos Hot Dry Rock Program, interest in geothermal energy waned for decades. But as interest in clean energy has increased in recent years, geothermal energy is enjoying a renaissance in the form of enhanced geothermal systems (EGS)—essentially modern-day versions of the Los Alamos Hot Dry Rock Program.

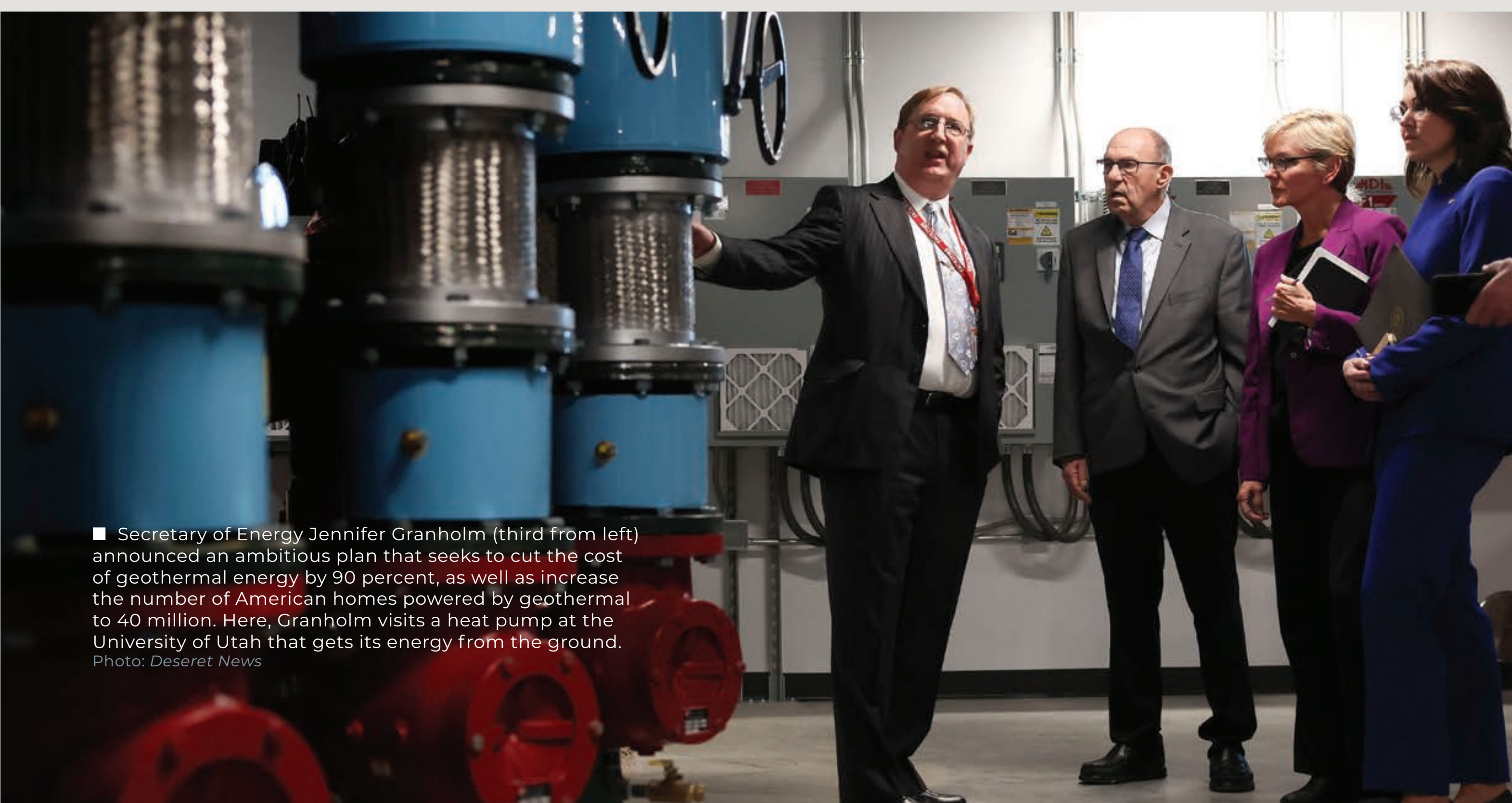
To refine EGS, in 2014, the U.S. Department of Energy (DOE) funded the Frontier Observatory for Research in Geothermal Energy (FORGE). Located in Utah, FORGE



■ Scientists at Los Alamos were the first to develop the concept behind EGS, which fractures rock to create the underground systems needed to heat water into steam.

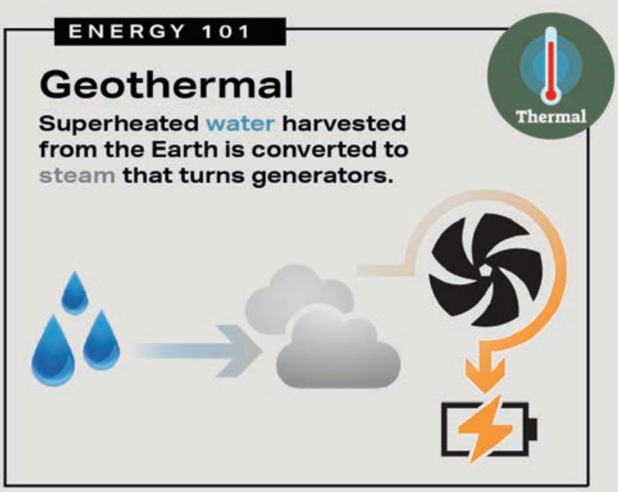
SCAN QR CODE WITH A SMARTPHONE CAMERA

Read about the Hot Dry Rock program at Los Alamos.



■ Secretary of Energy Jennifer Granholm (third from left) announced an ambitious plan that seeks to cut the cost of geothermal energy by 90 percent, as well as increase the number of American homes powered by geothermal to 40 million. Here, Granholm visits a heat pump at the University of Utah that gets its energy from the ground.
Photo: *Deseret News*

Reaching hot dry rock—sometimes several miles below the surface—requires complex drilling equipment and deep understanding of the Earth's subsurface. Photo: Piyush Bakane



operates as a testbed for the latest EGS advances. In 2021, FORGE completed construction of the world's first angled injection well—the hole through which water is pumped down into hot rock—that will be used for EGS. The hole goes two miles deep into 430-degree-Fahrenheit granite.

"These new investments at FORGE, the flagship of our EGS research, can help us find the most innovative, cost-effective solutions and accelerate our work toward wide-scale geothermal deployment," Secretary of Energy Jennifer Granholm said in 2022, as she announced a request for innovative research that would contribute to the site's mission.

As geothermal drilling and fracking technology continues to improve, so has the technology that allows scientists to understand exactly what is below the Earth's surface and how it can be most efficiently and effectively used for geothermal energy.

"The subsurface is uncertain, it's opaque, and we have very little data on the rock in some areas," Viswanathan says.

But now, nearly 30 years after the Hot Dry Rock Program was defunded, Los Alamos is supporting geothermal energy research once more—this time by developing machine learning technology to more accurately predict what lies beneath the Earth's surface. Machine learning uses algorithms to parse data much faster than any human can. These algorithms can also learn, becoming better and better at their given tasks with more data and practice.

For example, humans have traditionally manually pinpointed promising geothermal sites. Experts gather known data about a region, such as type of rock, fault lines, and if silica are present (silica often indicate a geothermal reservoir). Each piece of data is assigned a value.

"Researchers find the individual attributes, or variables, in a dataset that they believe are most important to defining the presence of geothermal reservoirs," explains Bulbul Ahmmed, a scientist in the Lab's Energy and Natural Resources Security group. "Then, by accounting for the importance of each variable, they compute a composite score. Based on that score, they determine if a hot spot is likely to exist."

Los Alamos, working with DOE, has developed a machine learning program that can parse this data much more efficiently. In a test run on the Great Basin region, the Lab used machine learning to key in on 18 attributes that relate to potential geothermal hot spots. The program then produced a detailed map that indicated sites with the greatest potential. The method accurately identified sites more quickly than humans could.

However, once a potential geothermal site has been located, experts need to know as much as possible about the rock they intend to drill.

Typically, geothermal experts use seismic sensors to gather data about subsurface rock. Similar to echolocation, sensors project inaudible signals that ricochet at different

The advantage of machine learning is that it develops patterns, and from those patterns we can make inferences.”

—Youzuo Lin

speeds off of different types of rock (rock types have unique characteristics, including densities). Experts might also use magnetotelluric sensors, which infer the Earth’s subsurface features using electrical signals. Data collected from these sensors helps researchers map fault lines, natural fissures, and rock orientation (similar to the direction of wood grain). This information informs researchers about the rock’s properties, which in turn helps them understand how the rock will crack under hydraulic fracturing.

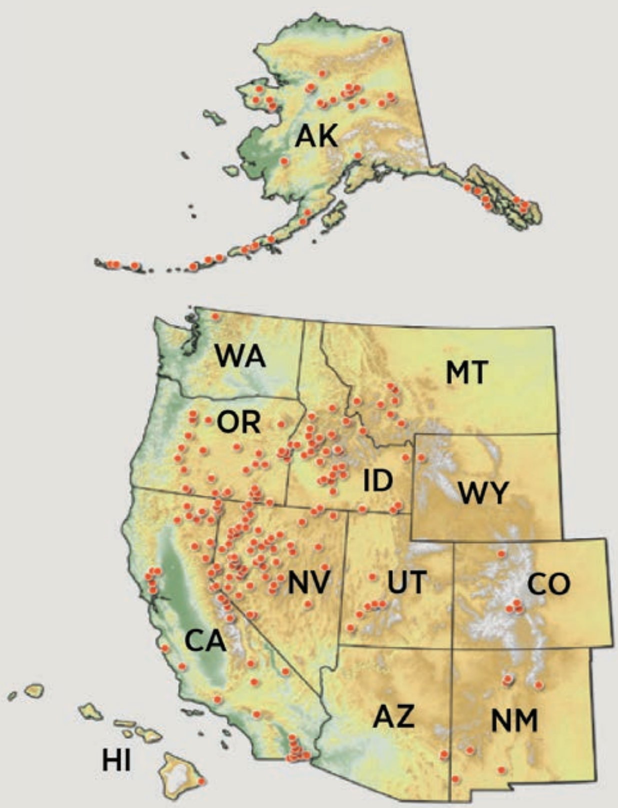
“These images of the subterranean rock that this data creates are helpful, but they leave a lot to be desired,” says Youzuo Lin, of the Lab’s Sensors and Signatures team, who notes the images are two-dimensional and may not paint a comprehensive picture of a specific area. So, to close the knowledge gap, researchers rely on something called seismic inversion, which applies physics-based mathematics to obtain the structural information of the subsurface. Another approach is to treat the lack of information as an image-to-image translation problem—basically converting an image with poor resolution to an image with higher resolution.

Lin says neither option is perfect, which is why he and his team have used machine learning to combine both methods. The new approach is called Unsupervised Physics-informed Full-Waveform Inversion (UPFWI).

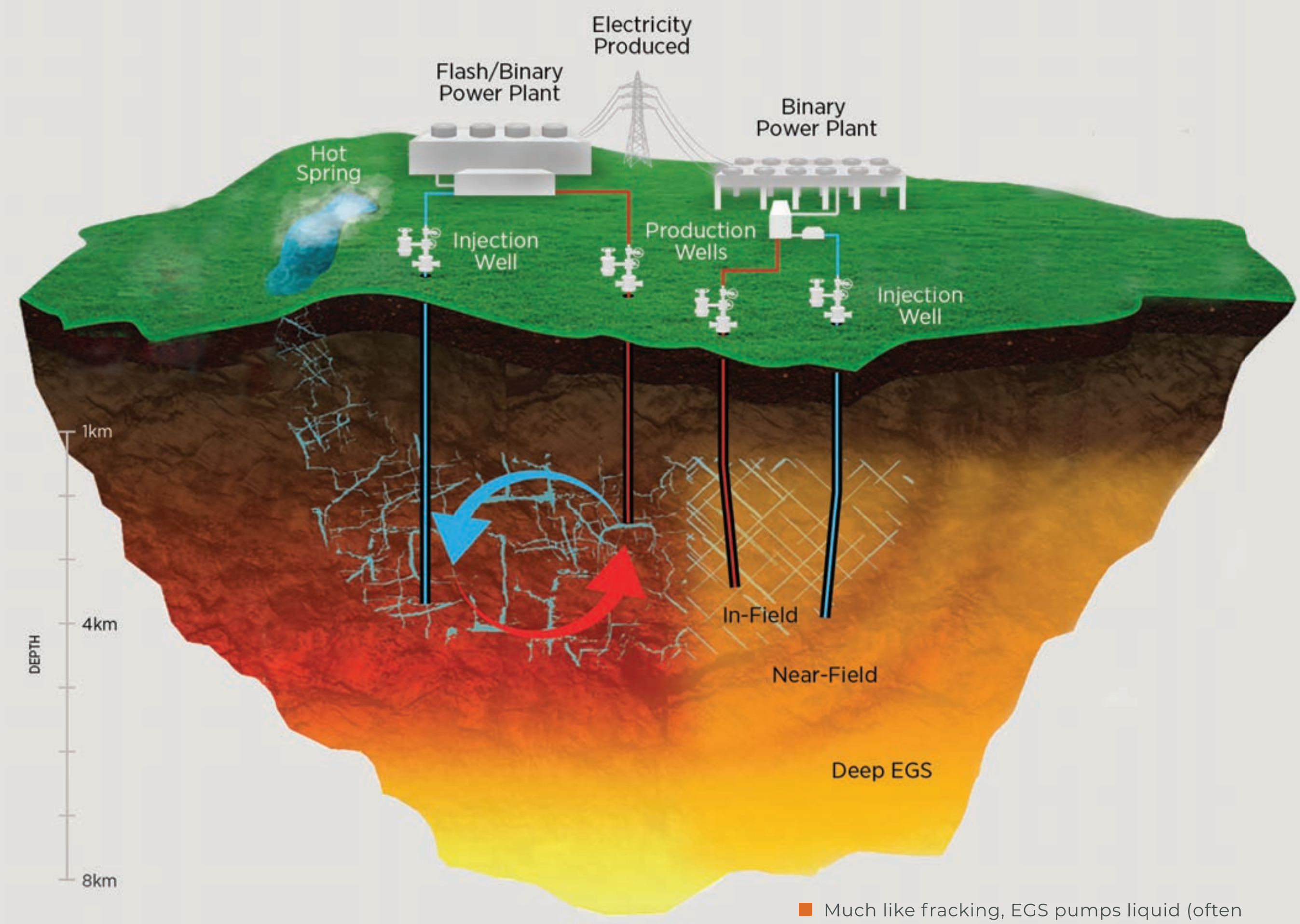
“Subsurface geophysics is complicated because often we don’t have the luxury of large sets of data; there just isn’t always a lot of information for a site,” Lin says. “But aside from being able to process lots of data quickly, the advantage of machine learning is that it develops patterns, and from those patterns we can make inferences.”

UPFWI combines nearly all available information about a location: everything from field testing data to the known physics of similar rock formations. It uses forward modeling and the image-to-image method and, importantly, it then produces thousands of simulations of how the subsurface rock *might* appear. The *might* is important because these are UPFWI’s best guesses: a full range of scenarios. From there, UPFWI can produce detailed 3D images based on the average of these simulations. The end result is a more realistic depiction of the rock than any other method might produce.

“Los Alamos was the first institution to apply this type of machine learning to help characterize subsurface rock,” Lin says. “We’ve had to develop these techniques to support our national security mission [for example, to monitor for underground nuclear explosions], but they can be applied to oil and gas exploration, carbon sequestration, and certainly for mapping the subsurface characteristics of geothermal sites.”



Scientists have located many areas across the western United States that could be particularly good for harvesting geothermal energy. Photo: DOE



■ Much like fracking, EGS pumps liquid (often water) at high pressures into the ground in order to create a network of fissures. The water is then superheated by the natural hot dry rock, then pumped to the surface. Photo: DOE

Delving deep

Once operators know more or less what type of rock they're dealing with, the next step is understanding how the rock might fracture as fluid is pumped into it, and how that fluid will then flow through the fractures. The entire system of fractures is what's known as the reservoir.

Enter Discrete Fracture Network Modeling Suite (dfnWorks), a computer program—really a suite of machine learning algorithms—developed by Los Alamos. dfnWorks is already in use in the oil and gas and nuclear storage industries, and the technology holds great potential for EGS.

A fracked fissure is similar to a tree—a long "trunk" with "branches" radiating outward that break off into smaller "branches." Data from seismic and other sensors can reveal larger fissures, which are sometimes meters in size. The dfnWorks suite uses machine learning to build statistical models of the smaller fractures, which might be only millimeters in size. Each fissure, large and small, is displayed on a computer screen using an advanced spatial mesh, a way of representing mathematical data in 3D. This allows operators to view the fracked EGS reservoir almost like a 3D underground map, with the ability to rotate the image any direction desired.

"Once we've built the fractures on the mesh," says Dan O'Malley, a team leader with the Lab's Subsurface Flow and Transport group, "we can use dfnWorks to demonstrate the flow path of a fluid through the fractures, and that can help us infer how much heat the fluid will pull from the rocks."

Because dfnWorks operates on supercomputers (as well as laptops), the program can churn out hundreds of thousands of predictive simulations within hours, making it the quickest and most accurate program of its kind.

But the Lab hasn't stopped there. O'Malley's role as a quantum computing expert is to transfer dfnWork's capabilities to the Lab's IBM Q Network, a series of cloud-based quantum computing systems. Quantum computing uses an entirely different framework than classical computers do to solve problems—the most important difference being that quantum computing can arrive at an answer millions of times faster. O'Malley's work, when completed, will allow Los Alamos researchers to simulate complicated EGS sites and reservoir flow patterns more accurately and quickly than anyone using classical computers.

> **Quantum computing holds the potential to perform heroic calculations."**
>
> **—Dan O'Malley**

"The holdup for EGS geothermal has really been efficiency, both in knowing how much energy we can get from a site and how to best operate the site," O'Malley says. "Quantum computing holds the potential to perform heroic calculations, mapping fracture networks that are massive, and doing this with more accuracy."

Geothermal autopilot

In any enhanced geothermal system, a potential complication called short circuiting exists.

"In geothermal, short circuiting is a huge problem," Viswanathan says. "Let's say you have two wells [drilled holes deep into the rock] and a bunch of fractures in between. The ideal scenario is that you use all those fractures because it will heat your liquid more quickly. But imagine that all the water goes through one big fracture, one big artery, rather than the smaller veins. Then the hot rock will cool off and short circuit the entire site."

To help operators constantly monitor the health and productivity of EGS sites, Los Alamos developed a machine learning program called Science-informed Machine Learning for Accelerating Real-Time Decisions in Subsurface Applications (SMART).

Funded by DOE and developed by a host of universities and national labs, including Los Alamos, SMART helps operators understand how to most efficiently run a geothermal plant, even under changing conditions. The program offers instantaneous model visualizations for the state of subsurface rock, fluid pressure management, and pressure anomaly detection that might indicate the fluid path has changed. If, over time, the fluid path does alter, SMART will not only detect changes but also offer recommendations on new operational strategies, such as changing the flow rate.

SMART allows operators to more confidently make decisions and get the most out of current and future geothermal plants. "As the United States begins to develop geothermal sites that are lower in temperature, and there are many of these across the nation, knowing how to effectively extract heat from these sites becomes very important," Viswanathan says. "It could be a big game changer."

Seismic sleuthing

The subsurface can be deceptively delicate, but under the Earth's surface, fault lines, tectonic forces, plate boundaries, and gravity are all interacting. Pumping fluids into that fragile system can sometimes result in things moving around—aka earthquakes.

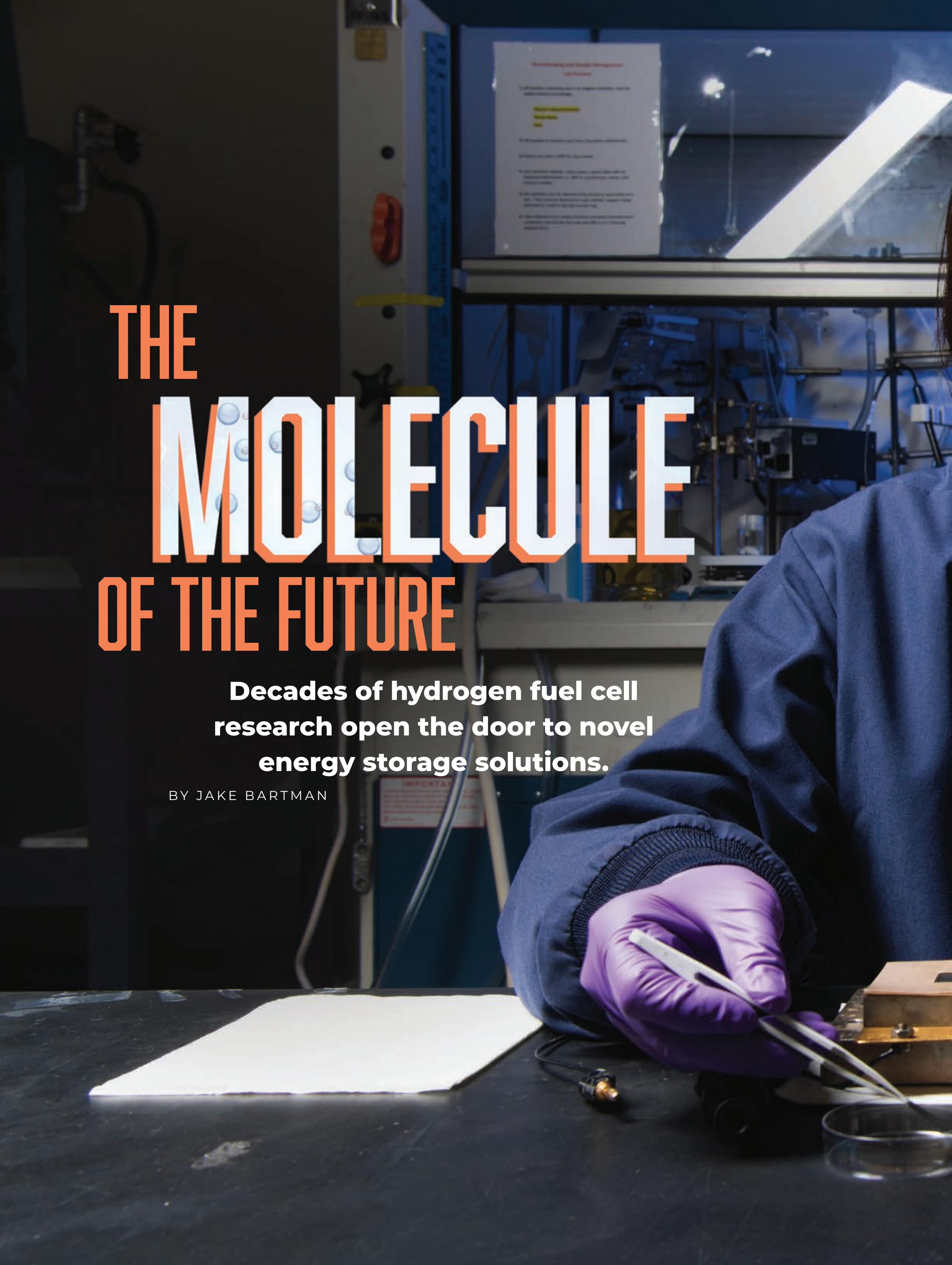
"As you produce a subsurface reservoir, you're changing the stress fields in these systems because of the injection and extraction of fluids," says Paul Johnson of the Lab's Geophysics group. "You may introduce stress on a fault that was previously inactive, so it's important to monitor all these stresses."

In locations such as California, Iceland, France, Switzerland, and South Korea, geothermal drilling and operations have been linked to earthquakes. In some cases, the tremors were strong enough to close the fracked fissures, thus rendering the geothermal sites obsolete. In other cases, geothermal sites have closed because local populations perceived them as dangerous.

But Johnson and his colleagues have developed machine learning tools that, using historical data as well as laboratory simulations, can recognize subtle indicators that precede an earthquake. When paired with satellite information that detects slight variations in the ground surface, this same method can also be used to monitor geothermal sites during drilling and operation so experts can recognize early earthquake warning signs. With that information, they can—ideally—avoid tremors caused by geothermal construction.

"Imagine you've invested a tremendous amount of money into developing a geothermal location, then a governmental regulator shuts you down because you triggered an earthquake," Johnson says. "We can help prevent this."

Johnson sees his work as part of a bigger initiative that is critical to ensure the longevity and health of our planet. "Just imagine being able to generate electricity almost anywhere in the country from the hot rock beneath our feet," he says. "When we think of addressing future climate change, geothermal energy has got to be one of the solutions to reaching our clean energy potential." ★



THE MOLECULE OF THE FUTURE

Decades of hydrogen fuel cell research open the door to novel energy storage solutions.

BY JAKE BARTMAN

■ Postdoctoral researcher Katie Lim works with a hydrogen fuel cell.

Researchers at Los Alamos National Laboratory developed a hydrogen-powered golf cart in the late 1970s.

Hydrogen is the most abundant element in the universe. It is also the lightest, consisting of only one proton and one electron. But don't let its featherweight fool you: hydrogen has enormous potential for energy storage. When used in a fuel cell—a small device that converts chemical energy into electricity—hydrogen can power forklifts, passenger cars, or heavy-duty trucks, while yielding only heat and water as byproducts.

For decades, Los Alamos National Laboratory has led the development of fuel cell technologies. Today, in an era of increased investment in renewable energy, the Laboratory continues to use its extensive background in fuel cell research to improve technologies for emission-free hydrogen fuel cell electric vehicles.

Researchers at Los Alamos are also leveraging their fuel cell expertise to help develop a new generation of technologies to produce hydrogen from water molecules. When powered by wind, solar, or other renewable energy sources, the process of splitting water to make hydrogen, which is called electrolysis, can yield "clean" hydrogen produced with zero greenhouse gas emissions. (Currently, 95 percent of hydrogen in the United States is produced through a process called steam methane reforming, which involves heating natural gas and yields greenhouse gases that are mostly emitted into the atmosphere.)

New technologies that integrate hydrogen fuel cells and energy production may go even further, helping to stabilize the nation's power grid as the Department of Energy (DOE) pursues the Biden administration's goal of achieving a 100 percent clean energy power sector by 2035.

A lengthy history

The first hydrogen fuel cell was invented more than 180 years ago, when, in 1842, British scientist William Robert Grove developed what he described as a "gas voltaic battery" that combined hydrogen and oxygen to produce electricity.

However, Grove's invention lay dormant for more than a century, until Francis Bacon, a chemical engineer at Cambridge University, rediscovered Grove's research and worked to develop it further. In 1959, Bacon demonstrated a 5-kilowatt fuel cell that could power a welding machine, a circular saw, and a forklift. The fuel cell garnered the attention of engineers with the National Aeronautic and Space Administration (NASA), which was on the lookout for technology to power its space missions.

NASA chose Bacon's fuel cell over batteries, which were bulky and suffered from a relatively short lifespan, and solar panels, which were not yet efficient enough to be practical. In addition to producing electricity, the fuel cells also produced potable water as a byproduct, which the Apollo 11 astronauts, who reached the moon in 1969, drank while in spaceflight. President Richard Nixon commended Bacon for his invention, saying, "Without you, we would not have gotten to the moon."

Around the same time that NASA was designing its fuel cell-powered spacecraft, General Motors (GM) developed its Electrovan, the world's first fuel cell electric automobile—that is, the first vehicle to use hydrogen to produce electricity and power a motor.

"The current state-of-the-art fuel cell design was developed here at Los Alamos a little more than 30 years ago."

—JACOB SPENDELOW

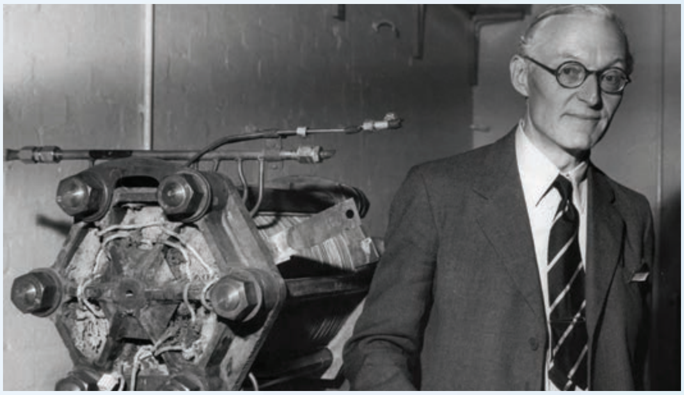
The Electrovan, which GM introduced in 1966, had a top speed of 70 miles per hour and a range of some 150 miles. But the vehicle had shortcomings. Along with taking three hours to start—drivers had to follow a convoluted series of procedures in order to prevent mechanical mishaps—the Electrovan weighed more than 7,000 pounds. Its components so filled the chassis that in addition to a driver, only one passenger could fit inside.

Moreover, the van's fuel cell required platinum as a catalyst. In a hydrogen fuel cell, a catalyst is necessary to split electrons from hydrogen molecules, producing an electric current. While today's hydrogen fuel cell electric vehicles also rely on noble metal catalysts, the Electrovan required so much platinum that for the same cost, one might have purchased a whole fleet of gasoline-powered vans. In the end, GM scrapped the Electrovan after producing just one.

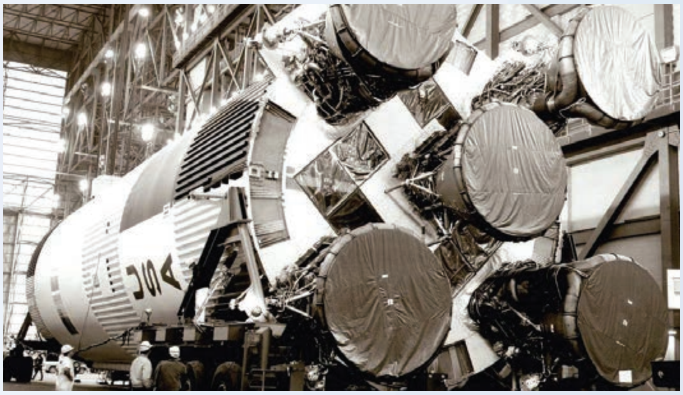
Fuel cells at Los Alamos

Interest in powering automobiles with hydrogen waned until the mid-1970s, when rising oil costs prompted a handful of scientists at Los Alamos to ask whether any

British scientist William Robert Grove developed the first hydrogen fuel cell in 1842. Photo: Wikipedia



Chemical engineer Francis Bacon improved on William Robert Grove's fuel cell. Photo: Encyclopædia Britannica



Bacon's fuel cell design helped provide power and water for astronauts on NASA's Apollo 11 mission. Photo: NASA

General Motors' Electrovan was the first fuel cell electric automobile. The vehicle's limitations were such that only one Electrovan was ever produced. Photo: Speedhunters/Mike Garrett of the research they'd conducted for Project Rover—which aimed to build a nuclear-powered rocket—could contribute to the nation's energy security. That question led, in 1977, to $25,000 in Laboratory funding for hydrogen fuel cell research.

Nearly half a century later, the fuel cell program has become Los Alamos' longest-running non-defense program. Work conducted in the fuel cell program has yielded hundreds of patents and produced many of the technologies that make fuel cells a viable technology today.

In fact, DOE's Hydrogen and Fuel Cell Technologies Office—which directs an annual research budget totaling more than $100 million and oversees a portfolio spanning diverse national laboratories, universities, and industries—has its roots in Los Alamos' fuel cell program. The program's work has also helped advance electrolyzers, which electrochemically split water molecules to produce hydrogen in a process that is essentially the inverse of what takes place inside a fuel cell.

"The Los Alamos program has changed a lot over the years," says Rod Borup, who is the Laboratory's fuel cell program manager. "Today, our concentration is really on materials. We work on essentially all the different internal components of fuel cells and electrolyzers."

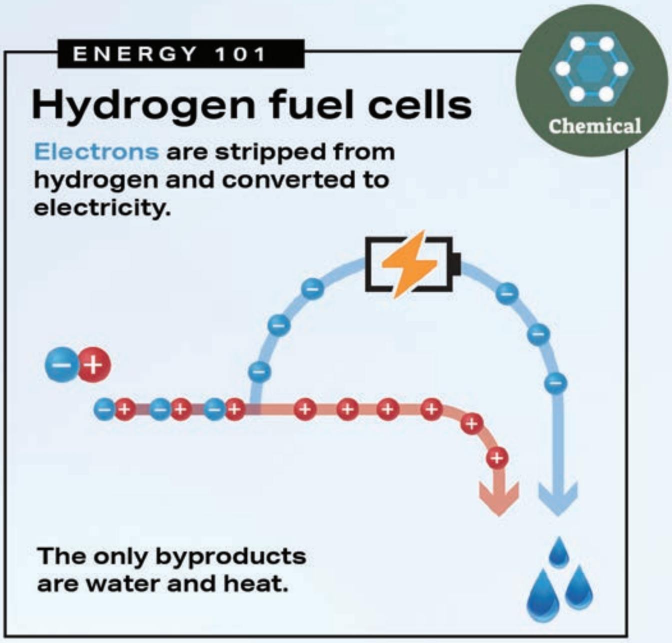
Not all fuel cells use hydrogen as a fuel, but those that do consist of three basic components: an electrolyte sandwiched between two electrodes. The electrodes on either side of the electrolyte, the anode and the cathode, are porous. When hydrogen molecules enter the anode side of the fuel cell, they interact with a catalyst—usually platinum—which splits them into protons and electrons.

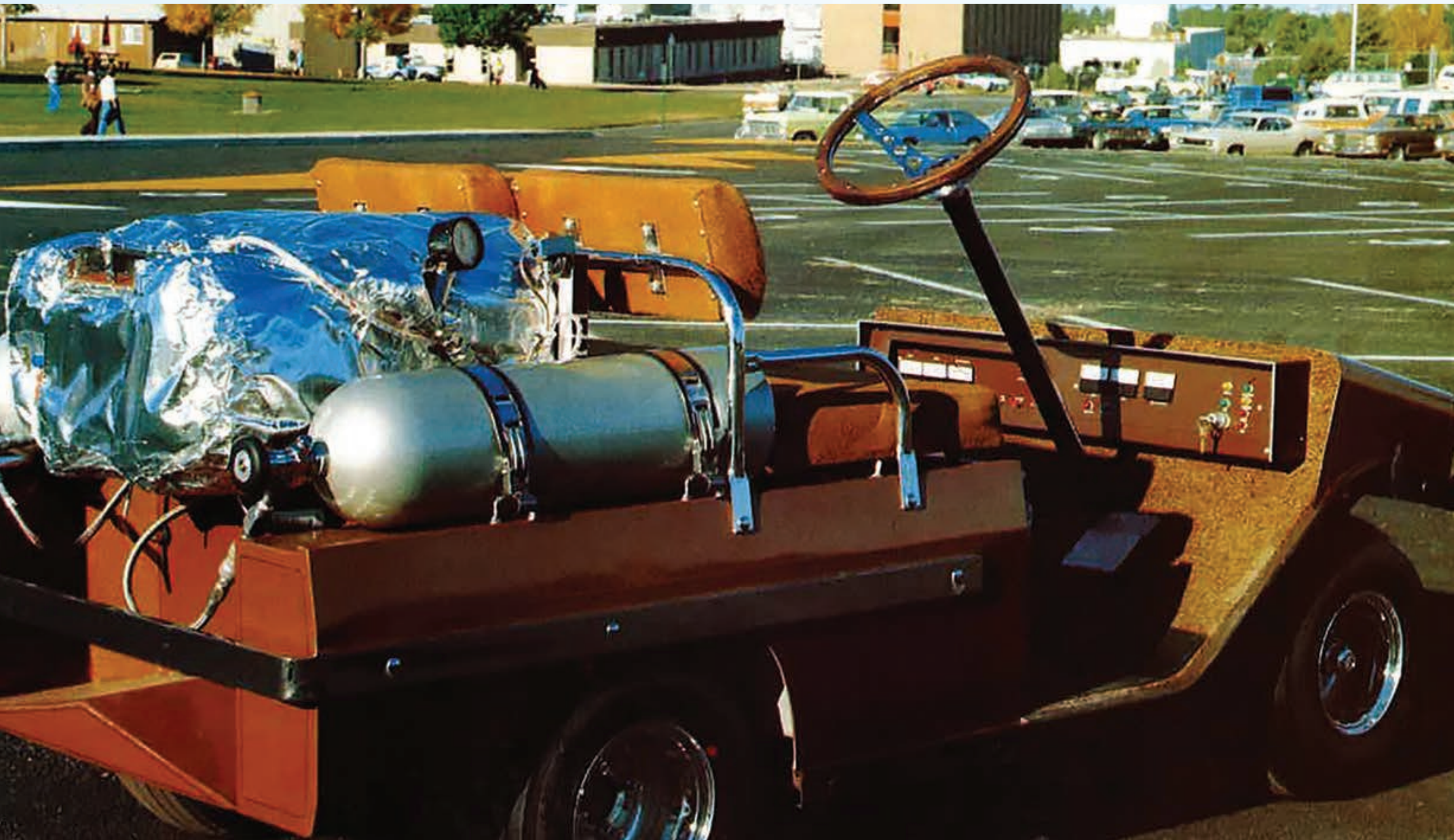
The positively charged protons then pass through the electrolyte to the cathode. Meanwhile, the negatively charged electrons travel along a circuit, creating an electrical current. At the cathode, oxygen molecules join with the protons that have passed through the electrolyte to yield heat and H2O—water.

Los Alamos had early successes in hydrogen fuel cell research and development, producing, among other

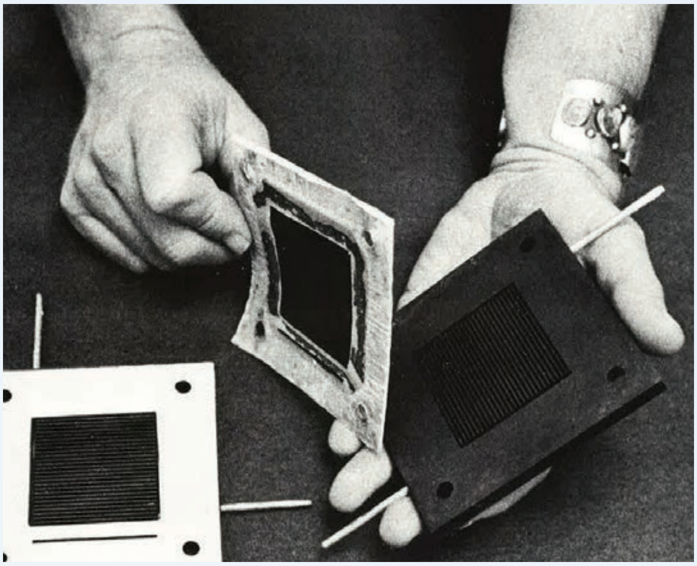
ENERGY 101

Hydrogen fuel cells





The hydrogen-powered golf cart developed at Los Alamos National Laboratory in the late 1970s.



Hydrogen fuel cells consist of three primary components: an electrolyte and two electrodes.

things, a hydrogen-powered golf cart by 1980. But a key breakthrough for the fuel cell program came in the early 1990s, when researchers developed a way to produce platinum-bearing electrodes that required 20 to 40 times less platinum than had hitherto been necessary. That advance alone lowered the cost of platinum needed for a passenger car's fuel cell from tens of thousands to hundreds of dollars—an achievement that led automobile manufacturers to take an interest in hydrogen once more.

"Before, we were using way more platinum. The electrodes were based on what NASA was using," Borup says. "The new electrode design was really the invention that got automotive companies like General Motors interested in fuel cells again."

Today, nearly every major automobile manufacturer is researching or developing fuel cell electric vehicles. Fuel cell electric vehicles are already available from several manufacturers, including Honda, Hyundai, and Toyota. These vehicles all rely on proton exchange membrane fuel cells, or PEMFCs, which use a polymer membrane for their electrolyte. PEMFCs are the fuel cell with the greatest potential for use in automobiles and other forms of transportation. For this reason, PEMFCs are the subject of most of Los Alamos' fuel cell program research.

PEMFCs have several advantages over other types of fuel cells. Unlike fuel cells that use liquid electrolytes, PEMFCs' solid electrolytes are adept at ensuring that protons, but not electrons, pass directly through from the anode to the cathode. PEMFCs operate at lower temperatures than other fuel cells, which means that they can start quickly and easily. They are also small and relatively lightweight.

Despite these advantages, PEMFCs aren't without their drawbacks. Historically, PEMFCs have been able to operate only within a relatively narrow temperature range—between 50 and 100 degrees Celsius. They also need moisture, meaning that they require expensive radiators and humidifiers to function in fuel cell electric vehicles.

New avenues for materials research

Los Alamos' fuel cell program focuses on improving the materials inside fuel cells to better address shortcomings like temperature and moisture requirements. During the past decade, a team led by the Laboratory's Yu Seung Kim developed a fuel cell with a redesigned electrolytic membrane that operates between 80 and 200 degrees Celsius—an optimal range for applications such as heavy-duty trucking—and that isn't as sensitive to variations in humidity.

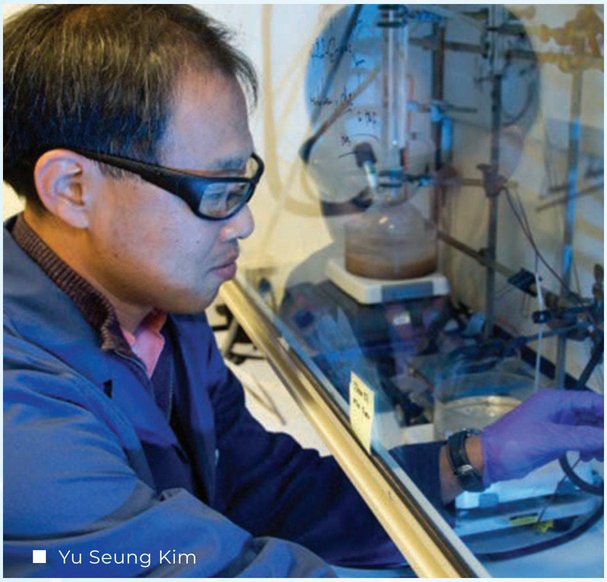
These advances will allow for fuel cell electric vehicles that can operate without the radiators and humidifiers that to date have helped drive up their cost. Kim won the Battelle Memorial Institute's 2022 Inventor of the Year award for his research, and Massachusetts-based Advent Technologies recently opened a commercial fuel cell factory to manufacture membrane electrode assemblies based on his design.

Other research at the Laboratory has focused on redesigning fuel cells' electrodes, updating a technology that had changed relatively little since the Laboratory's platinum breakthrough in the early 1990s. The electrode that was developed then consists of a carbon-supported platinum catalyst and an ionomer that are mixed in an ink slurry and deposited onto a membrane or gas diffusion layer. This process produces an electrode whose structure is randomized—a fact that significantly reduces the flow of oxygen through the electrode, thereby inhibiting performance.

"The current state-of-the-art fuel cell design was developed here at Los Alamos a little more than 30 years ago," says Jacob Spendelow, a researcher in the fuel cell program. "That electrode was a big breakthrough at the time. But since then, progress has kind of stagnated. We asked, if we could redesign the electrode from the ground up, what would it look like?"

"Today, our concentration is really on materials. We work on essentially all the different internal components of fuel cells and electrolyzers."

—ROD BORUP



Yu Seung Kim

Spendelow and his colleagues wound up developing what they describe as a “grooved electrode.” (A draft of a paper that the team eventually published in *Nature Energy* initially referred to the electrode as a “groovy electrode,” but the journal’s editors insisted on the more staid “grooved electrode.”)

The Spendelow team’s electrode is designed with microscale grooves and ridges that resemble those of a Ruffles potato chip. Unlike a potato chip, however, these grooves are precisely engineered, having been optimized with machine learning and multiphysics modeling. The design significantly improves oxygen transport, yielding an electrode that performs 50 percent better than the older model.

“Most of the work on improving fuel cell performance and durability has focused on improved materials,” Spendelow says. “What we did with the grooved electrode was different. We didn’t change the materials, but just the way that the materials are put together.”

Interlaboratory collaboration

In addition to operating more efficiently than its predecessor, Spendelow’s grooved electrode is more durable, capable of exhibiting 170 percent higher current density after 500 activity cycles. Durability is an increasingly important goal for Los Alamos’ researchers, in part because the fuel cell program has shifted its focus to designing fuel cells for heavy-duty applications.

Indeed, Los Alamos’ fuel cell program now plays a leading role in the Million Mile Fuel Cell Truck consortium, which Borup co-directs. The consortium unites five national laboratories’ efforts to develop PEMFCs for heavy-duty applications, with long-haul trucking as its focus.

Medium- and heavy-duty vehicles generate more than 20 percent of the transportation sector’s total carbon dioxide emissions, making the development of alternative trucking technologies important. Hydrogen makes sense for trucking because as a fuel, the element is relatively lightweight. Battery-powered semitrucks, for example, require batteries so heavy that a third of cargo capacity can be lost.

Research assistant Alaba Ojo (left) and postdoctoral researcher Nina Pappas inspect a membrane sprayed with a platinum catalyst.

> "What we did with the grooved electrode was different. We didn't change the materials, but just the way that the materials are put together."
>
> —JACOB SPENDELOW

Developing the infrastructure to support hydrogen trucks might also set the stage for adoption of other kinds of hydrogen vehicles. At present, 60 hydrogen refueling stations exist in the United States. Fifty-nine of those are in California (the other one is in Hawaii). Because semitrucks tend to travel along regular routes, building a series of refueling stations to accommodate the trucks on those established routes—creating a so-called "hydrogen highway"—would be easier than building enough stations to service fuel cell-powered passenger cars.

"DOE is looking at heavy-duty hauling as a way to get the hydrogen infrastructure to fill out," Borup says. "And then, at a later date, that infrastructure could be expanded to medium-duty and light-duty vehicles."

Durability has become a key objective for the fuel cell program's research because long-haul trucks, which often log 40,000 miles per year or more, put significant wear on their components. In particular, the heat produced by a PEMFC tends to degrade the fuel cell's electrolyte membrane. The Million Mile Fuel Cell Truck consortium's name refers to its ultimate ambition: to develop a fuel cell that can withstand one million miles of use—well beyond the 500,000 miles that many internal combustion engine-powered semitrucks log in their lifetimes.

The consortium also reflects a shift in programmatic emphasis away from smaller projects and toward increased collaboration with other laboratories and institutions. For example, Los Alamos, in collaboration with Argonne National Laboratory, is leading ElectroCat 2.0, a four-laboratory consortium that seeks to develop platinum group metal-free catalysts that will help make fuel cell and electrolyzer electrodes more durable and affordable.

"We're employing a systematic approach in which potential catalysts are synthesized and analyzed comprehensively using a variety of techniques, including high-throughput combinatorial methods," says Los Alamos' Piotr Zelenay, who co-directs ElectroCat 2.0. "One approach recently introduced at Los Alamos to accelerate electrocatalyst discovery involves using machine learning to guide catalyst synthesis based on the performance of earlier-developed materials."

Producing clean hydrogen

The Laboratory is also involved in the H2NEW (H2 from the Next Generation of Water Electrolyzers) consortium, which is co-led by the National Renewable Energy Laboratory and Idaho National Laboratory. Los Alamos participates alongside five other laboratories to develop technologies related to the large-scale production of hydrogen with electrolysis—that is, by applying an electric current to water molecules, splitting them into oxygen and hydrogen.

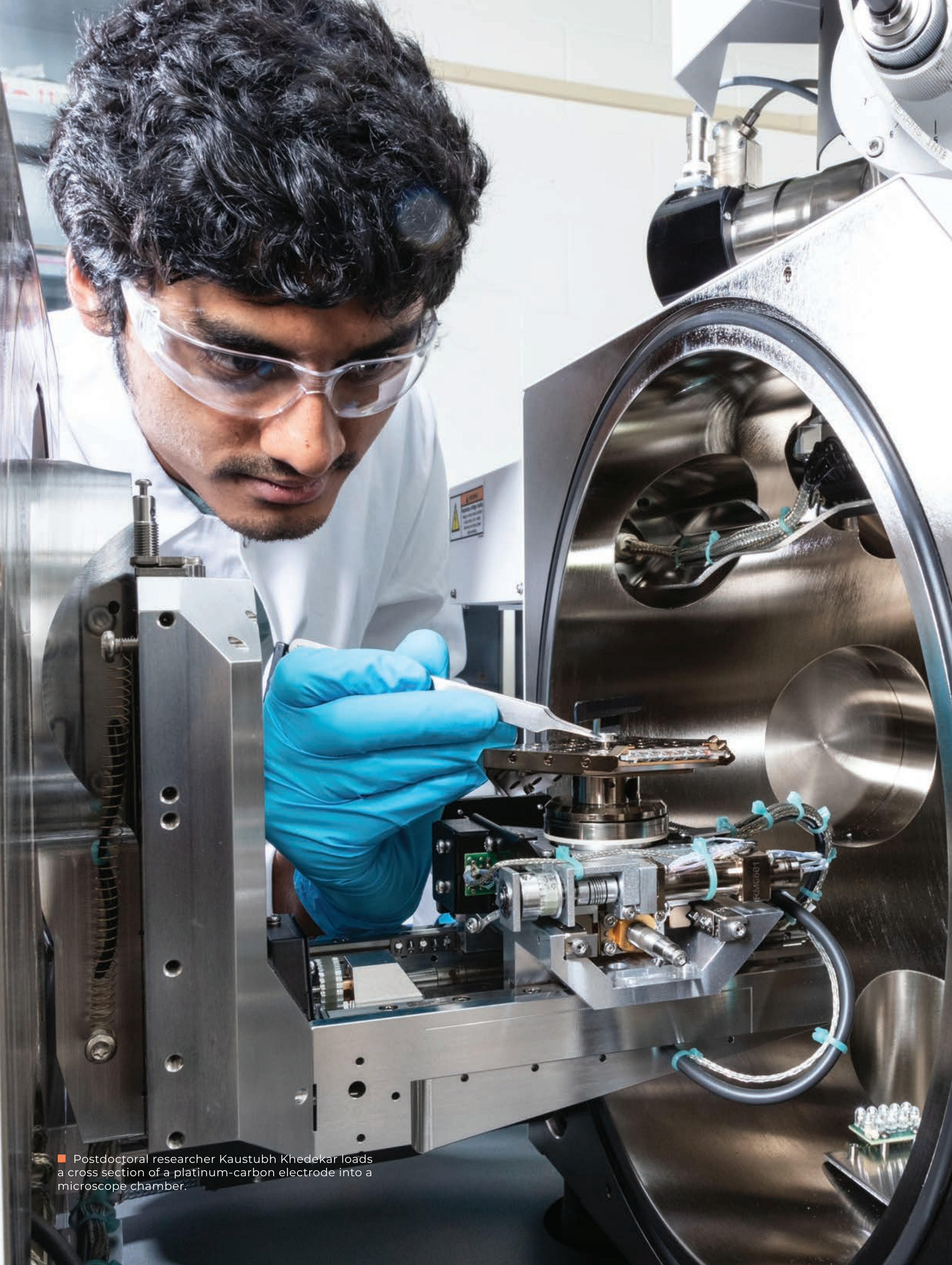
Hydrogen can be produced in several ways, but at present, in the United States, approximately 95 percent of hydrogen is produced from natural gas by a method called steam methane reforming. In addition to the carbon monoxide and carbon dioxide produced in this process, steam methane reforming is—like most of the United States' energy grid—powered primarily by fossil fuels.

Hydrogen produced from steam methane reforming and used in a fuel cell electric vehicle amounts to a 50 percent reduction in greenhouse gas emissions over those of a standard internal combustion engine. By using technology to capture and sequester the carbon dioxide emitted in steam methane reforming—and by detecting and addressing the methane leaks that often occur as a part of the production process—even cleaner hydrogen production is possible.

However, carbon capture and sequestration technologies have yet to see widespread adoption, meaning that most of the greenhouse gases produced in steam methane reforming are emitted directly into the atmosphere. DOE is encouraging the production of "clean" hydrogen, which includes hydrogen produced from natural gas with carbon capture technology. The cleanest hydrogen is produced by electrolysis, powered by renewable energy. An electrolyzer can convert solar or wind energy into hydrogen gas that can be used in fuel cell electric vehicles, with no greenhouse gases generated in the process.

Secretary of Energy Jennifer Granholm has said that "Clean hydrogen is the future." At present, though, clean hydrogen is also expensive: a kilogram of hydrogen produced with electrolysis costs more than $5, versus $1–2 per kilogram of hydrogen produced from natural gas.

DOE's Hydrogen Energy Earthshot plan aims to address that disparity by reducing the cost of producing a kilogram of clean hydrogen to $1 by mid-2031. "If we can



Postdoctoral researcher Kaustubh Khedekar loads a cross section of a platinum-carbon electrode into a microscope chamber.

lower the cost of clean hydrogen," said Granholm at the DOE's 2021 Hydrogen Earthshot Summit, "we will have the means to decarbonize industrial manufacturing, to refuel hydrogen fuel cell trucks, make alternative low-carbon fuel for planes, produce clean ammonia and other chemicals, create longer-duration storage, and so much more."

At present, of the 10 million metric tons of hydrogen that the United States produces each year, less than 1 percent is clean hydrogen. DOE hopes to see clean hydrogen production reach 10 million tons of hydrogen per year by 2030, 20 million tons by 2040, and 50 million tons by 2050, with approximately half of this hydrogen produced from electrolysis.

To achieve these numbers, more and better electrolyzers will have to be developed. The Bipartisan Infrastructure Law, which was signed by President Joe Biden in 2021, provides $1 billion in funding for electrolysis research and development—an outlay that is spurring innovation in the field.

At first glance, electrolyzers—which produce hydrogen by splitting water molecules—are less well researched than, say, fuel cells, which consume hydrogen. "There has been a rapid acceleration in the number of publications about electrolyzers, but there's not the historical aspect that there is with fuel cells," says Siddharth Komini Babu, a researcher in Los Alamos' fuel cell program who represents the Laboratory in the H2NEW consortium, and who was a co-author on Spendelow's grooved electrode paper.

While the research on electrolyzers is relatively scant, fuel cells and electrolyzers have a lot in common for a simple reason: the technologies are in a sense the inverse of each other. "The overall reaction is similar between them," Komini Babu says. "In essence, you're running a fuel cell backwards as an electrolyzer. The things that differ are the catalyst and the materials being used."

Like fuel cells, electrolyzers rely on an electrolyte sandwiched between two noble-metal catalysts. In fuel cells, it is possible to use carbon-based materials. However, in an electrolyzer, the carbon-based electrodes that are commonly used in fuel cells tend to corrode, meaning that they must be metal-based instead.

The similarities are such that technology developed at Los Alamos, like the grooved electrode, might be adapted for electrolyzers. "All of our work on electrode design was done initially for fuel cells, but we're looking at adapting the technology for electrolyzer applications as well," Spendelow says.

Like the research that is being conducted for the Million Mile Fuel Cell Truck consortium, durability is a focus for H2NEW research. This emphasis is due in part to the strain placed on electrolyzers by renewable energy sources. Previously, electrolyzers were designed to operate continuously. But because renewable energy peaks at

> "Clean hydrogen is the future."
>
> —JENNIFER GRANHOLM

certain hours and declines at others—as the sun sets or the wind stops blowing, for example—the next generation of electrolyzers must be able to tolerate frequent cycling between on- and off-states.

"New systems will have to operate in more of a dynamic environment, which leads to a lot more degradation," Komini Babu says. "That's why there is a lot more interest in developing new materials that can work under these dynamic conditions."

Other research involves reducing the quantity of precious metals used in electrolyzers. While electrolyzers often use platinum, like fuel cells, they also rely on iridium, a byproduct of platinum mining that is one of the scarcest elements on Earth. This fact has historically driven up electrolyzers' cost, preventing widespread adoption.

The H2NEW consortium is two years into its five-year program. Komini Babu says that already the consortium has succeeded in establishing many of the degradation methods that were absent from the extant electrolyzer research. Now researchers are working to develop materials to construct electrolyzers that are better able to withstand the stresses of an irregular power supply.

Putting it all together

One recently funded project will see the Laboratory's fuel cell program attempt to combine electrolyzer and fuel cell technology into a single package with the potential to help stabilize the nation's electric grid.

For decades, scientists have grappled with the challenge of providing "baseload"—that is, round-the-clock energy generation—to the power grid with renewable energy sources like wind and solar. (Fossil fuel power sources can operate continuously, meaning that they don't struggle to provide baseload in the same way.)

Pumped storage is an emerging solution, but requires both water and favorable geology. This method uses energy produced during periods of peak production to pump water to a higher elevation. During off hours, that water is released, generating hydroelectric energy. Another method involves using lithium-ion batteries to store extra energy for later use. In California, a network of lithium-ion batteries can store up to 5,600 megawatts of electricity, enough to power 4.6 million homes for 4 hours. But such batteries are expensive and provide power for only a short time.

At Los Alamos, Spendelow is leading a recently funded project to produce a unitized reversible fuel cell (URFC) that could become a key energy storage technology. The idea is to combine the functions of a fuel cell and an electrolyzer into a single unit. At times of peak renewable energy production, such a system could use electrolysis to produce hydrogen. When energy production slows, the system could operate as a fuel cell, turning hydrogen into electricity.

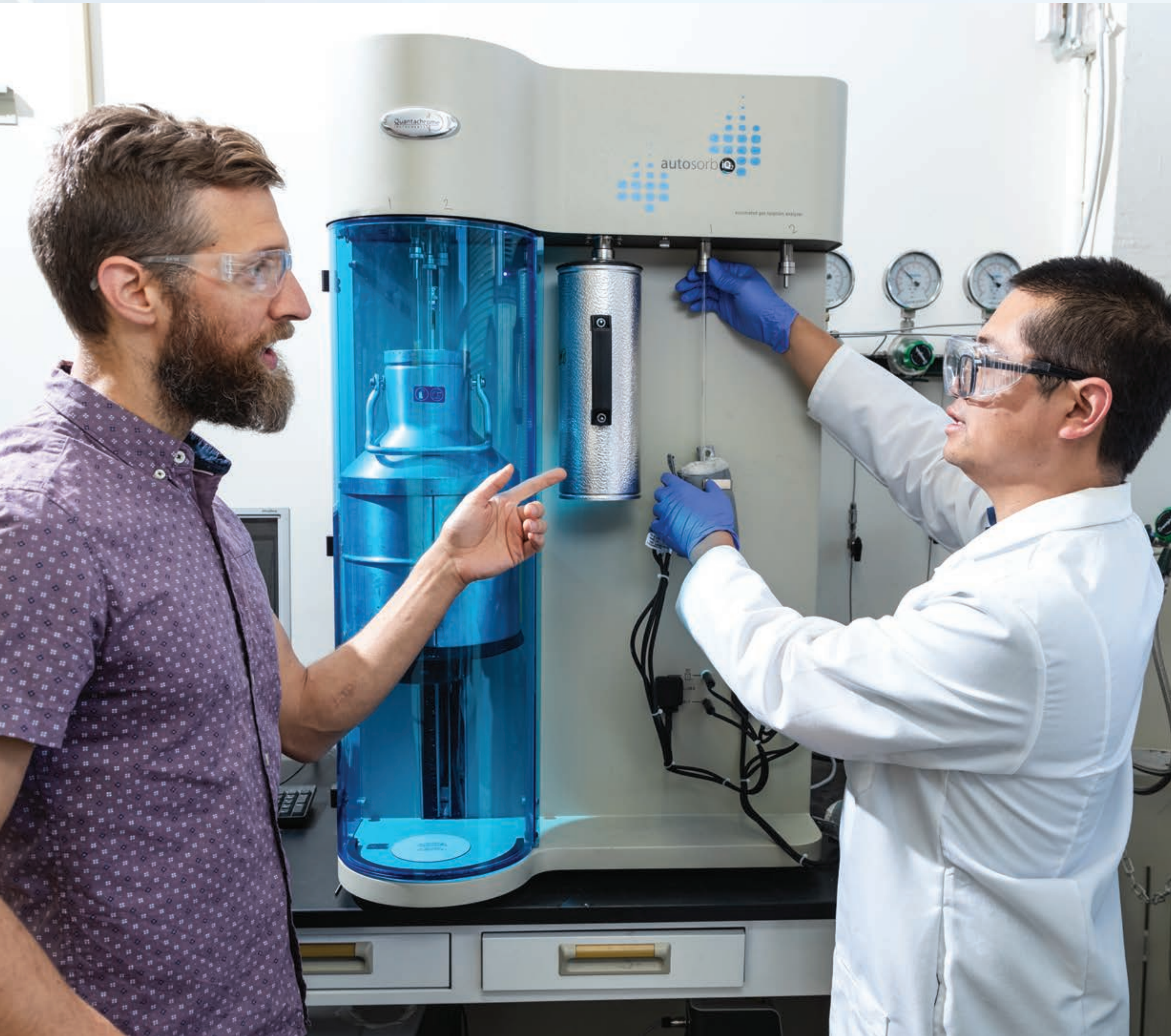
"This is a project where our knowledge of both fuel cells and electrolyzers will come into play," says Komini Babu, who will be a part of the project team. "We're designing new materials and combining them with our knowledge of fuel cells and electrolyzers into one single unit."

A unit that combines the functions of a fuel cell and an electrolyzer could be less expensive, and require a smaller

"We're designing new materials and combining them with our knowledge of fuel cells and electrolyzers into one single unit."

—SIDDHARTH KOMINI BABU

Scientist Jacob Spendelow (left) and postdoctoral researcher Kui Li load carbon support samples into an Autosorb iQ—a tool that plays a critical role in helping optimize fuel cell technologies.



Postdoctoral researcher Kaustubh Khedekar (left) and scientist Xiaojing Wang inspect an image of a novel electrode structure, called a dense pillar electrode, captured with a scanning electron microscope.

footprint, than two side-by-side units that perform these functions independently. And a URFC could have military and space applications as well.

While URFCs have been designed before, they suffered significant shortcomings in durability and efficiency that kept them from ever evolving beyond prototypes. The URFC that Spendelow and his team intend to pursue will draw on Los Alamos' expertise in fuel cells, deploying a polymer electrolyte membrane of the sort used in PEMFCs, along with the grooved electrode that Spendelow and his colleagues recently developed.

Among other challenges, the team will need to develop a porous transport layer—which is a key component of electrolyzers—that can be hydrophobic (water repellent) or hydrophilic (water attractant), depending on which mode the URFC is operating in. But with the fuel cell program's track record of producing innovative technologies, and with growing interest in developing novel hydrogen technologies, success seems within reach.

"There is a lot more focus on fuel cells and electrolyzers now," Komini Babu says. "The growing deployment of solar and wind power, and the whole hydrogen economy that's being developed, have the potential to be super beneficial."

For her part, Secretary of Energy Granholm is optimistic about the Laboratory's ability to help advance electrolyzer technology. In August 2023, the secretary visited Los Alamos, where she took part in a panel discussion that ranged from the legacy of the Manhattan Project and changes in the geopolitical landscape to the nation's clean energy transition.

Granholm noted that national laboratories like Los Alamos are poised to play a major role in helping to combat climate change and develop technologies like clean hydrogen. She added that much of the research that made electrolysis possible in the first place came from the United States' national laboratories.

"The ability to go through the labs to bring down the cost of electrolyzers for clean hydrogen is really, really important," Granholm said. "The mission—it's so great!" ★

MAGNIFYING THE MISSION

In a newly created position, Matt Heavner coordinates the Laboratory's climate and clean energy work.

BY WHITNEY SPIVEY

During thunderstorms, lightning sometimes travels up above the clouds—not down toward the ground, the way it's usually portrayed. This type of lightning—called sprites and jets—is what Matt Heavner studied during graduate school at the University of Alaska Fairbanks. Specifically, he studied the energy that this type of lightning releases into the middle atmosphere.

"The energetics and chemistry of the middle atmosphere increased my interest in studying and understanding climate," he says.

Heavner has sustained that interest throughout his career. At Los Alamos National Laboratory in the early 2000s, he worked on the FORTE satellite (which, among other things, helped scientists study lightning from space). Heavner has also worked at the University of Alaska Southeast—where he taught physics, climate, atmospheric science, and planetary science—and in the Office of Science and Technology Policy at the White House, where he worked on nuclear security and energy issues. Heavner recently returned to Los Alamos from the Department of Energy (DOE), where he helped establish the Arctic Energy Office. He is now the Laboratory's climate and clean energy coordinator, a new position that was created to synchronize the Lab's work in those areas.

Heavner sat down with *NSS* to discuss all things energy, federal policy, and why he hopes his new job might one day be eliminated.

Why does energy security equal national—and also global—security?

Energy security is fundamental to modern society and is the basis for personal, community, and economic security.

Globally, energy insecurity drives conflict and migration—just look at what's happening in Ukraine.

Domestically, U.S. policy clearly states that energy is directly tied to security. Presidential Policy Directive 12 established the policy that the U.S. energy system is one of 16 sectors of critical infrastructure. In this case, "critical infrastructure" is defined as systems and assets—physical or virtual—so vital to the United States that the incapacity or destruction of such systems and assets would have a debilitating impact on security, national economic security, national public health or safety, or any combination of those matters.

That sounds complicated. Where does Los Alamos fit in?

The challenge of climate change and energy transition is an all-hands-on-deck effort that absolutely requires DOE's national laboratories. Los Alamos specifically brings together the breadth of physics-informed modeling, natural and human complex systems, basic and applied energy research and development [R&D], demonstration and deployment, and place-based engagement to address the hardest security challenges.

Los Alamos has a diverse set of projects and programs related to climate and clean energy. These include climate modeling; infrastructure analysis; biotechnologies, such as biofuels and biomanufacturing; applied energy programs like fuel cell development, direct air capture technology, geothermal technology, and more; nuclear energy R&D, including small modular reactors and fusion; efforts to make Los Alamos operations more sustainable and resilient to climate-related threats such as wildfire and drought; and efforts to enable the achievement of the Biden administration's 2030/2050 climate and clean energy objectives.

The climate problem is much larger than what even one DOE lab can address, but Los Alamos' breadth and experience is required to strategically lead and partner across the climate and clean energy spectrum.

What's your role in all of this?

The impact of this work at Los Alamos can be magnified through coordination. My role is to facilitate the coordination, help identify and address gaps across the Laboratory's climate and clean energy efforts, facilitate and support cross-Lab partnerships as well as strategic external partnerships, and to make all of this the regular way Los Alamos executes across the climate and clean energy work being done. The ultimate success of my position is to eliminate the need for my role!

A significant part of my day-to-day work is spent in discussions with staff, program offices, and line management to understand current efforts and identify and facilitate cross-program integration that will accelerate the work and magnify the impact of the work across the climate and clean energy portfolio.

I develop documents to articulate—internally and externally—the Laboratory's climate and clean energy priorities and strategies. I work with Lab leadership to influence broader investment strategies to accelerate research, development, and deployment of climate and clean energy solutions, as well as respond to national security challenges that arise from a warming climate.

What work are you particularly excited about and why?

The urgency and the magnitude of the climate crisis and energy transition is personally very compelling. The breadth of the Laboratory's work in climate and clean energy, coupled with the general enthusiasm of the workforce for this type of work, is also exciting and gives me a lot of optimism for the future.

Planetary scientist Carl Sagan once said that "anything else you're interested in is not going to happen if you can't breathe the air and drink the water. Don't sit this one out. Do something. You are by accident of fate alive at an absolutely critical moment in the history of our planet." The work Los Alamos is doing can and will help the future of our planet. Knowing that I can perhaps make it happen faster and better is really motivating. ★

"The climate problem is much larger than what even one DOE lab can address, but Los Alamos' breadth and experience is required to strategically lead and partner across the climate and clean energy spectrum."

—Matt Heavner

■ Matt Heavner stands on the Arctic Ocean a few miles north of Oliktok Point, Alaska.
Photo: Matt Heavner

REVVING UP SOLUTIONS

Omar Ishak's auto repair skills come in handy as he navigates a futuristic research project in the laboratory.

BY J. WESTON PHIPPEN

Omar Ishak was 13 when he got his first car—or rather, the pieces of his first car.

Ishak grew up in Albuquerque, New Mexico, where he helped out at his dad's auto shop from a young age. So, he knew his way around automobiles. But the Acura Integra that his dad presented to him was missing most of one side and the engine.

"If you can piece together all the parts," Ishak remembers his dad saying, "you can have it."

Ishak, now a technical project manager in the Weapons Production associate directorate at Los Alamos National Laboratory, at first felt overwhelmed at the enormity of the large-scale restoration project. But like any budding scientist, he began with research. He looked over car part manuals and joined online forums, where others wrote about their experiences repairing cars of the same vintage. The more Ishak learned, the more his hesitation turned into excitement for what the vehicle might become.

Since reconstructing that first car, Ishak has completed 12 full restorations, plus countless partial overhauls. He's rebuilt suspensions, transmissions, supercharger systems, turbo systems, and even new engines. Ishak works almost exclusively on Japanese imports from the 1990s and early 2000s, mostly Hondas, Toyotas, and the occasional Subaru. "Japanese cars are iconic," Ishak says, "and when it comes to the bang for your buck they're unmatched for how they handle and the power per liter of displacement they produce."

FROM GARAGE TO LABORATORY

After graduating with a bachelor's degree in biology from the University of New Mexico and then a master's in public health from Tulane University's School of Public Health & Tropical Medicine, Ishak came to the Los Alamos National Laboratory in 2014. Working as a post-master's student in the Bioscience division, his first job was to research influenza-A mutagenesis and the propensity to manipulate successive genomic aberrations. When that work finished, he was tapped to work on the Lab's Advanced Tissue-engineered Human Ectypal Network Analyzer project, or ATHENA.

Started as a means to test new drugs and other toxic agents, ATHENA was an effort to build miniaturized bioengineered organs that simulate those in the human body, including the lungs, liver, heart, and kidneys. The project was a little outside of Ishak's specialization, but his work on cars gave him a unique perspective that allowed him to succeed.

"The logistical issues behind fluid mechanics are surprisingly transferable from cars to organs," he says, laughing. "When we were building the liver, it was very metabolically demanding and complex. It required various fluid circuits, as well as a dedicated gas supply to help control fluctuations in pH. With a car—it's not exactly apples to apples, of course—but you're essentially fighting similar issues, specifically maintaining laminar fluid flow, in addition to thermal management through various complex systems. So, I was able to bring a different approach to solving our issues at hand."

NEW CHALLENGES

When Ishak completes a build, he often takes the car to a racecourse. Performance on a course is a good indicator of the car's ability, testing not only horsepower but everything from its handling to braking. "Anyone can add a turbo or supercharger into a car and overpower it," he says. "But what really counts is how the vehicle functions holistically while balancing other aspects as well. That attention to this detail is what separates the pros."

These days, outside of the Lab, Ishak has taken up a different but closely related hobby: working on motorcycles. He's currently restoring a Triumph Daytona 675R, which he will be taking to the track soon. ★

■ Ishak recently restored this 2007 Honda s2000.


S2000

THE DISTINGUISHED ACHIEVEMENTS OF LOS ALAMOS EMPLOYEES

Deputy Director for Weapons **Bob Webster** received the Outstanding Nuclear Engineer (ONE) Award from Purdue University. The ONE Award is presented annually to outstanding School of Nuclear Engineering alumni in appreciation of their contributions to the nuclear engineering field. Webster holds doctorate and master's degrees in nuclear engineering from Purdue. (He also holds a master's in electrical engineering and applied physics from Case Western Reserve University, as well as a bachelor's degree in electrical engineering.)

Eric Brown was named director of the Los Alamos Neutron Science Center (LANSCE) and senior director for the associate Laboratory directorate of Physical Sciences. LANSCE is a premier accelerator-based user facility for research underpinning Laboratory missions in national security, energy security, and fundamental science.

Kim Scott is the new Weapons Programs executive officer and will manage the activities of the Weapons directorate. "In addition to supporting the deputy Laboratory director for Weapons and partnering with the Los Alamos executive officers on operational strategies," she says, "I would like to enhance how we partner to do our work in Weapons, foster new synergies across the Laboratory, and further strengthen our relationships with the National Nuclear Security Administration and the Department of Defense."

In mid-September, Deputy Laboratory Director for Science, Technology, and Engineering **John Sarrao** left Los Alamos to become the sixth director of SLAC National Accelerator Laboratory. "I am very proud to see him deservedly join the ranks of the national laboratory directors," says Los Alamos Director Thom Mason.

Four Los Alamos scientists received Department of Energy Early Career Research Awards: **Rich Fiorella** for improving modeling of coastal-urban environmental change using stable water isotope ratios and numerical tracers; **Kun Liu** for understanding the origin of the hadron mass; **Andrey Lokhov** for improving the mathematics underpinning machine learning for many-body quantum physics, power grids, turbulence, and field theories; and **Yu Zhang** for boosting multiscale modeling capabilities for molecular quantum electrodynamics on exascale computers.

Since the Perseverance rover landed on Mars on February 18, 2021, its SuperCam instrument has captured unprecedented data. Because of the SuperCam's success, NASA honored the SuperCam development team—led by **Roger Wiens**, **Scott Robinson**, **Tony Nelson**, and **Sam Clegg**—with the Group Achievement Award. This award is given to a team of government employees in recognition of an "outstanding accomplishment" that has "contributed substantially to NASA's mission."

Nine researchers who have made significant contributions in their respective fields were named 2023 Los Alamos National Laboratory Fellows: **Tariq Aslam**, **Rod Borup**, **William Daughton**, **Tess Lavezzi Light**, **Filip Ronning**, **Richard Van de Water**, **Hari Viswanathan**, **Ivan Vitev**, and **Scott Watson**.

Clarissa Yablinsky, of the Nuclear Materials Science group, earned the Silver Medal Award from ASM International, the world's largest materials science and engineering society. Yablinsky was recognized for "excellence in materials research and development supporting the nuclear deterrent and advanced nuclear energy and tireless volunteerism for the profession and STEM outreach."

Yu Seung Kim and **Rodman Linn** received the Laboratory Fellows' Prize for research, and **Kirsten Taylor-McCabe** received the Fellows' Prize for leadership.

Ruth Skoug was named Fellow by the American Geophysical Union for her far-reaching impact on experimental space plasma physics in the solar wind and magnetosphere.

John Bernardin, of the Modern Manufacturing Methodologies group, received the 2023 Outstanding Mechanical Engineer Award from his alma mater, Purdue University. He was selected for his "innovation, entrepreneurial spirit, dedication to leadership and community service" in mechanical engineering research.

Los Alamos National Laboratory was selected as one of the "Top Companies for Latinas to Work for in the United States in 2022," by Latina Style magazine. The Lab, which ranked 33rd out of 50, has appeared on this list for five consecutive years and is the only national laboratory honored.

BETTER SCIENCE = BETTER SECURITY

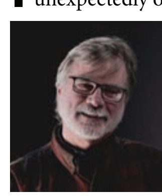
Hardworking people—the Laboratory's most important asset—enable Los Alamos to perform its national security mission.

IN MEMORIAM

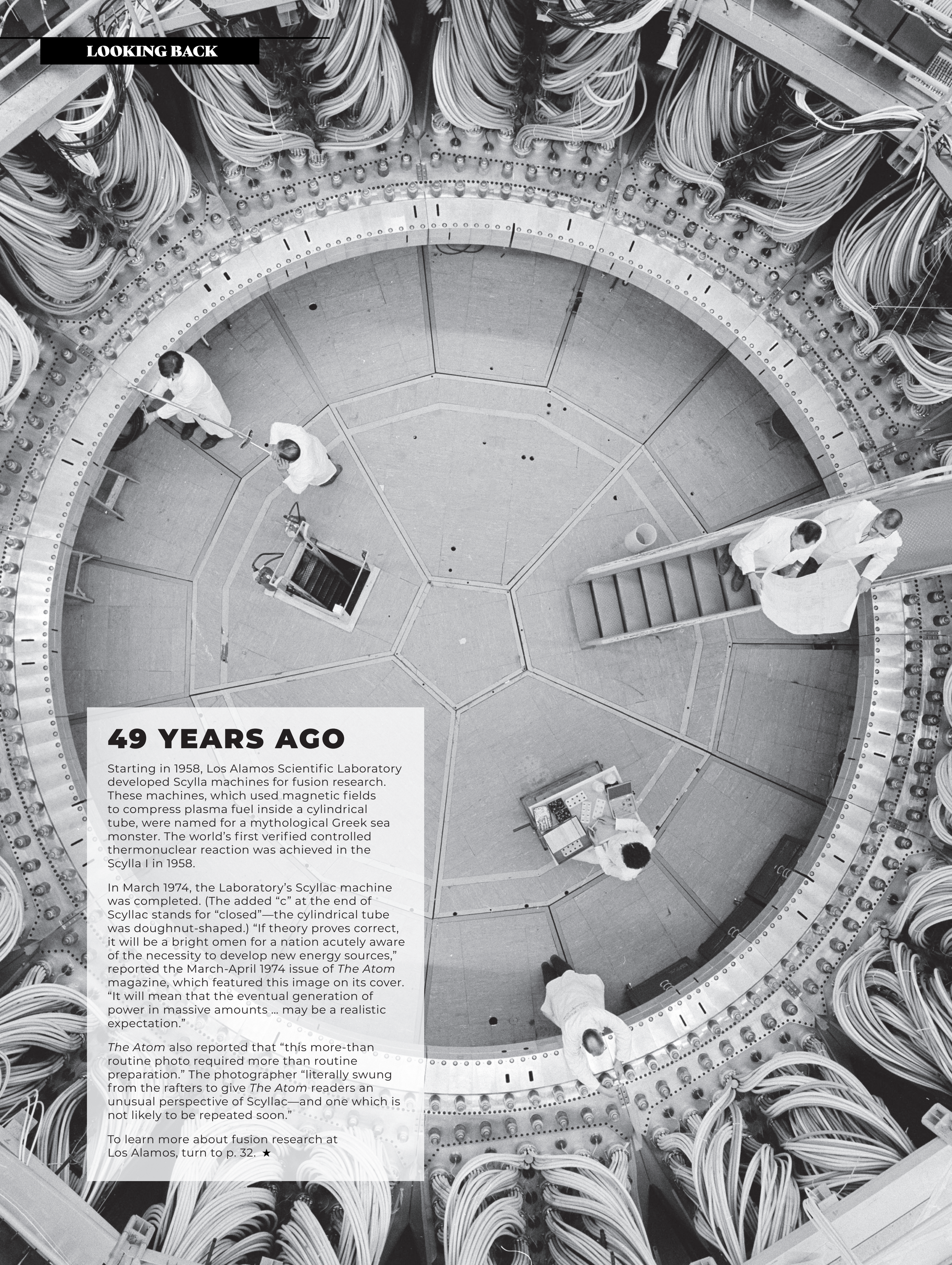
Based at Los Alamos during the Manhattan Project, John Tucker designed, built, and tested detonators and bomb-handling equipment and wrote check sheets for detonator disassembly, inspection, testing, and reassembly. In July 1945, he was sent to the Pacific Island of Tinian to work on Project Alberta, which ensured an atomic bomb could be successfully dropped by aircraft. He personally tested and selected the fireset that armed Fat Man, the implosion bomb released over Nagasaki, Japan.

Returning to Los Alamos after the war, Tucker led the development of the Lab's Detonator Firing Site and authored two major detonator science references, *The Los Alamos Detonator Catalog* and *Los Alamos Detonator History*, both still in use today. He also taught seminars (known as "Tucker Tech") to new engineers. He worked as a consultant for another decade after his official retirement in 1982. Tucker passed away on September 2, 2023, at the age of 105.

Seismologist William Scott Phillips, of the Laboratory's Geophysics group, passed away unexpectedly on October 3, 2023. Phillips



began working at Los Alamos in 1985 and was involved for a time with the Hot Dry Rock program (see p. 44 as well as the summer 2022 issue of this magazine). ★



49 YEARS AGO

Starting in 1958, Los Alamos Scientific Laboratory developed Scylla machines for fusion research. These machines, which used magnetic fields to compress plasma fuel inside a cylindrical tube, were named for a mythological Greek sea monster. The world's first verified controlled thermonuclear reaction was achieved in the Scylla I in 1958.

In March 1974, the Laboratory's Scyllac machine was completed. (The added "c" at the end of Scyllac stands for "closed"—the cylindrical tube was doughnut-shaped.) "If theory proves correct, it will be a bright omen for a nation acutely aware of the necessity to develop new energy sources," reported the March-April 1974 issue of *The Atom* magazine, which featured this image on its cover. "It will mean that the eventual generation of power in massive amounts … may be a realistic expectation."

The Atom also reported that "this more-than routine photo required more than routine preparation." The photographer "literally swung from the rafters to give *The Atom* readers an unusual perspective of Scyllac—and one which is not likely to be repeated soon."

To learn more about fusion research at Los Alamos, turn to p. 32. ★

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THEN & NOW

Students at the Los Alamos Ranch School, which operated in Los Alamos, New Mexico, from 1917 to 1943, often played ice hockey, either on Ashley Pond (pictured above) or in a rink they built in the bottom of a canyon. In 1943, the school shut down, and a wartime laboratory—Project Y of the Manhattan Project—sprung up around the pond. With the pond no longer suitable for recreation, the canyon ice rink became a favorite skating venue during the war and for years after—so much so that in 1950 the Atomic Energy Commission funded a larger rink (pictured below) that remains popular today. According to Los Alamos County, this rink is the only refrigerated, National Hockey League–regulation outdoor ice rink in New Mexico. ★

Photo: New Mexico Ice Wolves