LOS ALAMOS SCIENCE AND TECHNOLOGY MAGAZINE | FEBRUARY 2019

1663

Fusion's dark horse

Next-gen nuclear safety

Candy crystals

Chemistry's trophy molecule

Accidents and attacks threaten our aging energy grid.

What can be done to keep the lights on?

Los Alamos
NATIONAL LABORATORY
EST. 1943

Table sugar, or sucrose, is typically refined from sugar beets or sugar cane. Seen here magnified under polarized light, pure sucrose has a very complex microscopic crystal structure. To form a crystal, many identical molecules must align in a regular lattice-like configuration. The sucrose molecule consists of a hexagonal glucose joined to a pentagonal fructose by a shared oxygen atom. The chemistry of how sucrose molecules align to form sugar crystals is of interest to candy makers and national-security scientists alike. For more about candy chemistry at Los Alamos, see "Sweet, Sweet Science," on page 16.

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ABOUT THE COVER
Cell phones and computers, HVAC systems and dishwashers, bank accounts and hospital records, subways and security systems—without electricity, humanity is left in the dark in many important ways. The nation's energy grid is not only one of the most important networked systems in the country, it is also one of the most complicated. Scientists at Los Alamos are using mathematics, computer science, and engineering to make the nation's power grid more resilient, reliable, sustainable, efficient, and secure. The modernized grid will incorporate more renewable sources of electricity, withstand wind and water, recover quickly after an outage, and establish safeguards against threats of all kinds.

ABOUT OUR NAME
During World War II, all that the outside world knew of Los Alamos and its top-secret laboratory was the mailing address—P. O. Box 1663, Santa Fe, New Mexico. That box number, still part of our address, symbolizes our historic role in the nation's service.

ABOUT THE LDRD LOGO
Laboratory Directed Research and Development (LDRD) is a competitive internal program by which Los Alamos National Laboratory is authorized by Congress to invest in research and development that is both highly innovative and vital to national interests. Whenever *1663* reports on research that received support from LDRD, this logo appears at the end of the article.

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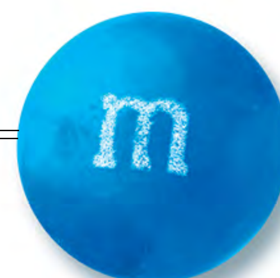

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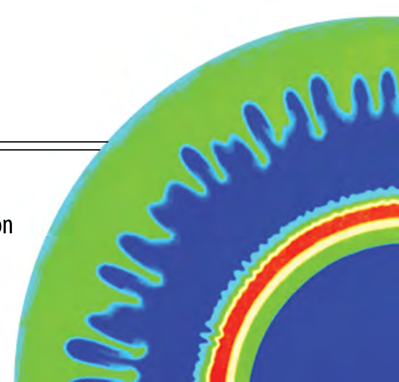


SPOTLIGHTS

A lighthouse radiation detector is named for its sweeping and scanning field of view, which comes from all but one side being shielded, in this case with tungsten plates, to attenuate the detection of gamma rays. The location of a radiation source is determined by comparing the changing signal strength as the detector pivots, "looking" around the room.

Radiation Detection Gets Direction

Scientists at Los Alamos recently learned something that they already knew: The ground at the Trinity site in south-central New Mexico is still radioactive. But not terribly so—eating a banana will deliver about as much ionizing radiation as 20 minutes at Trinity, where the first atomic bomb test was conducted. Further, the soil contains two kinds of radiation sources: direct decay products left over from the 1945 blast and elements native to the soil that were induced to radioactivity after capturing free neutrons released by the test. But while the radioactivity itself is not new, the way in which it was measured is.

Los Alamos engineer Jonathan Dowell has invented a suite of novel radiation detectors. Conventional radiation detectors operate on proximity—the closer the source, the stronger the signal—so pinpointing a source is a literal game of "hot-and-cold." But Dowell's detectors, which he named "lighthouse detectors" based on their sweeping and scanning field of view, are more sophisticated. They can pinpoint the direction of a radiation source without having to approach it and distinguish between sources when multiple sources are present, offering improvements to both safety and speed of material inventories, geological surveys, or radiological remediation. The survey at Trinity used a HAZMAT robot outfitted with lighthouse detectors and was a successful demonstration of how quickly large areas can be surveyed without sending in any people.

A self-described Ozark mountain hillbilly, Dowell was a teenaged ham radio operator. In 1989 he came to northern New Mexico for the skiing, stayed for the love of a lady, and in the meantime built an impressive engineering career at Los Alamos. In 2012, while surveying a contaminated glovebox, Dowell, being familiar with the directional nature of radio antennae, wished for a similarly directional radiation detector to pinpoint exactly which part of the glovebox was hottest. No such detector existed, so he invented one.

Similar devices block the radiation on all sides except one. But fully blocking gamma rays or fast neutrons requires a lot of bulky shielding material. What Dowell did differently, to keep his detectors small and agile, was to focus on attenuation, or reducing the signal, rather than trying to block it completely. Dowell likens it to a car with tinted windows—sunlight still enters through the rear and side windows but is attenuated, while the sunlight entering through the untinted windshield is not. Attenuated signals can be compared to unattenuated signals either through space—multiple detectors in different orientations to the source—or through time—one detector with a rotating field of view that intermittently points toward a source.

The gamma-ray lighthouse detectors consist of solid scintillator crystals surrounded on all but one side by attenuating tungsten plates. The fast-neutron lighthouse detectors consist of long narrow tubes filled with helium-3 gas and partially wrapped with an attenuating custom boron-carbide ceramic. At the back of each sits the electronics package, which is basically a small computer, including a power supply, signal processer, spectrometer, and web server, with both USB and Ethernet connectivity.

"The means by which we detect radiation is not new technology," Dowell explains. "We advanced the engineering mainly through custom electronics. That's how we got the detectors to be so versatile and portable."

After proving the efficacy of his prototypes in 2012, Dowell and Los Alamos teamed up with several industrial partners to miniaturize and refine the physical designs. In 2015 the team demonstrated undersea capabilities of lighthouse detectors arrayed aboard a remotely operated submarine vehicle. Then, after further miniaturization—in three months the electronics package went from the size of a lunch box to half the size of a business card—the detectors were ready for mass production, enabling a myriad of remote field capabilities.

The safety benefit of lighthouse detectors for automated mapping of complex sites is twofold. First, the time and amount of exposure are minimized because the detectors can quickly zero-in on the location of a source. Second, dangerous tasks—like entering a site after an event, which can include physical instability, cumbersome maneuvering in radiation suits, and eventual fatigue—can be exchanged for less dangerous tasks, like sitting in a control booth a safe and comfortable distance away, controlling a HAZMAT robot carrying lighthouse detectors.

In keeping with the noble job of their namesake, lighthouse detectors cast their gaze into the darkness, helping to keep people out of harm's way.

—Eleanor Hutterer

Megapower

Imagine an electrical power plant small enough to be delivered by truck, simple enough to be fully operational in a few days, and energetic enough to power a small town for a decade or more without refueling. It can provide electricity to remote communities, hardware installations, and deployed military bases. It can protect critical infrastructure like hospitals from reliance on the electrical grid. It runs with minimal moving parts, continuously self-regulates to match changing electrical demand, and produces zero greenhouse-gas emissions. It's coming soon to the places that need it. But where does it come from?

Mars.

Working in partnership with NASA, Los Alamos scientists recently unveiled Kilopower: a small, fully automated nuclear power plant designed to operate continuously for decades on deep-space craft, on the moon, or on Mars—providing abundant and secure power for human exploration or colonization. [*See "Power to the Planet" in the August 2018 issue of* 1663.] But in an unusual twist, instead of just adapting an existing technology for use in space, the scientists went on to scale up the space technology for use on Earth. Because Kilopower was already designed to work safely and reliably in an exceedingly hostile and remote environment, it was a natural model for safe, reliable, and especially portable power for sensitive or remote locales here at home.

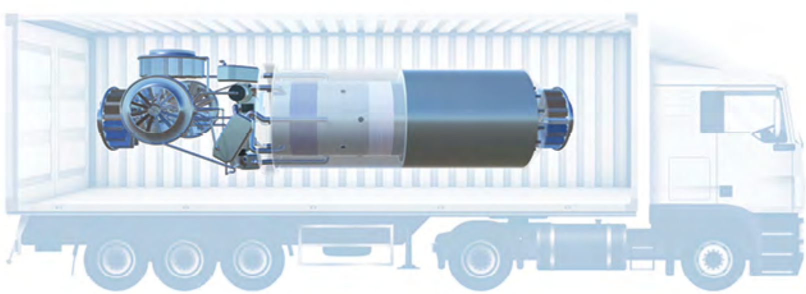
Thus, Megapower was born. Like its space-worthy predecessor, Megapower employs an entirely new kind of nuclear reactor, in which several pieces of specially arranged solid uranium undergo a fission chain reaction. The reaction generates heat (instead of, say, burning coal or gasoline), and that heat is delivered to an engine by a Los Alamos invention called a heat pipe. Whenever more power is needed, the heat pipe draws heat faster, cooling the reactor and therefore slightly shrinking the uranium. With the fissionable fuel now denser, the neutrons causing the chain reaction naturally encounter more nuclei to split, thus increasing the reaction rate; in this way, the reactor automatically increases power when it's needed and, conversely, cuts power when it's not.

This self-regulation also acts as a built-in safety guarantee. A conventional nuclear power plant constantly operates a network of valves and pumps to pipe in vast quantities of water from a nearby lake or river to cool the reactor; these components can potentially fail in an emergency. But Megapower is self-cooling; it requires no water and no specific safety subsystems to secure the reactor. Runaway reactions, such as those that might lead to a meltdown, are simply not possible because the reaction rate is always limited by the fact that rising temperature expands the solid fuel, thereby putting the brakes on the reaction.

Los Alamos has partnered with Westinghouse, a major producer of nuclear (and nonnuclear) power plants, to refine the design and manufacture the plants under the name eVinci™. For safety, reliability, portability, and ease-of-use that's sufficient for operation on another planet, it will have the Los Alamos-designed reactor core and heat-pipe systems. For efficiency and economy appropriate to Earth-bound applications, it will have a Westinghouse engine-generator system to convert reactor heat into electricity.

The unit is designed to be modular and produce about 10 megawatts of electricity. That's on the order of one hundredth of the maximum power output of a large nuclear power plant—plenty for a small town or remote research facility, such as a cluster of mountaintop observatories. A modest city like Santa Fe, New Mexico, with a residential population of 150,000, would probably require five to ten units. However, because Megapower is designed to sacrifice economy of scale in favor of versatility, the electricity would be somewhat more expensive than typical grid-based power. Therefore, the technology would be better suited for isolated and specialized applications requiring significant uninterrupted power than for existing grid-connected cities.

The Los Alamos team is currently maturing designs, testing materials, and exploring manufacturing options, with component and systems testing not far behind. If all goes according to plan, then anyone looking to retire off-grid with ten thousand households' worth of stable, automated power (and, not for nothing, a security perimeter suitable for safeguarding uranium) could see the ideal technology come online in as little as five years. LDRD



Megapower—a small self-regulating, carbon-free, standalone power plant—will fit in a standard shipping container for transport by road, rail, air, or sea.

—Craig Tyler

PHOTO CREDIT: Michael Pierce

IN THEIR OWN WORDS

Laboratory Fellow and chemist

JAQUELINE L. KIPLINGER

explains how to maintain a delicate balance between serendipity and perseverance on the path to discovery.

DOES ANYONE REALLY SET OUT TO BE A CHEMIST? I know I didn't. I went to college loosely intending to be a medical doctor. But plans have a way of shifting, bit by bit—an inspirational speaker here, a well-timed opportunity there—and as a result, my research career largely snuck up on me. I'm glad it did, and I'm glad I didn't fight it.

The first such shift in my career trajectory happened after the space shuttle *Challenger* burst into flames in a horrific midair explosion. One of my professors did a classroom demonstration illuminating the immense energy that can be released in an uncontrolled detonation, and I was captivated. Talk about making the best of a tragic situation! Just like that, a research career started to feel like a real option—and in chemistry of all things.

The same theme of chance timing, and perhaps a healthy dose of capitalizing on challenges revealed in current news and international events, seems to have guided parts of my research too. Every time I tried to solve some chemistry conundrum, whether I was ultimately successful or not, I ended up solving something else along the way, something people needed right then. Case in point: in graduate school, I set to work on Teflon™, essentially finding ways to break it down or bond to it—ways to stick to something expressly designed to be nonstick. But a Teflon molecule is a string of carbon fluorides (CF_2), and around the same time, people were really interested in the related fluorocarbons (CF_4) that contributed to the earth's ozone hole. My effort to defeat Teflon—which I considered fascinating and valuable in its own right—had positioned me to spend the next few years at the forefront of the successful international effort to assess and repair a hole in the earth's atmosphere.

I came out of that experience feeling like a serious scientist, a real expert. That feeling lasted until I got to Los Alamos as a Frederick Reines Distinguished Postdoctoral Fellow, where I quickly found out just how much I didn't know.

Can U=C it?

Since coming to Los Alamos, I spend most of my time mountain biking, gardening, hiking, and hanging out with my family, cats, and friends—and, of course, trying to make uranium atoms double-bond to carbon: U=C. For nearly two decades, I have been consistently pursuing that. (By "that," I mean the uranium-carbon double bond. If I had spent as much time mountain biking as I spent on that double bond, then it would be embarrassing how often I still fall down.) Before I came here, I didn't know there was anything I could devote 20 years to, off and on, without solving it many times over. But actinide chemistry—uranium being an actinide element—is really hard, and achieving the synthesis of a U=C bond has enormous potential scientific and programmatic impact.

HAVING AN OVERARCHING QUEST GUIDES NEW DISCOVERIES ON ITS PERIPHERY.

It's such a specific, simple-sounding thing to make U=C. But it just wouldn't happen, not for anyone, for a really long time. Only in the past year did my team make it happen. Sort of. Technically, we "trapped" it, which means we demonstrated a chemical reaction that would only occur if U=C had emerged along the way. We still haven't actually seen U=C itself. But at least now we know it's not completely impossible to make.

Trapping U=C has been tremendously gratifying for me. But like most scientific discoveries, it leads to more questions, more analysis, and more experiments. To be sure, my work on this is far from complete. But every once in a while, something pivotal happens, and that's how I see trapping this double bond.

For an element of such strategic importance as uranium, for both national defense and energy security, exploring all of its chemistry is obviously imperative. Here at Los Alamos, certain key aspects of our mission clearly depend on finding out everything you can do with it. From nuclear fuel to nuclear power to nuclear weapons to nuclear waste, uranium is key. People tend to focus on its nuclear properties, which stem from its nuclear physics, rather than its chemical properties, which stem from its electronic structure. But to extract it, refine it, repurpose it, store it, and really do anything at all with it, you need to understand the chemistry. And of course, the carbon I'm trying to attach it to—well, carbon is everywhere, and it's important to just about everything.

Yet I think the quest is even bigger than all that. The simple fact that this double bond is so incredibly, unexpectedly hard to make implies that something deeper is going on here—some new aspect of an atom's electronic structure that no one in the world knows about yet. And now that we've trapped it, we're much closer to understanding it.

Mother of invention

To the uninitiated (and, I suppose, to plenty of professional chemists), it may sound absurd to spend two decades pursuing this one troublesome double bond—which, by the way, other scientists had been pursuing for at least another decade before I ever got involved. And had that been my sole focus the whole time, it might have been a bit monomaniacal. But as with Teflon and the ozone hole, my uranium research produced a number of practical but unanticipated spinoff discoveries along the way.

Uranium is unique in a lot of important, useful ways. It can catalyze reactions that no other element can. It can be used to create superconductors and other specialty materials. It can be used to disintegrate petroleum contaminants. It can, of course, be configured into nuclear fuels. You study these things in the laboratory, making progress until nitty-gritty chemistry gives way to real-world materials science, and real-world materials science produces tangible technology.

But that initial laboratory work requires some starting material—some uranium compound that can be obtained, manipulated, and experimented upon in safe, reliable, and flexible ways. And suitable uranium compounds are not so easy to come by. Before I came to Los Alamos, the processes people employed to make uranium starting materials were cumbersome, dangerous, irreproducible, and astonishingly inefficient. Some produced toxic waste. Not surprisingly, over time, various safety and security protocols have been established that limit what you're allowed to do, and these restrictions motivated my research efforts.

The point is, practical starting materials containing uranium (and ones containing thorium, neptunium, plutonium, and other actinide elements) are sorely needed. My quest for the elusive uranium-carbon double bond took me in several different directions, and one of them led me to develop new safe, inexpensive, and environmentally friendly uranium starting materials, uranium iodides, in two particularly useful oxidation states [*see "Uranium Made Easy" in the August 2011 issue of* 1663].

THE FACT THAT THIS BOND IS SO INCREDIBLY, UNEXPECTEDLY HARD TO MAKE IMPLIES THAT SOMETHING DEEPER IS GOING ON HERE.

Unlike most elements, uranium has electrons in the 5f orbitals, one of which is shown here. The orbitals' geometry—showing where its electrons "live"—is extremely complicated and corresponds to a great deal of chemical flexibility and complex interactions with other f- and d-orbital electrons. (The two-tone coloring, while technically indicating the positive or negative sign of an electron's wave function, is displayed here for visual clarity.)

There's also important experimentation to be done on existing uranium compounds. Uranium nitride, for instance, has been proposed as a valuable nuclear fuel, and it has been produced in a practical, scalable way. My carbon quest had me working with nitrogen though, and I learned that uranium nitride is considerably more reactive with hydrogen than anticipated. Hydrogen is downright ubiquitous (in water, in plastics, in organics, etc.), which means that uranium nitride will only be a useful nuclear fuel if people can establish adequate isolation protocols that don't interfere with its use as a fuel.

Such practical applications and discoveries are a joy to find. But so are the impractical ones. Pure chemistry is a lot more captivating than early-college-me could possibly have known.

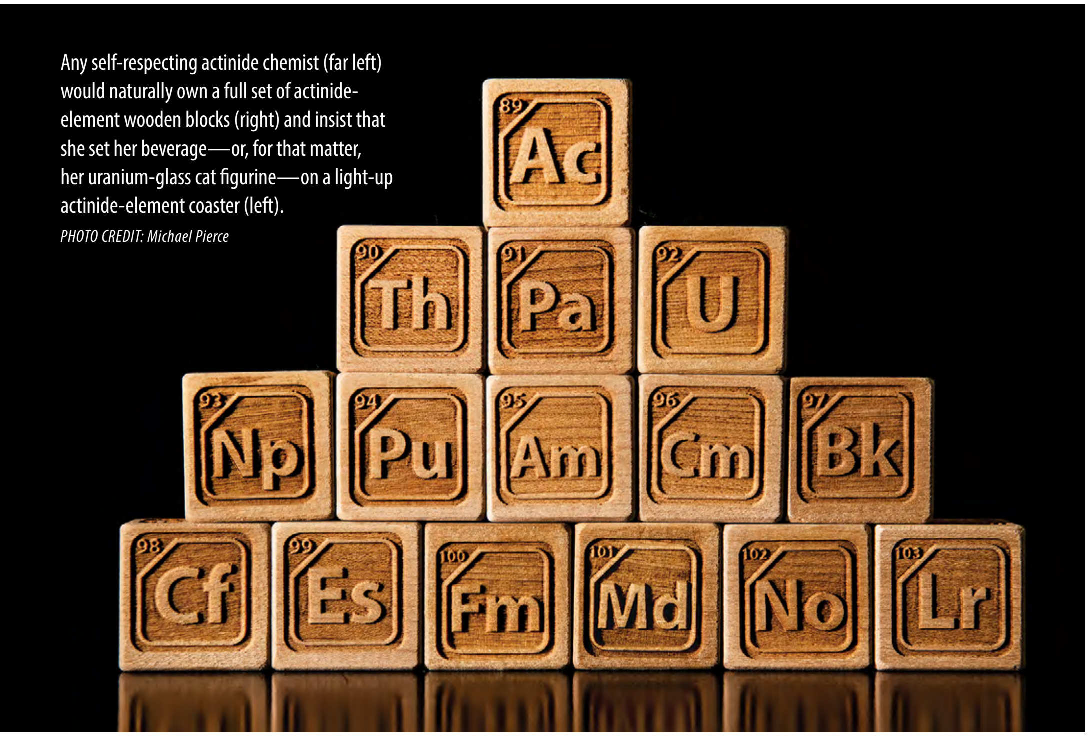
At the bottom of the periodic table

We do a really impressive job teaching chemistry in high school and college. We have the story down cold. As you work your way down the periodic table of elements, you're increasing the number of electrons on the atom. The electrons populate specific regions, called orbitals, according to a well-defined set of rules. Orbitals roughly indicate the zones that the electrons live in, and different ones have different shapes that get progressively more complicated. The s-orbitals are spherical; p's are vaguely shaped like a figure eight; d's are a mix of lobes and rings; and f's are, well, a more complicated mix of lobes and rings. Orbitals also have energy levels associated with them, and you start populating them with the lowest energies: electrons go in the 1s first: the lowest-energy s-orbital. Then the 2s. Then 2p. Then 3s, 3p, 4s, 3d, 4p, and upward, in a prescribed sequence. That's the recipe. That's the basis for the chemical behavior of elements as we teach it. Electrons in *this* orbital are more likely to bond in *that* way.

What we don't always teach is that these orbitals and energy levels were derived for hydrogen—which has just one electron. That electron can be excited into any of these higher-energy orbitals (although it is normally in the 1s ground state). An atom with many electrons is tremendously complicated because the electrons don't just interact with the atomic nucleus, like hydrogen's lone electron does, but also with all the other electrons. We develop approximations to minimize all that complexity—approximations like "elements in the same column of the periodic table tend to act the same" or "one electron interacts with the others not individually but as though they occupy a single coherent smear that does nothing but obscure the nucleus."

WE KNOW COMPARATIVELY LITTLE ABOUT F-ORBITALS. IT'S BOTH EXCITING AND HUMBLING TO STUDY THEM.

None of this is perfectly true, and when you get up to a 5f element like uranium, with 92 electrons, all bets are off. Interactions within and between atoms with occupied 5f orbitals constitute a game-changer—both introducing



Any self-respecting actinide chemist (far left) would naturally own a full set of actinide-element wooden blocks (right) and insist that she set her beverage—or, for that matter, her uranium-glass cat figurine—on a light-up actinide-element coaster (left).

PHOTO CREDIT: Michael Pierce

new behaviors and interfering with old ones—whereas, for most elements (except the actinides), the 5f orbitals generally don't get involved at all. We know s-, p-, and d-orbitals very well. We know comparatively little about f-orbital electrons, and especially the 5f actinide elements, which live at the bottom of the periodic table. It's both exciting and humbling to study them, and that's why I've chosen to make Los Alamos my professional home.

My white whale

So, what about that uranium-carbon double bond? I've been chasing it for a long time. If it can be coaxed into existence—and having recently trapped it, I think it can—it'll be a major stepping stone to producing an advanced nuclear reactor fuel called uranium carbide. It will also provide important new information to help with nuclear waste and nuclear separations technologies. And I have no doubt that making the double bond will teach us something profound about the electronic structure of actinide atoms, their materials science, and their chemical properties. After all, uranium can make this double bond with carbon's periodic table neighbors—nitrogen, oxygen, sulfur, and phosphorous, for example—but with carbon, which bonds to just about everything else in the world, it resists with all of its might. Something significant is clearly going on here.

Though it might seem like a self-imposed lifetime of professional frustration for me to keep fighting against nature, trying to make it do what it clearly doesn't want to do, I see the situation differently. This quest will ultimately pay off. Indirectly, it has already repeatedly paid off with a number of spinoff technologies—for example, with newer and better ways to produce starting materials for experimentation.

Having an overarching quest to guide my exploration has kept me focused, forcing me to make progress on the main goal while, at the same time, inspiring a number of valuable discoveries on its periphery.

My most recent spinoff rabbit hole, for example, had me examining a set of fascinating chemical constructs called aromatic actinide metallacycles. We take an aromatic, or ring-shaped, organic molecule, such as thiophene (a pentagon-shaped molecule with a sulfur atom at one vertex and carbon atoms at the other four vertices), and try to shove a uranium atom in there in place of the sulfur atom, where it has no business being—not by any natural process we know of, anyway. The result? Its 5f electrons engage in new ways and produce unusual chemical and electronic properties. We see how they'll participate in bonding and how they won't. We see them forming chemical complexes that transition metals (like iron or gold, with accessible d-orbital electrons) and even lanthanides (like neodymium or europium, with accessible 4f electrons) just can't, thereby teaching us about some of the more fundamental aspects of chemical bonding. And as a result, we see things no one has seen before.

We're so close now to isolating the U=C double bond. And once we do, we'll be able to study its chemical and physical properties using a combination of experiment and theory. We will also be able to do the major traditional analyses on it, such as electrochemistry, spectroscopy, and crystallography. We will learn the secrets of the U=C bond and use them to do old things better and do new things altogether.

How could anyone *not* be drawn to chemistry? LDRD

— Jaqueline L. Kiplinger

More **actinide chemistry** at Los Alamos

http://www.lanl.gov/discover/publications/1663/archive.php

- **Aging of plutonium**
  "In Their Own Words" | December 2016
- **Electron correlations**
  "A Community of Electrons" | October 2015
- **New kind of covalent bond**
  "Bond, Phi Bond" | January 2015
- **Uranium iodide starting materials**
  "Uranium Made Easy" | August 2011

from 1663

INTELL
INFRAS

PHOTO CREDIT: Michael Pierce

IN 1978, A NUCLEAR-MATERIALS FACILITY WORKER IN SIBERIA made a mistake that cost him both of his arms. It was the result of a series of actions—a combination of intentional and unintentional deviations from procedure—and he was lucky not to have been killed. If only there had been a way for him to know beforehand that despite thinking he was about to do the correct thing, or at worst a benign thing, he was actually about to do the exact wrong thing.

The safety of workers in nuclear facilities is paramount, so protocols and regulations are prepared with tremendous forethought and detail. This painstaking planning is good for safety, but it can also bring down efficiency. Now, scientists at Los Alamos are using augmented reality and other technology to create a smart nuclear infrastructure that can streamline safety procedures while advancing the efficiency of materials handling in special nuclear facilities.

IGENT TRUCTURE

The next generation of nuclear workers will benefit from next-generation safety technology.

Augmented reality (AR) is one of the latest technologies to come along and disrupt just about every industry from automotive manufacturing to fashion design, from video games to nuclear safety. A user wears a special headset that has built-in cameras, speakers, and a transparent projection screen. Unlike virtual reality (VR), which replaces the real world with a fully simulated artificial environment, AR inserts simulated elements into the user's actual physical environment. For example, a user might see, hear, and be able to read about the natural history of a life-sized 3D holographic rhinoceros, as it stands panting in the middle of her living room. Because AR technology dovetails digital content with the real world, it is a powerful tool for on-the-fly information storage and retrieval—with a swipe of the finger, a flick of the eye, or a spoken command, the user can see, hear, and interact with a whole new framework of information.

As Laboratory workers retire, younger workers naturally take their places. Many new workers are being trained to work with fissionable materials like uranium and plutonium—atoms with large atomic nuclei that can release energy by splitting into smaller nuclei. These materials are perhaps best known for their use in nuclear weapons, but they are also used in other technological applications, such as nuclear energy for electricity as well as heat and power sources for spacecraft.

The handling of fissionable materials—whether for the development of new technology or for meeting nuclear nonproliferation commitments, which necessitates chemical conversion or disposal of the fissionable materials—requires specific procedures to ensure containment. The danger is the radiation continually emitted by these materials, which in moderate doses can damage DNA and lead to certain types of cancer, and in higher doses (as might result from extreme improper handling) can kill human cells outright.

In order to protect fissionable-materials handlers, containment has to be multilayered and redundant. The material itself is typically contained inside a canister, which is contained inside a glovebox, which is contained inside a room, which is contained inside a facility. Each layer from the canister to the facility is specifically engineered for the safety of the workers and the security of the material.

Whether preparing samples for analysis, managing waste streams, or conducting chemical conversion, fissionable-materials handlers do most of their work inside gloveboxes. Gloveboxes are fully sealed steel chambers that have leaded glass windows and thick, protective gloves affixed to ports in the front panel. The worker interacts with the contents of the glovebox through the built-in gloves so that the protective barrier between worker and material always remains intact. Gloveboxes are connected in series to facilitate moving material between workstations, and special containers are also sometimes used.

In addition to maintaining complete containment, workers have to adhere to a number of other technical specifications that affect criticality safety. For example, there are strict limits on the quantity and type of fissionable material that can be present in any one location. This restriction is to avoid achieving a critical mass—the tipping point when a fission chain reaction goes from unsustainable to sustainable—which occurs when the quantity of material is too high. The limits are set conservatively, well shy of critical mass. While all procedural deviations are taken seriously, and violations by workers are rare, most are unintentional limit violations, not criticality violations, and thus have minimal impact on the safety margin.

To move a quantity of material from one room to another, the worker has to strategize a multistep route via connected gloveboxes and overhead trolleys. It's an elaborate process that can take hours. The worker has to first plan a route by computer, then physically walk the route, visiting each location to check current material inventory, confirm limits, and determine feasibility, then return to the computer and submit the proposed move for approval. This process relies heavily on printed pages, so if the information on one page needs to change midway through the move, the worker has to leave the glovebox, monitor her hands to check for contamination, walk to a computer terminal, sign in, make the change, reprint the page, sign out, walk back to the glovebox, and resume work.

"Operators have told me that the hours spent planning material moves are a big chunk of their overall effort and that time would be better spent on actual material processing," says Los Alamos engineer Troy Harden. "We've streamlined the process as much as possible with the technology we currently have, but with new technology like AR we can improve efficiency more without adversely impacting worker safety or material security."

As is often the case with infrastructure, the need to modernize was apparent before the technology to do so was ready. But now the technology is here.

With a swipe of a finger or a spoken command, a user can interact with a whole new framework of information.

Summon wizard

In an otherwise nondescript Los Alamos office suite, people carefully roam the halls, abruptly stopping to reach out and tap at… nothing. Muttering voices can be heard summoning invisible wizards, while other voices dismiss wizards. These are the scientists and engineers who are developing AR for nuclear criticality safety, and the fantastical voice commands "summon wizard" and "dismiss wizard" are how they initiate and terminate AR sessions.

For the past few years, Los Alamos engineer David Mascareñas and his team have been developing an AR system that will help track fissionable materials, update inventory databases in real-time, and provide on-the-fly information to fissionable-materials handlers. The commercial AR hardware they rely on is a headset called a HoloLens that was released by Microsoft in 2016. The HoloLens has been described as the first fully untethered holographic computer and is equipped with depth cameras, red-blue-green cameras, microphones, Bluetooth, WiFi, spatial sound, spatial mapping, and inertial measurement capabilities. Despite its unsurprising form—a ring of black plastic hardware worn about the head—the HoloLens is just the thing for Mascareñas's team to make its AR work a reality.

Long interested in human-machine interfaces, Mascareñas began developing VR tools for nuclear criticality safety several years ago. But for industrial operations, he knew that AR was going to be the better approach once it came of age. Unlike VR, AR allows the user to maintain a view of the real world, which is important for safety.

"People have long imagined this sort of thing being possible," he says, "it's exciting that it's actually happening now."

The HoloLens has a built-in spatial-mapping feature, so as the user looks around, the computer creates a 3D map of the space and its elements—walls, furniture, other people—that continually adjusts itself as the user or the elements move around the space. The headset then projects, either floating in midair or overlaid on a nearby surface like a wall, holographic images typical of computer displays: word-processing documents, websites, maps, photo libraries, videos, etc. With small movements of her head, the user can position a holographic cursor onto whichever element she wants to click, then make a pinching gesture within the camera's field of view, and the HoloLens opens the chosen file, folder, or window.

A glovebox worker can read updated instructions, log her actions, watch a video of a container being sealed, confirm the history of a sample, or instantaneously retrieve just about any information she might need without touching anything or leaving her workstation. With a detailed 3D map of the facility and real-time material tracking, she could even plan her material move right from her glovebox.

In addition to the standard sensors of the HoloLens, Mascareñas and his team have retrofitted several other sensors of specific import to nuclear criticality safety. They added a thermal imager, so a user can see that an object is hot. They also interfaced a higher-resolution camera, which, when combined with data from other sensors, can reveal internal structural differences that aren't apparent by superficial inspection. Most recently, the team has demonstrated AR manual remote control: when the user moves her arm, a holographic arm copies the movement, and elsewhere, perhaps in a place unfit for a human arm, a robotic arm makes the same movement.

Plutonium and other fissionable materials are handled inside glovebox facilities like this training lab (no fissionable material allowed), where operators learn how to work in gloveboxes. Material can be moved to adjacent gloveboxes through ports or to gloveboxes in other rooms via a contained overhead trolley system. A material move is complicated and takes a lot of time, but smart nuclear infrastructure can streamline the process.
PHOTO CREDIT: Michael Pierce

> A glovebox worker can retrieve the information she needs without removing her hands from the glovebox.

The potential of AR for nuclear criticality safety and other national security applications is hard to overstate. The untethering of a worker from a traditional computer workstation will allow unprecedented efficiency, especially when combined with other technological updates.

Failsafe framework

While AR is a flashy new technology, it's not the only technology being tapped for the smart nuclear infrastructure. As the broad term "infrastructure" implies, the goal is a system overhaul, a full upgrade that will automate the more cumbersome operations of a special nuclear facility.

A less flashy, more foundational element of the smart nuclear infrastructure is the data-management system that operates behind the scenes, which is being reconfigured to work with AR. Tracking the immediate location of fissionable materials as well as their ownership—who or what is in control at the moment—is the main data-management task. After a material move, the same lengthy process it took to plan is used to manually update the material inventory database. This means that during the move and for some period of time after the move, the information in the database is wrong. Certainly there are mechanisms in place to handle this lag, but they are workarounds, and it would be better if it were just faster.

Right now the whole process is paper driven. There are "use every time" instructions that a worker has to carry with her at all times during an operation, and there are reference documents that must be readily available. Both categories would be accessible via AR.

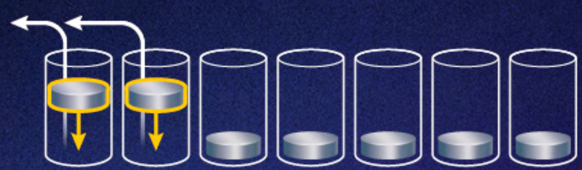
"This is a tool for improving our conduct of operations across the board," says Julio Trujillo of the Laboratory's Plutonium Strategy Infrastructure Division. "Material moves are one example: a worker conducting a move, if asked by a manager, has to be able to access the latest revision of her reference document quickly. The improved managing of documents will help workers perform their work more efficiently."

If the database is the backbone, and the AR capabilities are the sensory organs, then the connective tissue of the smart nuclear infrastructure, the thing that ties it all together, is the smart-cart system for automatic updating. This is a material-transportation system whereby push carts essentially "know" what they are carrying, where it is coming from, where it is going, and who is driving. The carts, as well as the users, canisters, rooms, hallways, gloveboxes, and safe boxes, all have unique near-field-communication (NFC) identification tags. These get scanned by NFC readers as they go by or get used, enabling the database to keep track of the activity in the facility in real time. Some elements, like canisters, gloveboxes, and safe boxes also have quick response (QR) codes that the camera in an AR headset can read; then the headset displays up-to-date need-to-know information in holographic form. A QR code on a canister could, for example, confirm the canister's contents to a handler before the handler opens it. Although NFC and QR technologies aren't new, putting them together, along with AR and the reconfigured database for a smart nuclear infrastructure, is a novel approach to nuclear criticality safety.

AN ACCIDENT IN SIBERIA

A criticality accident at the Siberian Chemical Combine in 1978 resulted in a worker having both arms amputated at the elbows. The accident was the result of multiple deviations from procedure and poor communication between workers.

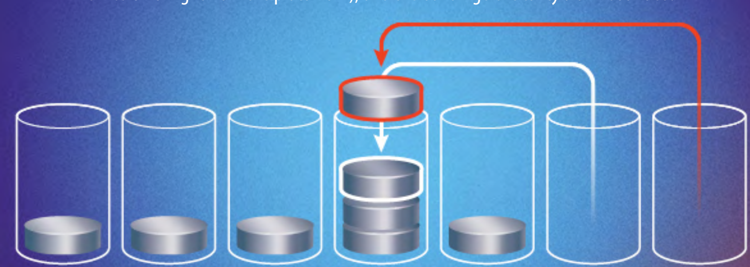
The worker was conducting measurements, an operation that included moving plutonium ingots into and out of heavily shielded containment canisters inside of a glovebox. The administrative limit for this glovebox was set at one ingot per canister, and it was difficult to see inside the canisters. Operators were supposed to complete their assigned operations themselves: Operator A was to remove six ingots from his canisters, one at a time and in a prescribed order, and then put new ingots into each of the empty canisters.



Instead, he removed and replaced two ingots, then asked Operator B to step in for a few minutes—a violation of procedure—and gave him only verbal instructions.

Instead of removing and replacing two more ingots as instructed, Operator B moved one ingot into a canister that already contained one ingot—a violation of the administrative limit—and then placed a new ingot into the empty canister.

When Operator A returned, he assumed Operator B had followed instructions and proceeded to move two ingots from their canisters into the canister that already held two ingots. When the fourth ingot was added, the contents of the canister went supercritical, and the top ingot was ejected. Operator A felt immediate heat on his arms and saw a flash of blue light (caused by a perturbation of the water and photoreceptors inside his eyeballs, not by an actual emission of light from the plutonium), and the building's criticality alarm sounded.



Intelligent infrastructure could prevent an accident like this at several points in the process. First, operators would not be able to leave their stations or step in for coworkers without the system recording the personnel change and alerting a supervisor. Second, written instructions and videos of each worker's actions would be accessible via AR. Third, the canister would alert both operators to its contents, so they could not unintentionally violate administrative limits, much less achieve criticality.

The present location and ownership tracking system, while accurate on a daily or hourly time scale, still suffers from time lags due to slow material moves and manual information updates. The smart nuclear infrastructure, on the other hand, has everything codified by NFC tags, enabling changes in location and ownership to be logged as they occur. While updates will be instantaneous and automatic, material moves will still need to be meticulously planned beforehand. But with up-to-the-moment accurate information and integrated 3D facility mapping, even that task will be expedited, thereby achieving the goal of fewer hours spent planning and more spent on mission-based operations.

Vision for the future

The ideal scenario for Harden, Mascareñas, Trujillo, and the rest of the smart nuclear infrastructure team is full implementation within the next ten years. The longish rollout is due to a fly in the ointment: Cyber security in special nuclear facilities categorically outlaws wireless networking, and Bluetooth-enabled devices are not allowed at the Laboratory at all. HoloLenses use both of these technologies, so the proof-of-principle work has been done in a mock facility. It's not going to be easy to reconcile this problem—it may require adapting to new AR hardware, or it may entail developing new security technology—so the team is setting a realistic time frame.

Even without the HoloLens part in place, the real-time database and smart cart system will enable pseudo-real-time updates and ensure that information is correct at all times. The material tracking and ownership updates will occur in real time, but retrieval of that information will still suffer a time lag because it will rely on desktop computer stations. But that's enough of an improvement for the project to keep moving forward while the cyber security issues get worked out.

There are intermediate possibilities too. One option is to put a Bluetooth-disabled digital tablet in every room for workers to plan and visualize material moves. This isn't as seamless as AR, but nor is it as cumbersome as a desktop computer terminal.

> The next generation of facilities workers are already fluent in these kinds of technologies.

Despite the wireless-communication speed bump, the AR portion is moving forward. In the next year or two, a mock smart nuclear infrastructure tool will be implemented for training new personnel. The next generation of nuclear-facilities workers will consist largely of people who are already fluent in these kinds of technologies, so it makes sense to train them using a familiar platform.

The technology is also highly transferable, and there are several nonnuclear-facility offshoots in the works. Conventional infrastructure—roads, bridges, and buildings—is generally built for a 50-year life span. When a crack in concrete appears, AR can help with safe inspection and documentation. A user can visually map and measure the crack from a safe proximity and store that information for future users. Additionally,

With a smart nuclear infrastructure, glovebox workers will be able to access and update information in real time without relying on printed pages or manual data entry. In this training glovebox (no fissionable material allowed), a QR code communicates information about the contents of a canister, which the headset displays in hologram form. *PHOTO CREDIT: Michael Pierce*

Mascareñas recently collaborated with the city of Los Alamos and assistant professor Fernando Moreu from the University of New Mexico to use AR to measure non-rectangular areas of concrete in various public spaces. It proved to be less resource intensive than a survey crew and had comparable accuracy.

New technologies like AR present an opportunity to improve how infrastructure of any kind is built and maintained. People whose job it is to handle dangerous material or go into dangerous places will see their work experiences transformed. No longer will they be fettered by desktop computers or bound by paper printouts. The possibilities for intelligent infrastructure, especially when it comes to national security, do indeed seem to be endless.

—Eleanor Hutterer

INTERMISSION

Sweet, Sweet Science

"MELTS IN YOUR MOUTH, NOT IN YOUR HAND" is more than just a catchy tagline. It speaks to the very feature behind the immediate and enduring success of one of America's favorite chocolate candies, M&M'S®. The candy shell keeps the chocolate from making a mess when it melts, which made it a favorite among soldiers of World War II, when M&M's were new and sold exclusively to the U.S. military.

Modern M&M's varieties further rely on the candy shell because they include peanuts, almonds, and other core ingredients that go stale or rancid if exposed to air for too long. But two things remain unchanged since M&M's early days: they are still a staple in modern military rations, and they are still made according to the original methodology, which is time- and energy-intensive.

Creating the candy shell involves coating chocolate centers with a mist of liquid sucrose (table sugar), then tumble-drying them. It takes multiple hours and large quantities of warm air to create the smooth coating. In pursuit of a better way, Mars, Incorporated, the maker of M&M's, has funded a collaboration with Los Alamos scientists to study sucrose crystallization in order to identify new opportunities for energy savings and improved production efficiency.

Not traditionally in the candy-quality business, Los Alamos is a world leader in supercomputer simulations of various chemical processes, including the formation of crystals from solution. The way a compound crystallizes affects the performance of the final material, so Laboratory scientists model these processes to study composite compounds used to make stronger materials, or crystalline materials used to make quantum dots and solar cells. In the case of a candy shell, performance would be gauged by strength, texture, and uniformity, all of which help to protect the perishable center and maintain M&M's unique quality.

The first phase of the project is to use computer models to optimize the sucrose-crystallization process in terms of time and energy consumption. Based on what they learn from that, the researchers may explore additional modifications down the road.

Antonio Redondo, of the Richard P. Feynman Center for Innovation at Los Alamos, explains, "We have been doing the computer modeling for about one year, but now we are beginning some experimentation. Crystallization is important in many materials, so this work represents dual-use technology—in studying sucrose crystallization, we'll learn things about quality, stability, and performance that we can apply to other materials more central to the Laboratory's mission."

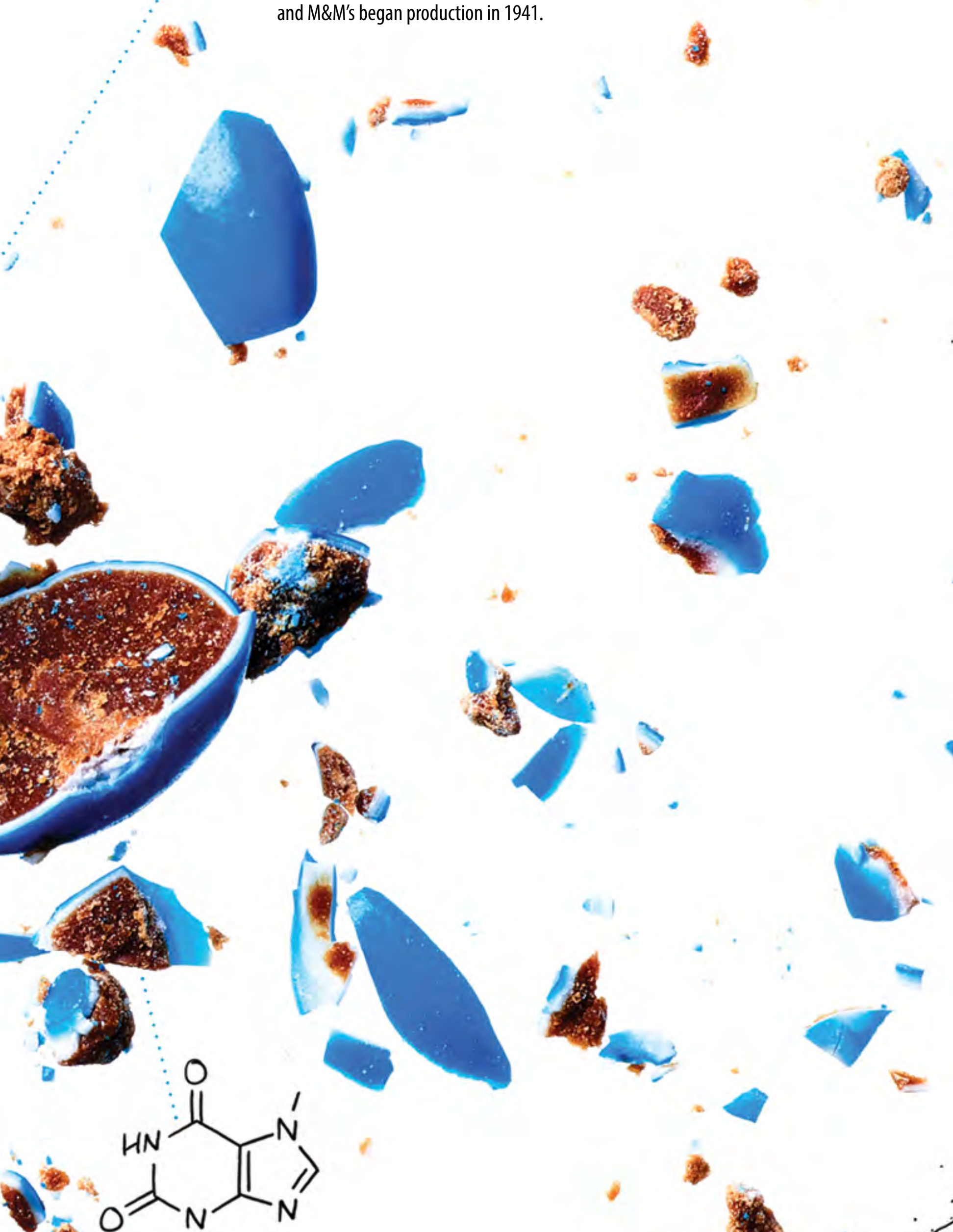
By applying scientific know-how through unconventional partnerships, the making of traditional treats like M&M's (and Skittles®, another Mars, Incorporated product) can be modernized while ensuring that they continue to melt in mouths and not in hands.

—Eleanor Hutterer

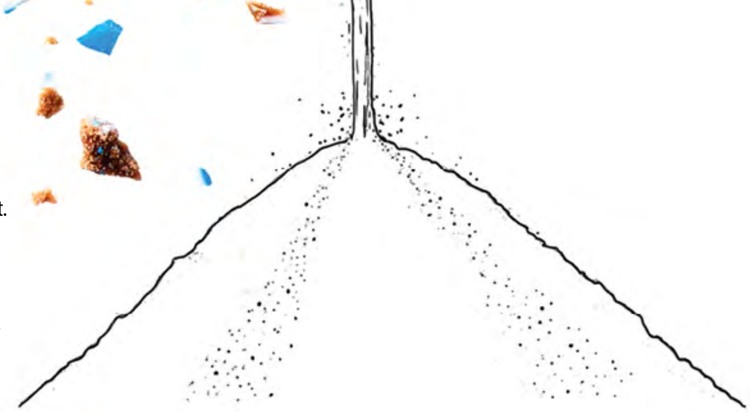
 PHOTO CREDIT: Michael Pierce

m m

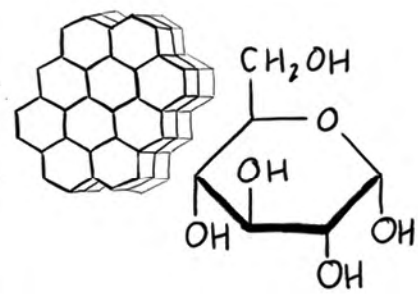
The two m's come from the initials of Forrest Mars, of Mars, Incorporated, and Bruce Murrie, of The Hershey Company. Mars was familiar with a British chocolate candy button that was popular among soldiers because it was "melt proof" by virtue of being encased in a hard sugar shell. Mars wanted to bring something similar to America, but because of wartime rationing, only Hershey was allowed to produce chocolate. By partnering with Murrie and using Hershey chocolate, Mars was able to escape ration regulations, and M&M's began production in 1941.



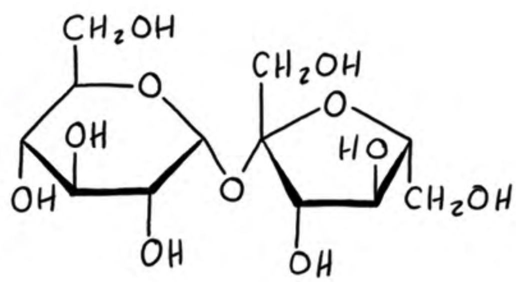
Theobromine is a bitter alkaloid that is chemically related to caffeine and has a similar, though milder, stimulating effect. It is the main alkaloid found in the cacao plant (from whence chocolate) and is also present in the tea plant (black tea) and the kola nut (cola soft drinks). It is the theobromine that makes chocolate—especially dark chocolate—toxic to dogs, as well as cats, bears, rabbits, and possibly other animals.



Stacking sucrose is a lot more complicated than merely building a pyramid out of sugar cubes. The white grains we scoop from bowls or pour from packets are the crystalline form of sucrose, or table sugar. Once mixed into a liquid, the crystal dissolves as individual sugar molecules are pulled away by water molecules. During crystallization, the opposite occurs: molecules of sucrose align into a regular lattice as molecules of water are excluded, typically by evaporation.



For a monosaccharide, like glucose, which has a six-carbon ring structure, the alignment of many molecules to form a crystalline lattice is relatively straightforward to conceptualize.



But for a disaccharide like sucrose, which is a glucose molecule joined to a fructose molecule via a shared oxygen atom, the lattice-like arrangement is much more complicated.

OUT OF TH

 PHOTO CREDIT: Guillaume Gaudet

LIGHTS OUT

FRIDGE WARMING

WIFI OFF

CELL PHONE DYING

ELEVATOR STUCK

SUBWAY STOPPED

GASOLINE PUMPS OFFLINE

E DARK

Los Alamos scientists strategize about how best to keep the lights on with a modern and secure national power grid.

WORK SHIFTS CANCELED

FINANCIAL MARKETS DOWN

HOSPITAL GENERATORS AT CAPACITY

COMMUNICATIONS LIMITED

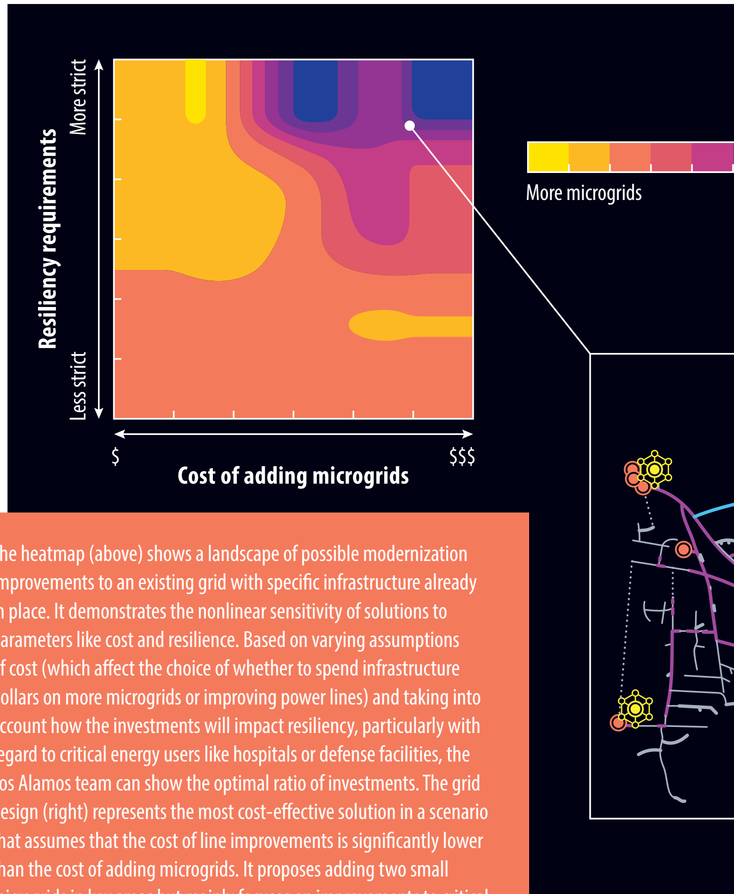
AIR TRAFFIC CONTROL DISRUPTED

SECURITY AT RISK

IN THE PEACE OF ONE'S OWN HOME, A POWER OUTAGE can be a minor inconvenience and perhaps even a welcome opportunity to sit by candlelight and take a break from the usual hustle and bustle. However, when electricity is missing for hours or even days, outages begin to threaten lives and cost billions of dollars. When the power grid goes down, access to medical care, clean water, and fresh food is threatened, and personal safety is ultimately at risk. In addition, disruption to the economy is daunting as closed businesses and interrupted financial markets jeopardize people's livelihoods.

Some natural disasters, such as hurricanes and solar storms, come with prior warning so that utility companies can prepare. But even with advance notice, the power can still be out for long periods of time while companies scramble to fix downed lines. When Hurricane Sandy soaked New York City on October 29, 2012, about eight million customers across 21 states lost power, and some did not get it restored until Thanksgiving. In 2017, Hurricane Maria pummeled the island of Puerto Rico, and it took nearly a year to restore power. Although the deaths associated with this disaster are attributed to a variety of causes, a portion of them were due to the need for medical respirators, which require electricity.

One reason that restoring power can take an extended amount of time is that the nation's infrastructure is old. Although access to electricity is the lifeblood of modern society, the power grid itself is not modern. As Americans' demand for, and dependence on, electricity steadily increases, many experts have been calling for an upgrade to make the grid more reliable and resilient. But reducing the time it takes to turn the power back on after a blackout is not the only reason to modernize the grid: incorporating renewable sources of electricity would make energy consumption more sustainable, and adding usage sensors and feedback mechanisms could make its distribution more efficient. Last, but certainly not least, not all potential power outages are due to natural disasters. Society's critical dependence on electricity makes the grid a target, and that is an issue of national security. Making sure the power grid is secure is an essential part of any upgrade.



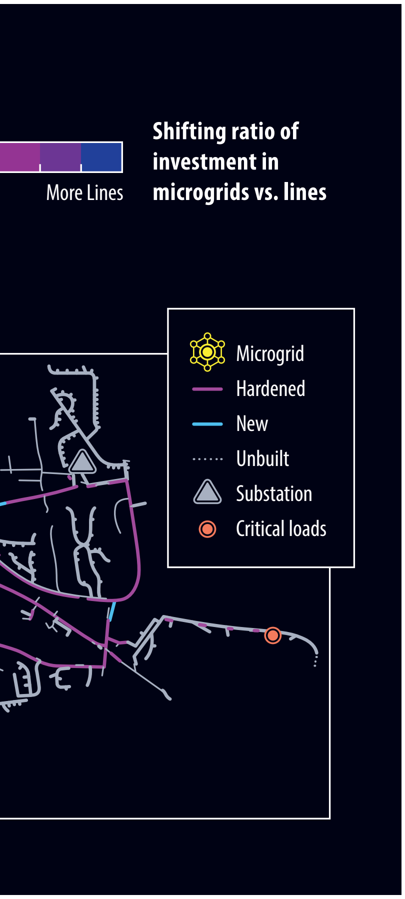
The heatmap (above) shows a landscape of possible modernization improvements to an existing grid with specific infrastructure already in place. It demonstrates the nonlinear sensitivity of solutions to parameters like cost and resilience. Based on varying assumptions of cost (which affect the choice of whether to spend infrastructure dollars on more microgrids or improving power lines) and taking into account how the investments will impact resiliency, particularly with regard to critical energy users like hospitals or defense facilities, the Los Alamos team can show the optimal ratio of investments. The grid design (right) represents the most cost-effective solution in a scenario that assumes that the cost of line improvements is significantly lower than the cost of adding microgrids. It proposes adding two small microgrids in key areas but mainly focuses on improvements to critical lines in the network. In an alternative scenario where microgrids are inexpensive, more microgrids could be installed instead to achieve the same high level of resiliency (upper left region of heatmap).

SOCIETY'S CRITICAL DEPENDENCE ON ELECTRICITY MAKES IT A TARGET, AND THAT IS AN ISSUE OF NATIONAL SECURITY

Los Alamos National Laboratory is tackling all of these challenges. Lab scientists are using advanced mathematics, computer modeling, machine learning, and cyberphysical network science to determine the best approaches to both protect our national power grid today and prepare it for tomorrow.

From Pearl Street to the Pacific

The very first power distribution in the United States began in 1882 on Pearl Street in lower Manhattan when Thomas Edison built a system that used a coal-fired electrical generator to illuminate buildings for about 85 customers. Today, the national power grid is comprised of nearly 200,000 miles of high-tension transmission lines stretching from the Atlantic to the Pacific, operated by hundreds of utility companies. According to the U.S. Energy Information Administration, the grid distributes electricity that has been generated by over 8600 power plants: 63 percent of them use fossil fuels to create electricity, 20 percent are nuclear, and 17 percent use renewable sources, such as wind, solar, and hydropower. While most communities considered the economy of scale and began electrification by building one large power plant, often fed by fossil fuels, and a distribution network, many communities today are powered by combining electricity from many large-scale generators, deriving energy from an aggregate of sources.



Unlike other natural resources, such as water, electricity cannot easily be stored in large quantities, so it must be used quickly after it is generated. What doesn't get used immediately is wasted, making it vital that utility companies constantly monitor and accurately predict the demand in their areas in order to meet their needs. This is more challenging than it used to be because communities have grown in population and individuals have increased their desire for electricity; American households today have dozens of electronic devices hungry for power. To meet this demand, the heart of each regional utility network contains a control room where highly trained operators work day and night to maintain a form of "stasis" by matching demand and availability—and keeping on the lookout for dramatic changes in either one.

In what has become a rather stressful job in some regions, operators make hour-to-hour decisions about where to purchase electricity and how best to distribute it. Their work is constrained by a lengthy list of factors that include the market economy, political and environmental regulations, hardware limitations, power-generation logistics, and, on occasion, unusual circumstances that could lead to catastrophic outages. For instance, nuclear power plants cannot ramp production up (or down) quickly enough to meet a sudden increase in need; coal plant production occasionally has to be slowed or stopped due to limits on allowable pollution; and wind and solar are only available when the weather permits. Furthermore, extreme weather, such as heat waves or cold snaps, can be an unexpected strain on the system. Computer algorithms help operators make decisions in real time, but overall, day-to-day normal operation is a constantly moving target.

In addition to addressing these constraints, an operator will also have to consider the laws of physics governing the power itself and the fact that one can't directly control the flow of electricity. Unconstrained, electricity flows according to the path of least resistance and naturally seeks equilibrium. However, not all power lines are created equal; they have varied capacities based on where they are located, when they were constructed, and what the resistivity is of the materials used. Plus, some parts of the grid have not kept up with population

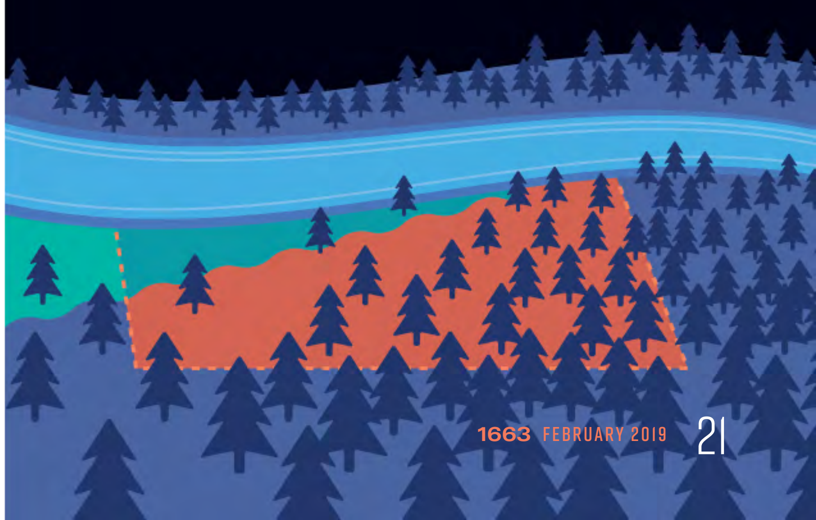
BEST-CASE SCENARIO

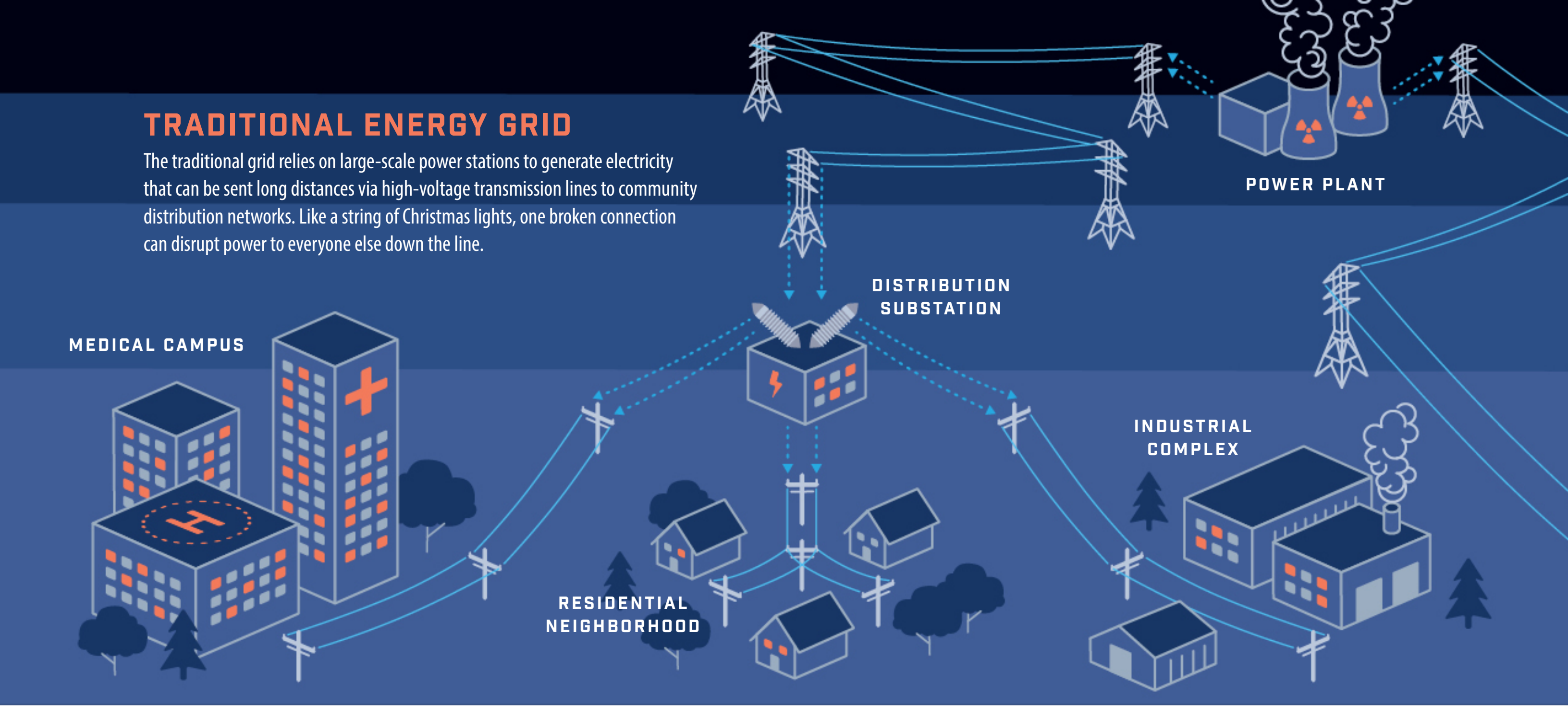
As the complexity of the world increases, seemingly simple tasks, such as sending electricity from a power plant to a neighborhood, become elaborate problems to which there is not a singular right or wrong approach. Complex problem solving is often an exercise in finding the best solution for a specific situation after weighing benefits and risks of many options—and the more options and potentially conflicting objectives there are, the more difficult it is to find the best approach.

Mathematical optimization is a collection of principles and methods used to find solutions to complex problems. Optimization problems are often defined by seeking a maximum or minimum, such as the lowest cost or the most reliability. For instance, a simple optimization problem could be: "What is the fastest route to drive to work when the main thoroughfare is under construction?" Or, as in the classic optimization problem illustrated below, "What is the maximum area that can be enclosed with a fixed length of fencing, using an existing barrier, such as a river, as one of the four sides?"

But what if the problem added the requirement that the fewest number of trees should be cut down without leaving any inside the fence? Or that the fence should enclose a minimal area of an existing flood plain? When the variables and constraints increase, so does the complexity of the calculation.

Utility companies may be looking for the least expensive way to deliver electricity to their customers on a given day, but the constraints they face include a litany of factors from generator limitations and environmental regulations to the physical constraints of the power lines and the laws of physics. Scientists at Los Alamos are using high-performance computers to run optimization algorithms that can include as many as 2^{100} possible combinations of variables to answer just one question. This capability allows them to tackle all sorts of grid-optimization challenges, such as incorporating the most renewable energy to a specific area, restoring energy to the most customers after an outage, or adding security features in the most effective places for the least cost.





growth. If one line becomes overloaded because the demand is too high, the operator will need to address this by adjusting production levels at the power plants, of course without any consumers losing electricity. The capacity of each power line becomes especially important in the event of an outage; once a line is down, the power instantaneously redistributes to other lines, but if they become overloaded, a single outage can have a cascading impact.

Basically, maintaining the power grid is a multifaceted problem on a regular day. However, the complexity increases many-fold when companies consider making changes to the system, such as increasing the use of renewables, upgrading hardware or security features, or preparing for a coming storm. Furthermore, the grid can't turn off for an upgrade. Harsha Nagarajan, a Los Alamos control theorist who works on grid resiliency, sums it up vividly when he says, "Changing a system in the power grid is like upgrading an airplane while it is flying."

Ready for anything

For more than a decade, Los Alamos scientists have applied their expertise in advanced mathematics, physics, engineering, and machine learning to the challenges of operating and upgrading the power grid. The projects are numerous; some have been internally funded, while many are funded by the DOE Grid Modernization Laboratory Consortium (GMLC), which began in 2015. Furthermore, over the last few years, Los Alamos scientists have developed a Grid Science Winter School and Conference to educate and promote interdisciplinary solutions to problems in the energy sector.

Although they are varied, the Los Alamos grid science projects essentially address two central themes. First, the scientists seek to obtain a better understanding of how the grid works—where it is strong and where it is vulnerable. Second, they are working to optimize the grid for different purposes—on one hand improving resiliency, efficiency, and the use of renewables, while on the other hand striving for maximum cyber and physical security.

One such project is led by Russell Bent, a computer scientist and mathematician in the Lab's Theoretical Division who is working on extreme-event modeling to help with understanding risk and performing contingency analysis. His team begins with data about a specific region's power grid, such as the status of switches and current values of loads and impedances. The team then seeks to quantify the effects in a specific area with regard to which lines are likely to go down (or already have), why, and how they impact the surrounding area's power supply. These data help to identify which specific lines or substations are the most important to protect.

Identifying high-stakes components in the network is useful for many reasons. For one, it may help focus attention in the right area after a hurricane or other emergency wipes out the power, so that priority can be given to restoring electricity to the largest number of customers. Another reason is to prioritize how periodic upgrades are rolled out—such as reinforcing or hardening utility poles, creating water-blocking barriers around substations, or increasing security measures. It might sound straightforward, but one of the reasons that this mapping is difficult is that the power grid is not uniform. Bent explains that although his team is able to get quality information about load capacities and the physical condition of high-tension, long-distance power lines, when it comes to residential power lines, there is much variation in how and when the grid was built, so information is lacking about everything from load capacities and sensors to the sturdiness of the utility poles.

Due to the complexity involved in evaluating this system, Bent and his colleagues use optimization to answer many questions about the data they are analyzing. Optimization algorithms are designed to help make decisions: they seek patterns in the data that achieve a maximum or minimum—the fastest route, the least expensive upgrade, or the most power output. For instance, the algorithms may draw on a combination of many possible upgrade choices to determine a system design that is best able to withstand future extreme events.

Carleton Coffrin, a computer scientist who works with Bent, describes how difficult this is. He explains that in order to make a decision about routing power through the energy grid, humans must consult pure data and statistics as well as models that show relationships between them. If both of these levels of data are available, a human can examine various possible scenarios and usually make a decision. However, sometimes there are an astronomical number of scenarios to consider; this is where computer optimization can help.

"Optimization uses algorithms to do this complex analysis in order to advise a person on the ideal decision," says Coffrin. "It lets us compute the best-case scenario with a mathematical guarantee."

Using optimization, the Los Alamos team has developed a software program called the Severe Contingency Solver that has been used by government agencies. This tool includes a graphical user interface to enable use by local analysts who might be preparing for an incoming storm. The Solver can't prevent the power from going out, but it can be used prior to the storm to quickly identify places that will be the most vulnerable based on current infrastructure and usage, and after the storm it can determine the fastest way to restore electricity to a key location such as a hospital or military base.

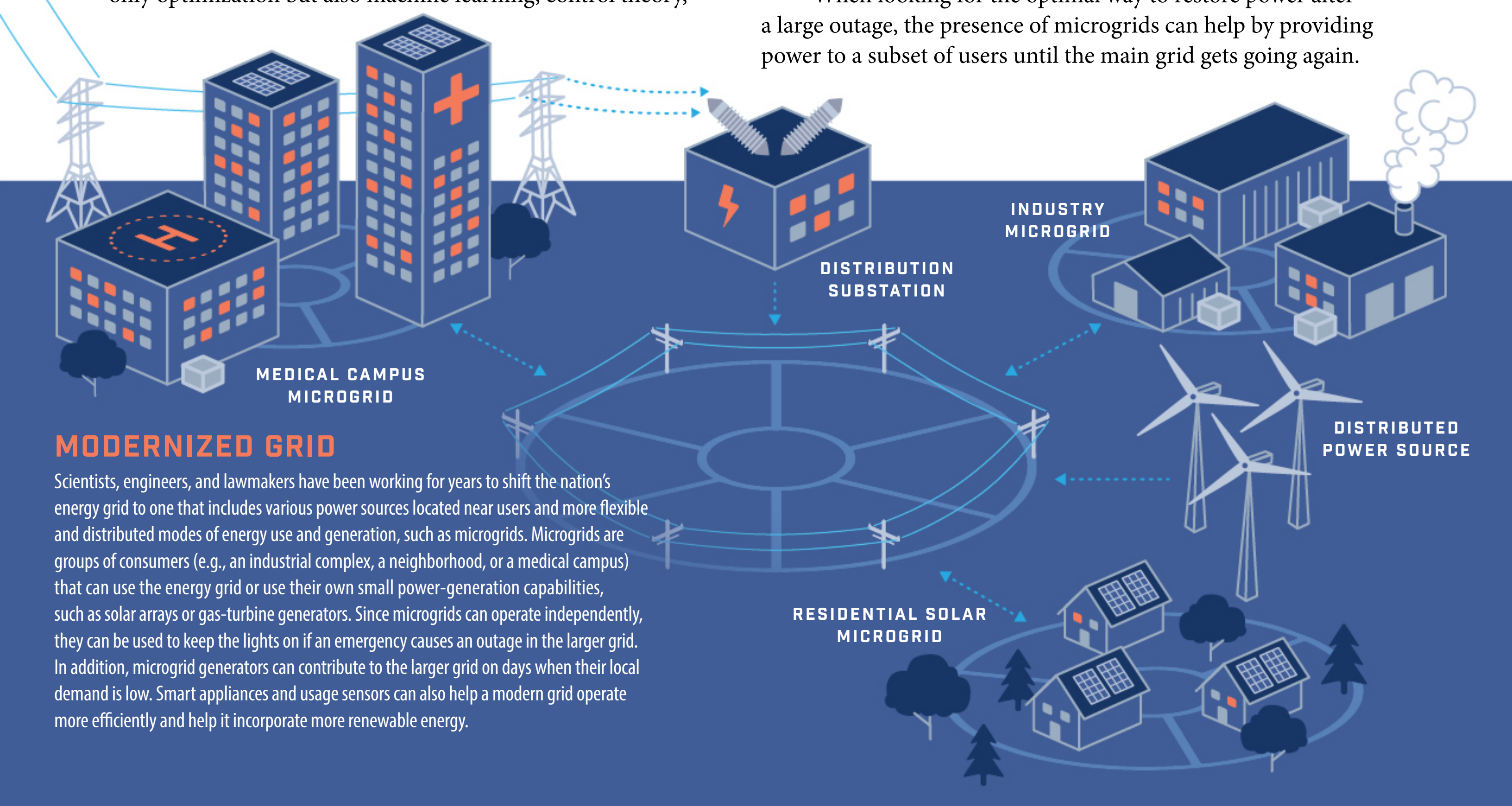
Bent and Coffrin work with many colleagues in the Analytics, Intelligence, and Technology Division and the Computer, Computation, and Statistical Sciences Division under Los Alamos's Advanced Network Science Initiative. Through their combined expertise—which includes not only optimization but also machine learning, control theory, statistical physics, and graphical modeling—the researchers have been able to give science-backed advice to the DOE on many types of perils that threaten the power grid, such as cyber-physical attacks, solar geomagnetic disturbances (see page 33), and nuclear electromagnetic pulses. The scientists have also advised the state of California on the reliability of its energy system that couples natural gas and electric power. Gas is being used more widely to fuel electric-power generation, but this infrastructure interdependency can also lead to more-complicated outages of not one but two major resources: a gas disruption brings about an electrical disruption as well.

CHANGING A SYSTEM IN THE POWER GRID IS LIKE UPGRADING AN AIRPLANE WHILE IT IS FLYING

Diversify, diversify

In the aftermath of Hurricane Sandy, there were a few places in the hardest hit communities that remained illuminated because they were not dependent on only one source for electricity. The investment company Goldman Sachs, for instance, had a generator for its Wall Street office building, and Princeton University had a small power station, enabling its entire campus to operate as a "microgrid." Microgrids are relatively small electricity networks (ranging in size from just one building to a few blocks' worth) that have their own power sources. They can operate in tandem with the large utility grid—even contributing power to it when possible—or they can disconnect and operate independently as "islands."

When looking for the optimal way to restore power after a large outage, the presence of microgrids can help by providing power to a subset of users until the main grid gets going again.



MODERNIZED GRID

Scientists, engineers, and lawmakers have been working for years to shift the nation's energy grid to one that includes various power sources located near users and more flexible and distributed modes of energy use and generation, such as microgrids. Microgrids are groups of consumers (e.g., an industrial complex, a neighborhood, or a medical campus) that can use the energy grid or use their own small power-generation capabilities, such as solar arrays or gas-turbine generators. Since microgrids can operate independently, they can be used to keep the lights on if an emergency causes an outage in the larger grid. In addition, microgrid generators can contribute to the larger grid on days when their local demand is low. Smart appliances and usage sensors can also help a modern grid operate more efficiently and help it incorporate more renewable energy.

This concept of integrating diverse generation sources not only increases resilience for a community but also encourages the incorporation of more renewable sources of energy, such as residential solar panels. For these reasons, the GMLC and others in the field envision a modern utility grid as one that incorporates "both centralized and distributed generation and intelligent load control."

Since fossil fuels are a finite resource, and energy use will only continue to rise, a modern grid cannot only address the need for reliability and resilience; it must also address efficiency and sustainability. With these criteria of a modern grid in mind, Los Alamos scientists have applied their suite of expertise to grid design, grid control, and grid resiliency. These complex optimization problems take into account new technologies and needs such as residential solar panels that can provide energy to the grid on sunny days but not at night, smart appliances that can be programmed to run at times when demand on the grid is low, and a proliferation of electric vehicles that require charging for large periods of time.

Key to this modernization is connectivity. Sensors at home and distributed around the grid give feedback about demand and availability—but, as with many things in life, these benefits come with a few risks. The interconnectedness also opens the door to new threats.

A 2016 ATTACK ON THE UKRAINIAN POWERGRID PUT ENERGY VULNERABILITIES INTO THE SPOTLIGHT

Threat of a cyber storm

Clearly, not all power outages are caused by hurricanes. In recent years, Americans have become increasingly aware that cyber attacks threaten many areas of daily life, which could very well include the power grid. Since the vision of a modernized grid includes a good deal of automation and connectivity, it also requires significant attention to cyber security. In fact, a relatively minor power outage in Kiev, Ukraine, in December 2016 has since been identified as the result of an attack using malware that has been referred to as Industroyer or Crash Override. This particular malware is considered to be sophisticated in its ability to use code to disrupt physical systems. Not only that, the malware is adaptable and deletes files to hide its presence.

This relatively new phenomenon of interdependencies between computers and infrastructure has created a whole new area of concern. Cyberphysical security refers to the idea that there are physical systems and devices with computational capability—similar to that of general purpose computers—that need to operate securely. These devices are found everywhere, such as a refrigerator that has a camera for its owner to check its contents while at the store or a coffee machine that can be activated by a household virtual assistant. Safety cameras and controls in modern cars are a good example of why cyberphysical devices need to be kept secure. For instance, it isn't safe for a driver to have to enter a password before braking, so how does one authenticate the command to brake and ensure it is actually coming from the driver?

Usage sensors, circuit protectors, cameras, and even fire-suppression systems are cyberphysical devices that could be vulnerable in the power grid because of their networked operation. In the past, these devices were designed with functionality, reliability, and safety in mind, but not cyber security. Conversely, the tools and methods developed for defending classical cyber systems don't always work for cyber-physical systems. When assessing the security of the current and future grid, Los Alamos scientists are trying to identify how to choose or improve upon physical devices and components in order to make a system that is robust against deliberate attacks.

"Security is not a goal that you achieve and then you're done," explains Alia Long, a Los Alamos electrical engineer. "It's an ongoing process determined by your need and the potential threat." Long insists that although it may be tempting to shy away from modernization for fear of hackers, it is not in

One of the tools developed by Los Alamos scientists is called the Severe Contingency Solver, which has been used by government agencies to prepare for and respond to potential outages caused by hurricanes or other events. The Solver uses data on specific grid infrastructure and usage to create maps that show the best way to restore power to the most people or to critical locations, such as hospitals or military bases. Here, a hypothetical grid network demonstrates the kind of output the Solver can produce; the orange connections indicate power lines that are under stress or without power.

PHOTO CREDIT: NASA

the best interests of the grid. She explains that although a more modern, automated grid may introduce new vulnerabilities due to connectedness, the updated grid will ultimately make it easier to detect and respond to problems. For instance, if the grid has to be shut down to fix a cyber problem, then the attacker might have achieved his goal.

In addition to assessing how to secure cyberphysical devices, Long is also working with Los Alamos theoretician Nathan Lemons on a project to detect suspicious behavior. Lemons is using statistical learning theory to understand the normal activity on the power grid as a way of spotting anomalies. This project is difficult because of the sheer amount of heterogenous information traffic: there are both continuous variables, such as electricity demand, fluctuating up and down and discrete variables, such as an outage from a downed power line. Although a lot of research has been put into models that use these two types of data, there has been much less theoretical work in combining both discrete and continuous data into one model.

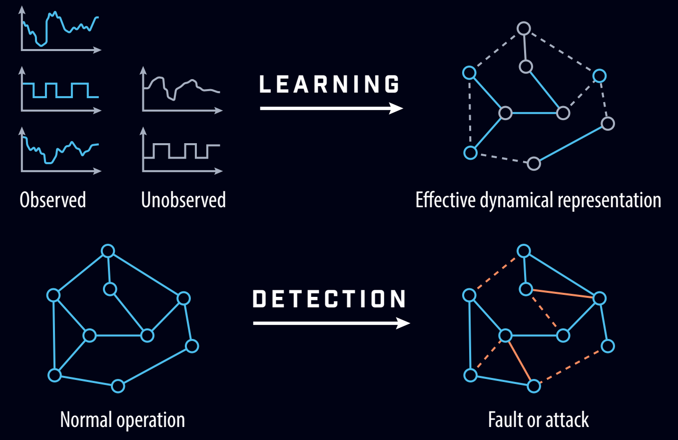
"It is especially novel and difficult to try and create a model in a dynamic setting where one learns from the data how the model is expected to evolve over time," says Lemons. In addition to this, Lemons must include and assess the presence of latent, or hidden, data in the grid. These data could be unknown or unavailable, such as unknown activity on a given line or unavailable information on the status of a switch. By correlating observed data with unobserved data, Lemons is able to infer relationships about dependencies in the network.

Lemons is trying to determine how much data is needed to create a reliable model of the cyberphysical system that can be used for detecting anomalies. For instance, if a network switch is turned off when it should be on, it would be an obvious red flag. However, if the switch is on when it is supposed to be on, can scientists detect if the electrical activity on the other side of the switch is normal or abnormal?

Substation substantiation

Across the Lab, the breadth of work addressing the challenges of maintaining and improving the power grid is formidable. And some of it, in the form of scientific advice to the DOE and industry, has already been applied to improve the national grid. However, with such a complex national system and lengthy list of external participants, there has not been an easy mechanism for real-world, or real-time, feedback about the effectiveness of the science.

Fortunately, validation is about to become much easier. The Los Alamos Lab's electrical grid is currently being upgraded—including a rebuild of the Supervisory Control and Data Acquisition system. Seizing this unique opportunity, Lab teams are positioned to set up a cyberphysical-systems testbed within the Lab's new network so that they can experiment, study, and validate everything, from usage optimization algorithms to anomaly or intrusion detection, in a real power grid. The Power Validation Center, as they are calling it, will be up and running in 2020 and, by all accounts, will be a one-of-a-kind capability.



Los Alamos scientists are developing novel methods for learning complex models of normal power grid activity in order to better identify when something has gone wrong. In the general approach (upper row), streaming data from available sensors is used to learn the effective probabilistic model of the system. This can include dependencies (solid lines) between observed data streams and inferred dependencies (dotted lines) between observed (blue) and unobserved data streams (unknown or unavailable data, in gray). Any abrupt change is a sign of a fault or a cyber attack. For instance, the dashed orange lines (lower row) indicate connections that no longer exist and the solid orange lines indicate new, abnormal connections. The Los Alamos team is working to improve detection of attacks by creating signatures of these anomalies so that problems can be identified quickly.

"We hope to use this system to train people for incident response, improve power grid operations, and test updates so they don't impact operations," says Long. She explains that the Center will be "ideally suited for addressing the emerging science of cyberphysical systems with access to unique data sets and the ability to perform experiments on critical cyberphysical infrastructure."

With an eye on the prize of a resilient, sustainable, and secure power grid, Los Alamos scientists are working hard to keep the lights on and the nation secure. Their extraordinary combination of expertise—and their upcoming Power Validation Center—enable them to investigate exciting new approaches to the mundane task of delivering electricity to buildings. With each improved algorithm, Americans can anticipate that when the power goes out, they should relax and enjoy the respite right away because it won't be long before the grid is going again. LDRD

—*Rebecca McDonald*

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MISSION IGNIT

An advanced nuclear-fuel capsule offers a new shot at a functional solar core here on Earth.


ION

NUCLEAR FUSION HAPPENS EFFORTLESSLY, even inevitably, at the temperature and density conditions found at the core of the sun. To make it work on Earth, however, something akin to an artificial solar core—except even hotter and denser than the real one—would have to be replicated here. But that's not the hardest part.

To make fusion into a power source, the artificial solar core would need to be contained rather than allowed to explode (as in a thermonuclear bomb). The sun accomplishes that containment via the gravity of its 2000 trillion trillion metric tons worth of mass. Fusion scientists on Earth have to figure out another way. But that's not the hardest part either.

The hardest part, which humanity has yet to overcome in its quest for clean and abundant power, is doing those things—creating and containing an artificial solar core—without consuming more energy in the process (or losing it along the way) than is generated by the fusion itself. Achieving that—getting more energy out than what was put in—is called ignition. Yet after nearly seven decades of fusion-science research and development, ignition remains a fairly distant hope, perhaps requiring a massive expansion, redesign, and replacement of the world's already-extravagant fusion research facilities.

Or might there be another way?

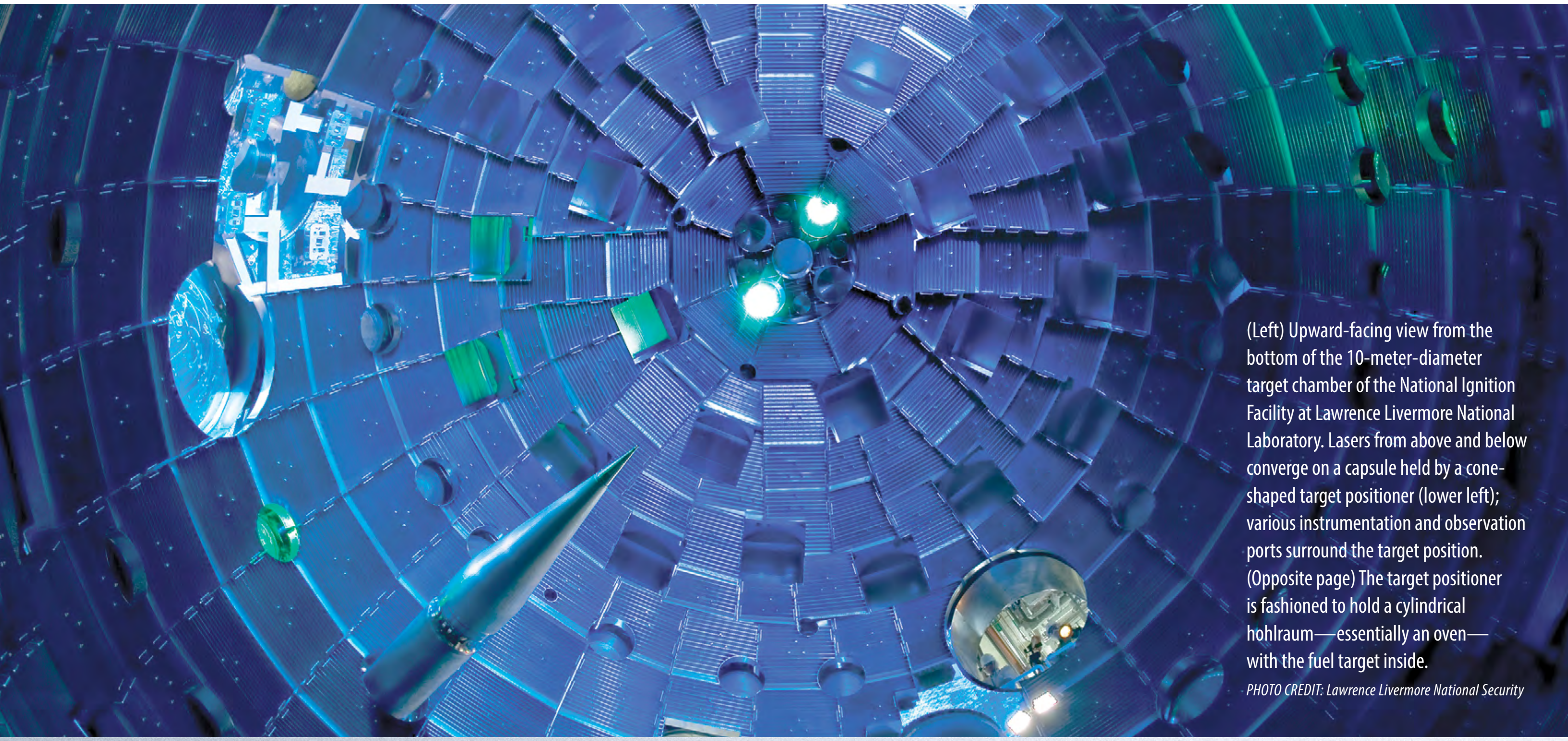
Moment in the sun

History has shown that fusion-based power is much more difficult to achieve than earlier predictions held it to be. Year after year, new design after new design, and dollar after dollar, fusion power—or even self-sustaining fusion for research purposes without all the attributes of a practical power source—has remained unattainable. Earlier in this decade, a campaign intended to cross that threshold once and for all at the National Ignition Facility (NIF)—which is exactly what it sounds like: a national facility designed, built, and operated primarily for the purpose of achieving ignition—came up short. NIF, and the undeniably brilliant concept behind it, apparently fell victim to the same deceptive difficulty that the quest for fusion has encountered time and again.

"It's discouraging, no question," says Los Alamos scientist Mark Schmitt, "but it would be a mistake to assume that means it can't be done." Schmitt and colleague Kim Molvig, both plasma physicists, along with their small team of scientists, are working hard to bring about a new twist on a NIF experiment, designed to avoid the shortcomings of previous tries. They call the concept "Revolver," a name handed down from earlier work at Los Alamos. "With Revolver, we are taking an unconventional tack—one that predicts the generation of a modest energy gain but is more robust against failure. It's an approach that might work."

At the same time, both Schmitt and Molvig are flirting with the increasingly nebulous number known as retirement age. NIF itself, in a way, is similarly flirting with—well, certainly not retirement, but diversifying its research portfolio away from a singular focus on ignition. For both the men and the machine, Revolver offers something worth holding out for: the hope of finally transcending the ignition barrier.

NIF lives at Lawrence Livermore National Laboratory in Livermore, California. A major research facility and a significant investment, NIF looks a lot like Professor X's "Cerebro" machine from the *X-men* comics and movies: a large hollow sphere with metal walls. Instrumentation located around the "equator" of the sphere keeps watch on a millimeter-scale fuel capsule at its center, where 192 ultraviolet lasers originating



(Left) Upward-facing view from the bottom of the 10-meter-diameter target chamber of the National Ignition Facility at Lawrence Livermore National Laboratory. Lasers from above and below converge on a capsule held by a cone-shaped target positioner (lower left); various instrumentation and observation ports surround the target position. (Opposite page) The target positioner is fashioned to hold a cylindrical hohlraum—essentially an oven—with the fuel target inside.

PHOTO CREDIT: Lawrence Livermore National Security near the sphere's "poles" converge. The laser energy—and this is the most energetic laser facility anywhere in the world—heats and implodes the fuel capsule so that the tiny ball of fusion-capable hydrogen isotopes at its center skyrockets to above-solar-core conditions.

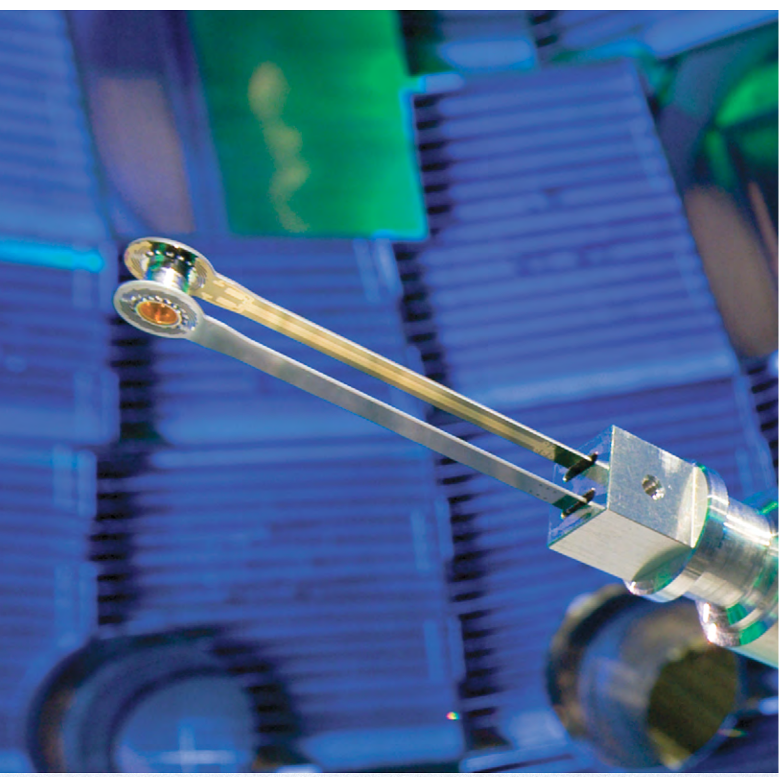
At that point, positively charged hydrogen nuclei are zipping around so rapidly and in such close proximity to each other that they slam into one another despite their mutual positive-positive electrical repulsion. They merge to produce helium nuclei and other particles with enough energy to spawn a tremendous release of heat. That heat is the point of the whole thing—heat to drive a steam turbine and electrical generator, for example. But so far, there's just not enough of it. Too much is escaping, and too few fusions are producing it in the first place.

THIS WAS ALWAYS GOING TO BE A LONG GAME.
BUT IT'S AN INCREDIBLY WORTHWHILE GAME.

Broken symmetry

Oddly, the trouble does not reside in the wildly complicated and ingeniously engineered NIF system itself. The chamber, the ultrapowerful and finely controlled lasers, and the operating procedures are all essentially flawless. By all accounts, the trouble seems to lie within the millimeter-scale pocket of nuclear fuel.

Fusion fuel is a mixture of deuterium and tritium, both rare isotopes of hydrogen. In conventional fuel capsules, the deuterium-tritium (DT) mix is encased in a spherical shell of solid material. The capsule is loaded into a small hollow cylinder known as a hohlraum that acts like an oven: when NIF's lasers enter through small holes at its top and bottom, they bounce around the inside and produce tremendous heat. The hohlraum's interior walls become hot enough to release x-rays, which cook the outer shell of the spherical fuel capsule and cause it to blast away, or "ablate," like a million tiny rocket ships launching from the fuel capsule in every direction. The recoil from the ablation produces an implosion, rapidly compressing and heating the DT fuel to spark fusion.



It might sound straightforward, and it basically works, but the compressed core where fusion occurs is utterly minuscule, and controlling the tiny but massively energetic implosion to get the core just right is both critically important and extraordinarily difficult. The DT mixture, initially arranged as a solid shell surrounding a vapor pocket, acts as both the fuel and, a little farther out, the agent that compresses the fuel. It must squeeze down to produce a 10,000-fold increase in density of the solid-fuel shell and a "hot spot" initiation region that grows with enough stability to achieve ignition. To do that, it needs particularly high temperatures and implosion speeds that produce a sophisticated convergence of shock waves, all of which has proven prohibitively difficult to control. Achieving the symmetry required for this method is what the hohlraum was intended to accomplish, but it introduces other variables and complications, and it has not performed as hoped.

If, with all this in the mix, the resulting compressed core shape isn't sufficiently spherical and uniform—if it becomes stretched or lopsided—then the fusion "burn" will be inadequate. If the core dissipates too quickly or just gets a little too thin somewhere, then the reaction will fizzle as energetic particles stream out through that thin patch. If the implosion isn't clean and ends up mixing vaporized shell material into the DT fuel, the fuel will become too cold and dilute. The core must maintain a uniform profile and spherical symmetry with minimal mixing for a long enough time to generate the required fusion energy. So far, the human race has been unable to make this happen.

What goes wrong? Most likely, it begins with minute imperfections in the fuel capsule and the uniformity of its implosive drive. A tiny bit thinner here or higher pressure there, and the implosion becomes slightly asymmetrical; as it progresses, the asymmetry grows and mixing renders the fuel less pure and not hot enough to burn. Despite the 192 exquisitely coordinated lasers and the apparent simplicity of the fuel-capsule design—fuel inside an ablator shell—the core still gets messy, and ignition remains out of reach.

Schmitt and Molvig decided to address the problem by reconceptualizing the fuel capsule.

"Instead of using a fuel capsule that looks simple but is actually quite complex in function," Molvig explains, "we are proposing one that looks more complex but is functionally much simpler."

Neatly pressed and wrinkle-free

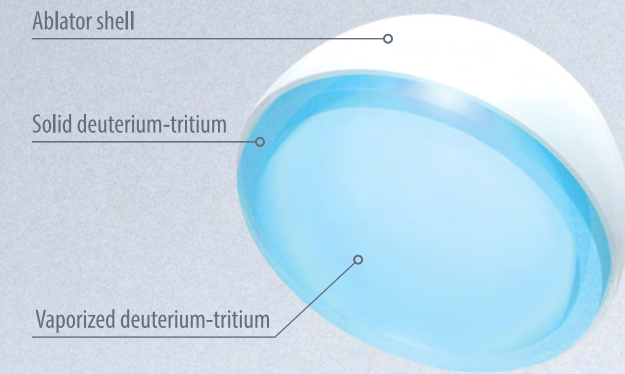
Schmitt and Molvig designed the Revolver fuel capsule to be an onion-like series of concentric spherical shells with the DT fuel at the center. The outermost shell, made of low-density beryllium metal, is the ablator. It starts the recoil implosion when laser heating ejects a fraction of its mass outward as ionized plasma; the beryllium not ejected accelerates quickly inward. Because of imperfections in the laser drive and material properties, asymmetries that look like wrinkles in the imploding shell develop and expand until they reach a copper layer surrounded by plastic. The plastic smooths the irregularities until their impact on the pressure variations impinging upon the copper shell is largely erased, and the copper shell's original spherical symmetry causes any residual wrinkles to restart their growth from small perturbations.

Now the copper carries the pressure kick inward, but with a higher density than the beryllium, forming an impulsive hammer to quickly strike the innermost metal shell, made of tungsten, which is denser still and extremely strong. Asymmetries reemerge along the way but are once again muted by a cushioning layer of plastic, this time surrounding the tungsten shell. That shell encapsulates the DT fuel and compresses it with adequate spherical symmetry for fusion to emerge and grow to ignition.

At each plastic-encased metal layer, two valuable things happen. Extant asymmetries are smoothed out, and because the metals get progressively denser—beryllium to copper to tungsten—the implosion's pressure is amplified at each stage. The net effect is a factor-of-100 amplification in the tungsten shell's pressure on the DT fuel relative to the initial beryllium ablation. This manner of pressure gain can be accomplished with a slower fuel-implosion speed than that of a conventional target. That slower speed dramatically reduces the amount of mixing between the fuel and the surrounding tungsten, keeping the fuel purity high.

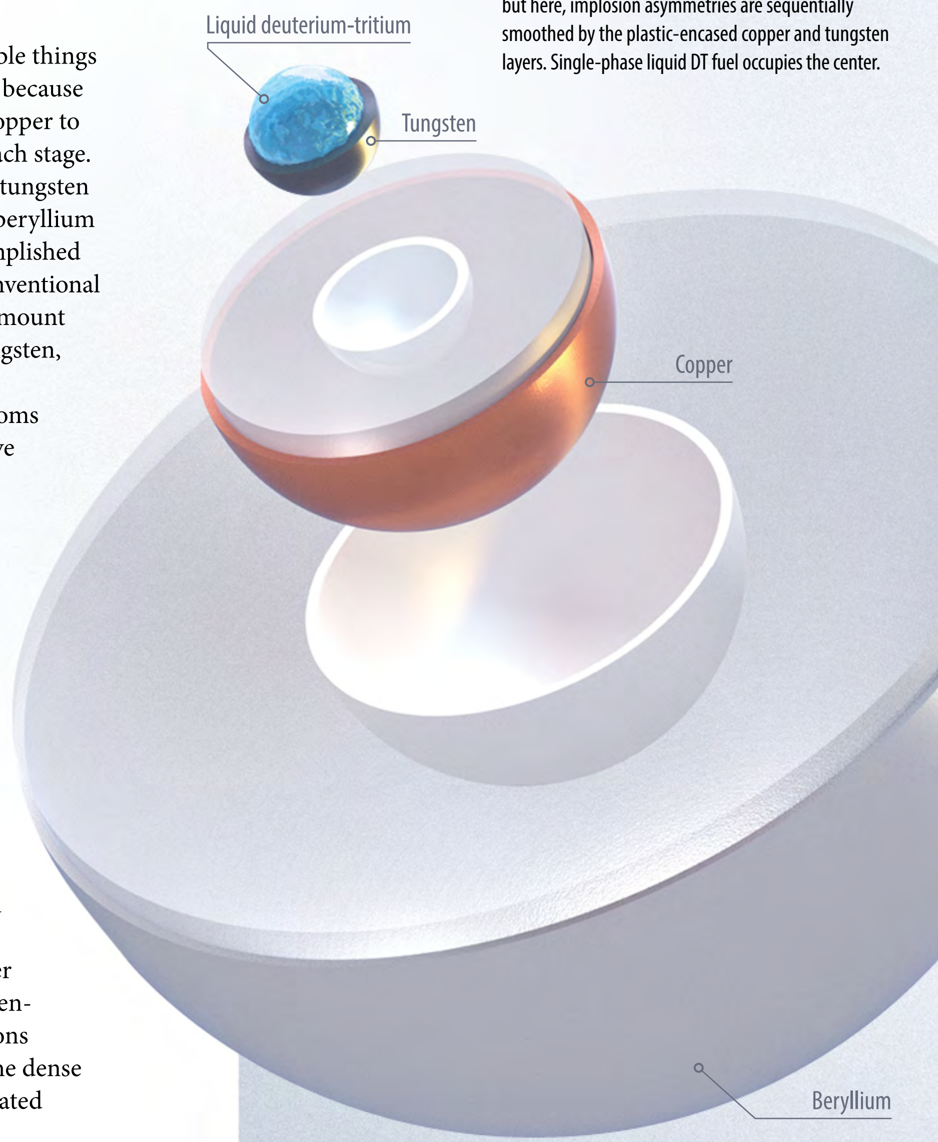
Crucially, this approach also means that the atoms in the tungsten shell, though rapidly vaporized, move inward as a monolithic envelope. They contain the nuclear core so that the fusion-generated heat and radiation remain in play for a relatively long time—supplying energy to spawn successive fusion reactions rather than leaking away and taking their energy with them. Consequently, solar-core conditions are maintained over a sustained burn with minimal losses in a way never before seen in any other target design. In the end, about half the fuel fuses before the energy buildup explodes the core, as contrasted with only 10 or 15 percent for a conventional target.

With these sustained, symmetrical burns, other difficult-to-manage conditions can be relaxed a bit. For example, the diameter of the fuel only needs to converge by a factor of nine, which is easier to keep tidy than the factor of 34 needed for a conventional NIF target. Lower-temperature burn conditions are also feasible, using less total fuel. And because the dense tungsten is so effective at trapping the fusion-generated



(Above) Inside the containment shell of a conventional NIF target is a cryogenically maintained mixture of solid and vaporized deuterium-tritium (DT) fuel, with the solid along the interior wall of the shell and the vapor in the cavity at the center. That capsule is placed inside a hohlraum for oven-style heating.

(Below) The new direct-drive design doesn't use a hohlraum. Lasers converge directly on an outer surface of beryllium metal. Like the conventional design, the outer layer's ablation drives the capsule's implosion, but here, implosion asymmetries are sequentially smoothed by the plastic-encased copper and tungsten layers. Single-phase liquid DT fuel occupies the center.



radiation to avoid energy losses—as contrasted with the conventional design, in which the very lightweight DT fuel must stand in, rather less effectually, as its own containment envelope—high implosion speeds and their concomitant mixing problems can be reduced.

But perhaps the biggest benefit is this: because of these reduced fuel-implosion requirements and the fact that the outer capsule radius is large, the energy needed to produce the requisite pressure drive at its surface drops from the level of hohlraum-generated x-rays down to what can be obtained from a brief ultraviolet laser pulse striking the surface of the fuel capsule directly. This "direct-drive" laser intensity can be relatively low, effectively eliminating pernicious laser-plasma instabilities that can rob a conventional target of energy and induce gross asymmetries in its implosion. Yet even with reduced intensity, seven times more laser energy can be deposited into the outer shell because none of it is wasted heating the hohlraum itself.

SO WHAT IF IT WORKS IN SIMULATIONS? AFTER ALL, ON PAPER, **EVERYTHING ELSE WAS SUPPOSED TO WORK TOO.**

Deep inside, as a result of direct laser-energy deposition and subsequent shell smoothing, the DT fuel rapidly reaches peak convergence and then lingers in a stable burn for three to four times longer than in a conventional target. Ultimately, the brief laser pulse is converted to a single, sharp pressure pulse on the innermost metal shell, generating a clean, enduring, spherical fusion zone. At least, that's the expectation.

Say yay or nay?

Still, with something as notoriously elusive as ignition, every new proposal invites skepticism. So, what specifically do the naysayers say when they say nay?

Some say that direct drive is a problem, since NIF's current configuration—which would cost a pretty penny to change—was designed for a hohlraum, with lasers entering from above and below but not from all sides. But Schmitt's research indicates that the existing laser configuration can be arranged to cover the entire target surface many times over. Every spot on the target would be covered by overlapping between 5 and 7 of the facility's 192 laser spots. And the inequality in beam strength caused by the target's "poles" being hit at nearly right angles while its "equator" is hit at more grazing incidence can be sufficiently offset by adjusting the laser intensity profiles of the individual laser beams. What little degree of uneven cooking remains should, in principle, be smoothed out by the copper and tungsten shells and their cushioning layers.

Some naysayers argue that the Revolver target might be too large and complex to control. It must be manufactured to extraordinarily tight tolerances, with nearly perfectly concentric spherical shells, to avoid introducing asymmetries that will grow over the large implosion distance. It's certainly true that no such target has yet been manufactured or tested in a live experiment, and nothing short of that guarantees it will actually work. But Schmitt tried it in simulations. He offset the tungsten-encased DT fuel within the target by a conservatively large distance and still obtained adequate implosion symmetry to induce ignition. He also tried offsetting the entire target within NIF's target chamber—a broadsword-rather-than-scalpel approach to introducing laser-drive asymmetry—and again obtained a successful result.

In addition, Revolver benefits from the simplicity of using a single-phase liquid DT fuel, which, in theory, should provide a uniform-density fuel region to be compressed. By comparison, to generate and maintain a conventional target's geometrically precise annular layer of solid DT fuel surrounding a central DT vapor pocket necessitates stringent cryogenic-handling procedures. "We have a concept to allow the target to be constructed and used at room temperature," says Schmitt, "which would greatly simplify the fielding of future high-yield experiments at NIF."

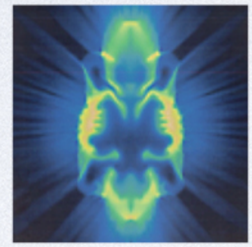
Besides all of that, Revolver is also simpler in the sense that it eliminates the hohlraum and the x-ray drive-asymmetry baggage that comes with it.

So far so good. But then there's the wide swath of naysayers comprised of anyone, really, with any knowledge of the disappointing history of the decades-long quest for ignition. They say: So what if it works in simulations? After all, on paper, everything else was supposed to work too. Simulations can't fully capture the nuances of such an intense region of high temperature and density. The computing requirements are too great to obtain more than just an approximation, and key properties of matter under such extreme conditions, such as opacity and "equation of state" (which links a material's behavior to its temperature), are only known approximately anyway.

This is an undeniably valid concern. One can't rely on anything—certainly nothing so grand or elusive as ignition—demonstrated by simulation alone. But supercomputers and simulations have been getting better, with both Los Alamos and Lawrence Livermore being absolutely state-of-the-art in this area. And importantly, the triple metal-layered target's slower, lower-temperature implosion brings the simulations into a domain where material properties are better known. It's not a sure thing, but it means the simulations are more believable for this approach than others. Besides which, notes Schmitt, "Revolver is relatively insensitive to changes in equation-of-state or opacity models because the radiation is trapped in the fuel region, and the entire fuel region ignites simultaneously." By contrast, the physics of conventional-target ignition—with multiple shocks that must precisely converge at the vapor pocket to produce exacting conditions for hot-spot ignition and burn propagation—is extremely challenging to fully capture in simulations.

Okay, but with these kinds of concerns about predictive uncertainty, why use three metal shells instead of two? Why not just have the ablating beryllium layer impact the tungsten layer directly, without copper in between? Why introduce the extra design complexity and increase the odds of something not working as expected—either in simulations or in experiments?

"I wish we didn't have to," answers Schmitt. "There are people working on two-shell, indirect-drive designs too. But with our direct-drive approach, it's not the way to go. The imploding ablator shell can't transfer energy to the tungsten shell fast enough before the tungsten shell converges, so the fuel doesn't get hot and dense enough to ignite. It's like trying to drive a nail with a bag of sand. The copper shell is our hammer."



(Right) Simulations with conventional targets at NIF reveal that complex asymmetries develop by the time the fusion begins. Instead of resulting in a clean, spherical region with consistent temperature and density amenable to a nuclear "burn," these asymmetries reduce the fusion's effectiveness and energy output, forestalling ignition.

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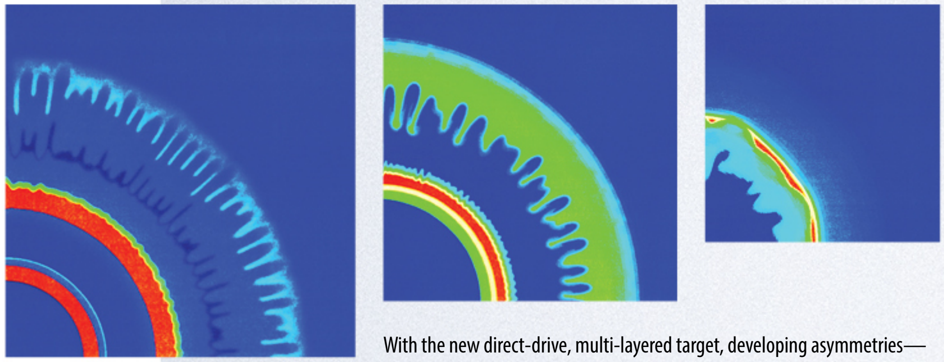

With the new direct-drive, multi-layered target, developing asymmetries—shown here in sequence, starting with the outer beryllium shell (left), then the copper (middle), and finally the tungsten (right) enclosing the nuclear fuel—are attenuated upon encountering each subsequent metal shell encased in a plastic cushioning layer. According to this simulation, the DT region in the last frame has sufficiently uniform conditions to produce simultaneous and prolonged ignition.

Illuminate. Implode. Ignite.

Initial testing, led by Los Alamos team member Scott Hsu, was carried out with the OMEGA laser at the University of Rochester's Laboratory for Laser Energetics, using scaled versions of the outer ablator shell. The limited laser energy available at that facility, compared to NIF, required miniaturization of the target to only about 20 percent of the diameter of the intended design. Nonetheless, the results were promising, showing no problems with laser-plasma instabilities, energy losses, or the scientists' ability to predict the imploding capsule's profile. Intermediate testing with two-shell targets is slated for OMEGA this winter.

Subsequent steps will involve a series of increasingly realistic experiments at NIF to determine if there are any obvious show-stoppers. But this is chess, not checkers, and even if each experiment goes according to plan, the final test that (hopefully) results in successful ignition will require several more years of concerted effort to build and field the full-scale triple-shell design. Then, even if everything works and ignition is achieved, a fusion-based power plant would still be a long way off because "ignition" indicates only that the fusion energy generated exceeds the laser energy transferred into the target—not the electrical energy that went into the laser. The laser itself is only about 1 percent efficient, so the overall process would still be a net loss. Besides which, creating controlled, ignition-level fusion in the laboratory, while revolutionary, is not the same thing as a functional power plant. In the most direct extension of a NIF-style setup, one would need, at minimum, some kind of apparatus for carrying fusion-generated heat off to boilers and turbines and a system for shuttling spent targets out and fresh targets in, assuming the technology can be scaled to the power-plant level at all.

Schmitt and Molvig readily acknowledge these hurdles.

"It's a mistake to look too far ahead to fusion-based electrical power generation," says Molvig. "With successful ignition, we can assess what happens if we adjust various parameters and then update our simulations accordingly, to make them truly predictive. From there we can explore suitable configurations for fusion-based technologies. But we have to start with a reliable, reproducible system. Make a Model T, then evolve to a Ferrari."

The predictive-simulation capability Molvig mentions would also represent a major leap forward in capability for one of Los Alamos's key mission areas, that of understanding, maintaining, and servicing the nation's aging nuclear-weapons stockpile without detonating any weapons to obtain the necessary test data. Yet, beyond power plants and the weapons arsenal, there is also the academic study of nuclear fusion itself: a vital area of both pure and applied science.

"We're trying to build, harness, and learn from an artificial solar core," Schmitt says. "This was always going to be a long game. But it's an incredibly worthwhile game, and ignition is the crucial next step." LDRD

—Craig Tyler

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Solar activity can disrupt power grids on Earth. Shown here, a 2012 solar flare is accompanied by a coronal mass ejection in which solar matter blasts outward into space. If the matter interacts with Earth's magnetic field, it can cause magnetic fluctuations on the ground. While harmless to human beings and normal electronics, these fluctuations can induce significant electrical currents in very large circuits—in particular, cross-country power transmission lines in connection with natural conducting features, such as water or underground ores. The excess currents can permanently damage transformers, improperly trip other electrical components, and overload regional grids, producing prolonged blackouts. To learn about making the power grid more resilient to geomagnetic storms and other dangers, see "Out of the Dark" on page 18. *CREDIT: NASA*

ISSN: 1942-6631

Printed on
recycled paper

1663
Mail Stop M711
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Los Alamos, NM 87545

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Santa Fe style derives from a blend of early Native American and Spanish influences.

PHOTO CREDIT: Patricia Temer

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A U.S. Department of Energy Laboratory LALP-19-003

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