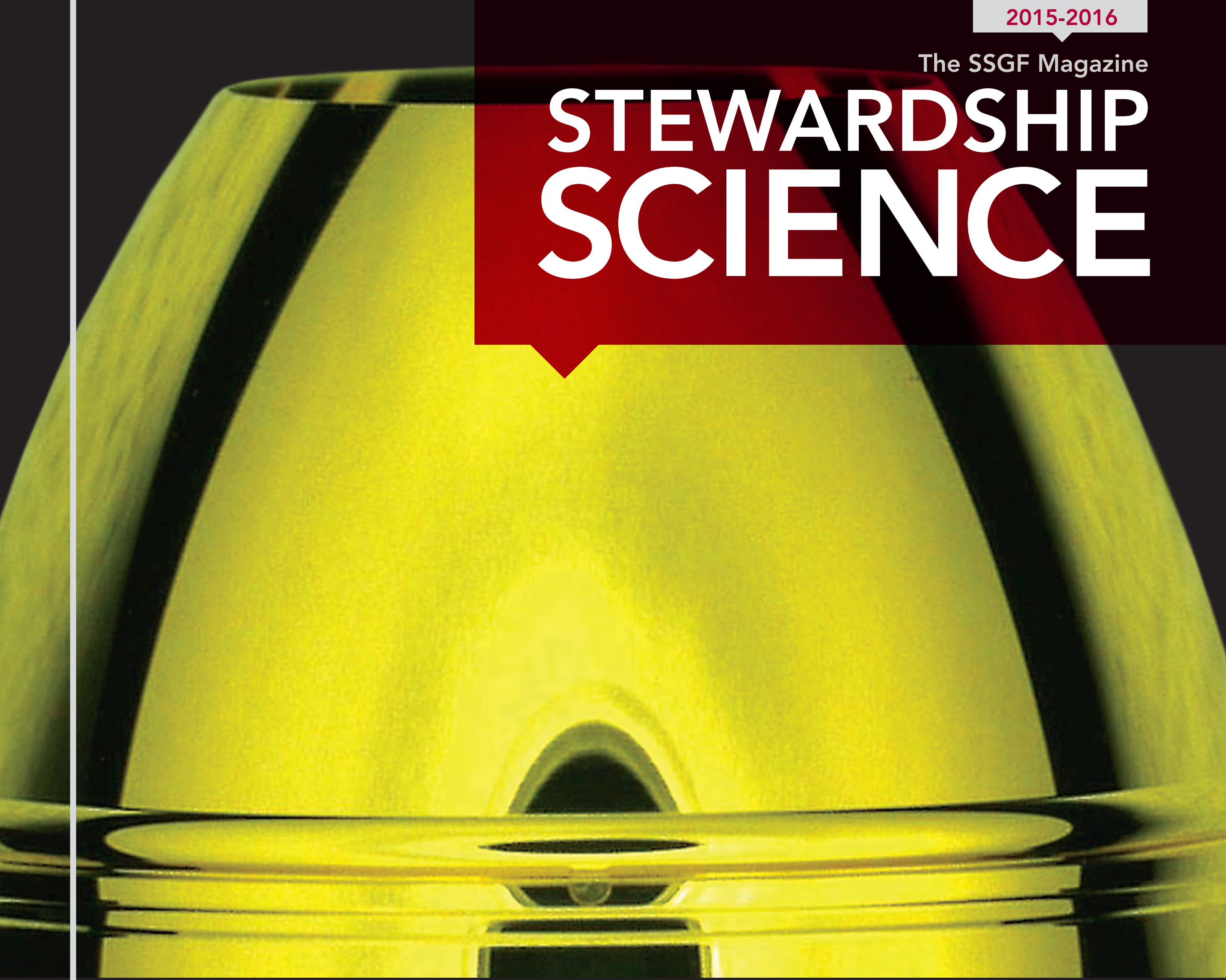
2015-2016

The SSGF Magazine

STEWARDSHIP SCIENCE



BETTER BULL'S-EYES

Livermore teams with industry to constantly tweak tiny targets used in big physics experiments

Los Alamos: Shock's aftermath

Sandia: Toll of age and radiation

Plus: Orion's pulse, spectral abundance, 40-millimeter wallop, fellows at the labs, a talk with an NNSA leader and a farewell to an unforgettable friend

Department of Energy National Nuclear Security Administration

Stewardship Science Graduate Fellowship

Lawrence Livermore National Laboratory

Sandia National Laboratories

Los Alamos National Laboratory

The Department of Energy National Nuclear Security Administration Stewardship Science Graduate Fellowship (DOE NNSA SSGF) program provides outstanding benefits and opportunities to students pursuing a Ph.D. in areas of interest to stewardship science, such as properties of materials under extreme conditions and hydrodynamics, nuclear science, or high energy density physics. The fellowship includes a 12-week research experience at Lawrence Livermore National Laboratory, Los Alamos National Laboratory or Sandia National Laboratories.

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STEWARDSHIP SCIENCE

DEPARTMENTS

FRONT LINES

SAMPLINGS

COVER

SHAPE OF THINGS TO COME

In early 2015, Peter Amendt and his Lawrence Livermore National Laboratory (LLNL) colleagues reported on rugby-ball-shaped hohlraums in the journal *Physics of Plasmas*. They proposed the shape as an improved alternative to standard cylindrical hohlraums, the gas-filled implosion targets used in fusion experiments at the LLNL-based Nation Ignition Facility. (Shown on the cover: a closeup of one end of the target's shell.) Our story, starting on page 10, details LLNL's long collaboration with General Atomics to design and build a range of targets used at NIF and in other extreme physics experiments.

SSGF

Stewardship Science: The SSGF Magazine showcases researchers and graduate students at U.S. Department of Energy National Nuclear Security Administration (DOE NNSA) national laboratories. *Stewardship Science* is published annually by the Krell Institute for the NNSA Office of Defense Program's Stewardship Science Graduate Fellowship (SSGF) program, which Krell manages for NNSA under cooperative agreement DE-NA0002135. Krell is a nonprofit organization serving the science, technology and education communities.

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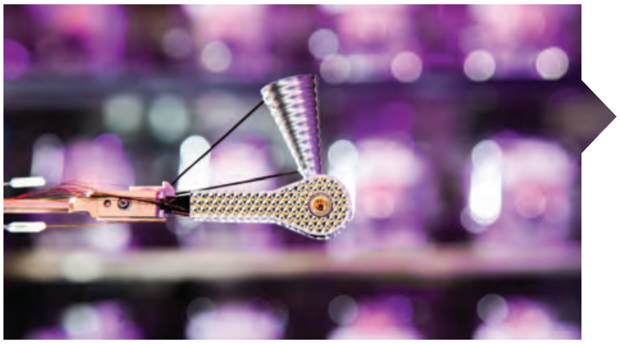

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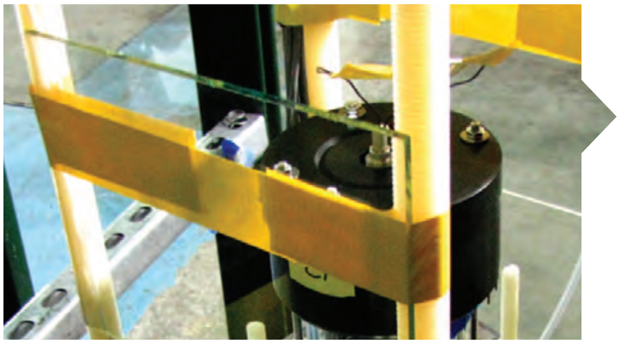

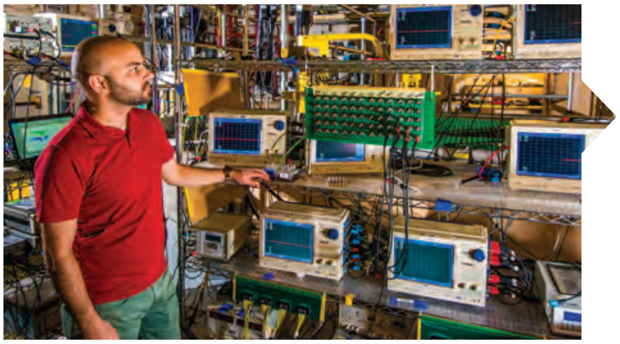

IMAGE CREDITS
Cover, Lawrence Livermore National Laboratory (LLNL); page 3, LLNL; page 7, Sandia National Laboratories (SNL); page 9, National Nuclear Security Administration; pages 10-13, LLNL; pages 15-19, Los Alamos National Laboratory; pages 20-21 and 23, SNL; page 24, Krell Institute; back cover, SNL.

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Orion's Bolt

About 50 miles west of London in a research facility named Orion, a laser pulse only six thousandths of an inch long strikes a sample of aluminum held between two pieces of plastic. In an instant, the bullet of light delivers 100 joules of energy – enough to lift 22 pounds more than three feet off the ground – to a dot of metal more than 100 times smaller than the head of a nail.

When the pulse hits the sample, the temperature of the metal spikes to millions of degrees centigrade, vaporizing it. But first, for a brief moment, the aluminum reaches pressures and temperatures that can be measured nowhere else on Earth. Orion laboratory instruments capture data from the hot, dense metal.

The key to success for this experiment is the minuscule size of the laser bullet. It's shaped to deliver all its energy at once, in one-half of one-trillionth of a second. "The aluminum has no time to expand and disassemble," says Peter Beiersdorfer, a researcher at Lawrence Livermore National Laboratory and a collaborator in the project. "It stays solid, and now you can measure the properties of hot, solid aluminum."

Such measurements are crucial for ensuring the reliability and safety of thermonuclear weapons. Scientists must determine how energy flows through materials under these conditions, providing data to validate computer models of weapon function.

Delivering accurate data about factors relevant to nuclear stockpile stewardship is a big scientific challenge, Beiersdorfer says. "You can test the underlying physics and bring the inputs into the 21st century," he says. "These experiments remove some of the uncertainty about the physics of hot, dense plasma."

Based in Aldermaston, England, Orion is part of the United Kingdom's Atomic Weapons Establishment (AWE), which shares vital goals with the U.S. Department of Energy National Nuclear Security Administration. Construction on Orion began in 2005. The lasers began operating in 2013.

Designed to succeed Britain's 25-year-old HELEN laser, Orion extends materials research into greater pressures and temperatures than ever before. The facility houses 12 neodymium lasers in a main space that's the size of a soccer field and cleaner than a hospital operating room. Ten of the devices can deliver long pulses of 500 joules each to compress samples, constrained between pieces of plastic or diamond. These lasers perform much like the far more powerful lasers at LLNL's National Ignition Facility (NIF). Each Orion laser is able to emit a pulse about a foot long.

An engineer installs a spectrometer that measures samples' densities during experiments on the Orion laser.

The two remaining lasers set Orion apart from other laboratories. Each can shoot a bullet of light that's smaller and more intense than any other pulsed laser. "It's just a dot moving through space," Beiersdorfer says.

When the pulse super-heats its target, scientists have only a few picoseconds (trillionths of a second) to record data from the resulting burst of X-rays. Orion uses an array of instruments to capture fluctuations in this pulse. The world's fastest camera, employing drive electronics developed and upgraded by Ronnie Shepherd and colleagues at LLNL, captures X-ray intensity changes in intervals shorter than a trillionth of a second. At the same time, crystal spectrometers reveal details imprinted on the X-rays, such as the sample's opacity and state of ionization. Pinhole imagers monitor the size of the sample, indicating when it has expanded beyond the desired density.

Beiersdorfer and his collaborator, AWE's David J. Hoarty, plan to delve into fine detail on the ionization properties of hot, dense matter to establish which of two competing ionization models researchers should incorporate into computer simulations.

So far, Beiersdorfer and Hoarty have compressed samples to three times the density of an ordinary solid. To achieve even greater densities, they intend to stack long-pulse laser shocks. This work will venture into questions of quantum physics: Once samples reach a 10-fold increase in density, classical mechanics will be unable to explain their properties. "You really need quantum mechanics to explain things because the atoms are right next to each other," Beiersdorfer says. "And there's no good quantum mechanical description of such high-density, hot objects."

They will take a step toward peeking inside the sun, where questions about heat, density and opacity remain open.

– Andy Boyles

Fellows on Location

The DOE National Nuclear Security Administration Stewardship Science Graduate Fellowship's outgoing class describes the national lab research experience.

TRACKING THE TURBULENT EDGE

Adam Cahill was a busy guy on his 2012 **Los Alamos National Laboratory** practicum.

His main task under Hans Herrmann of Los Alamos' Gamma-Ray Physics Team was coding a model of a diagnostic for the National Ignition Facility (NIF), the giant inertial confinement fusion (ICF) experiment at Lawrence Livermore National Laboratory.

The Gamma Reaction History (GRH) detector evaluates gamma radiation generated when NIF lasers implode a deuterium-tritium (DT) fuel capsule. The data, however, often are uncertain due to random noise from diagnostics and data-acquisition equipment. Cahill's Monte Carlo model evaluated how much that interference influences nuclear reaction conditions inferred from the data.

The model starts with a gamma burst from a DT fusion reaction and generates noisy oscilloscope traces. It estimates errors by inferring reaction parameters from the traces and comparing them with the starting point's true values. Cahill used multiple model runs to estimate GRH noise, giving researchers an idea of how much uncertainty is inherent in the data.

Cahill also went to the University of Rochester to help with ICF implosion experiments at the OMEGA Laser Facility. And in July he helped with X-ray spectral measurements at Idaho State University's PITAS accelerator.

Cahill knows his way around diagnostics. Under David Hammer at **Cornell University**, he studies radiating pinches – high-density, high-temperature plasmas compressed by pulsed power machines – and uses absorption spectroscopy to understand their structures.

NICKING NICKEL

Samantha Lawrence pursued a particular interest during her 2014 practicum at **Sandia National Laboratories'** New Mexico location.

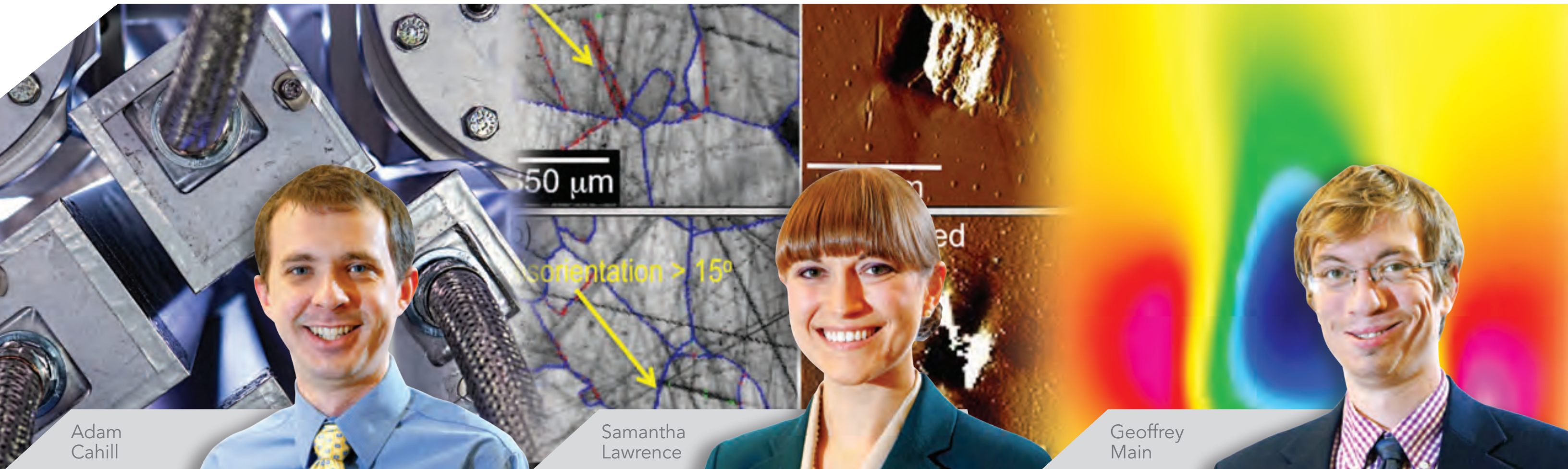
At **Purdue University**, where she studied under David Bahr, Lawrence investigated fracture mechanics, deformation and environmental resistance of materials at submicron scale. Much of the work revolved around nickel.

With Sandia's Brian Somerday, Lawrence extended that research, focusing on a nickel alloy to investigate how exposure to hydrogen makes materials brittle. She designed tests for three sample sets and used nanoindentation and scanning probe microscopy to characterize deformation and defect development in hydrogen-exposed Ni201.

"I'd been wanting to investigate hydrogen degradation of engineering alloys," Lawrence wrote in her practicum review. "Since I work extensively with nickel in my thesis research, using it as a model material system was an excellent choice."

Lawrence used electron backscatter diffraction to identify low-energy recrystallization twin boundaries and high-energy random boundaries for nanoindentation. Nanoindentation deformed the material along grain boundaries, she found, while thermal hydrogen charging altered the response to local

The final-year fellows, with images derived from their research in the background.



deformation. Other indentation tests within specific grains indicated hydrogen charging reduces elastic modulus – a material's resistance to deformation.

Lawrence also collaborated with researchers at Finland's Aalto University to quantify how material defects form in Ni201 and traveled there to participate in experiments.

The practicum sharpened her nanoindentation and atomic force microscopy skills, Lawrence wrote. "Additionally, this project provided ample opportunities for me to 'think on my feet.' I routinely had to develop a Plan B or C or D when things didn't work as expected for Plan A."

It was Lawrence's second Sandia practicum, following one in California in 2013. It turned out well enough that she started a postdoctoral fellowship earlier this year, with Somerday as her mentor.

OVERTURE TO A BEAM

Geoffrey Main's 2013 **Lawrence Livermore National Laboratory** practicum was on the beam – and on how it interacts with a moving fluid.

Main, with supervision from applied mathematician William Henshaw, worked on computational models capturing how fluids interact with linear and nonlinear beam models. Tracking or predicting such interactions is a challenging computational question but important to understanding many phenomena, including blood flow and airframe development. In particular, Main focused on coupling strategies for fluid-structure interaction on overset computational grids.

Main used Overture, a toolkit Henshaw's group developed, to implement the beam models. Overture is a hybrid of algorithms for fluid problems that adapts to complex boundaries. Main coupled the beam models to solvers for compressible and incompressible fluid flows, then analyzed the coupling for accuracy and stability.

To verify his work, Main developed exact solutions to some problems and compared results for other problems to experimental and published data. Finally, he documented the software and wrote a technical report.

The practicum gave him a chance to learn more about fluid-structure interaction for incompressible flow and allowed him to make some improvements to the Overture framework. He later used one of the methods he'd learned on the practicum to address a problem for his thesis research at **Stanford University**.

Before he graduated in November 2014, Main was in Charbel Farhat's research group, studying improved simulations of compressible multi-material flows, including interactions with flexible structures. He's now on a postdoctoral fellowship at Duke University.

TWO-FOR-ONE PRACTICUM

Elizabeth Miller's 2012 practicum gave her the unusual opportunity to work at both **Sandia** locations in one summer.

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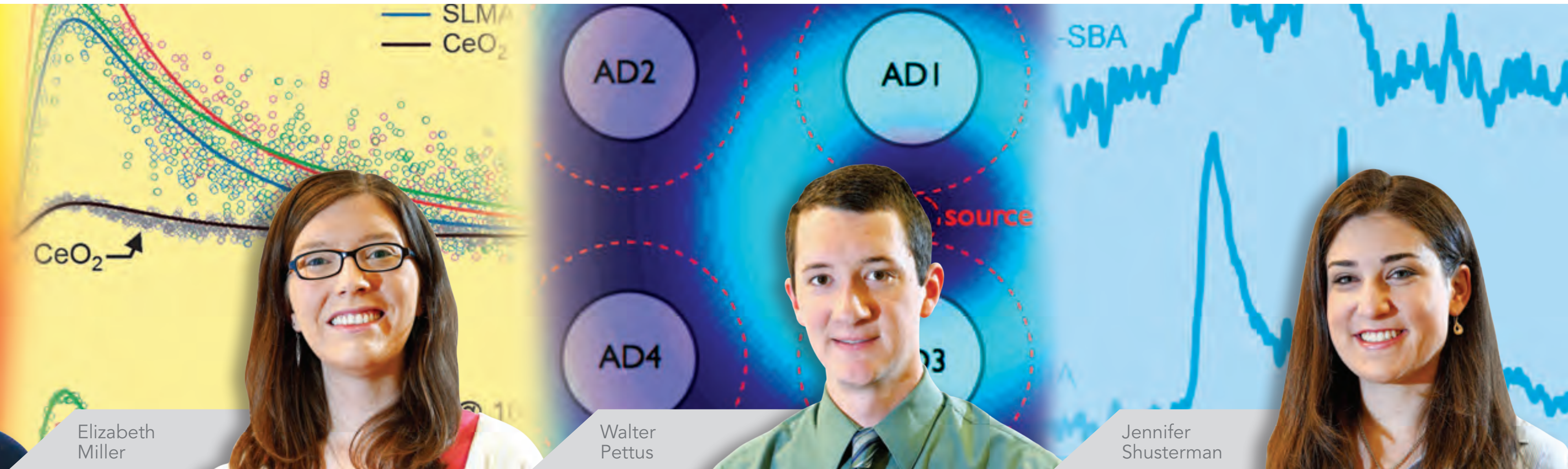

Elizabeth Miller

Walter Pettus

Jennifer Shusterman

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Miller, a **Northwestern University** materials science and engineering student, worked with Sandia's Sunshine to Petrol (S2P) project. Its goal is to use concentrated solar power for renewable transportation fuel production. The researchers seek materials that split carbon dioxide and water into carbon monoxide and hydrogen to make hydrocarbon fuels. Perovskite, commonly used in solid oxide fuel cells (which Miller studies in her doctoral research), is one target.

Working with Andrea Ambrosini at Sandia-New Mexico, Miller synthesized 19 perovskite compound pellets. She determined their crystallographic structure and cut them into bars for thermogravimetric analysis (TGA) to learn each material's carbon dioxide-splitting potential.

The samples that performed well in TGA and maintained phase stability went with Miller to Sandia's California campus. Working with Anthony McDaniel, she tested each in a laser-heated stagnation flow reactor, simulating conditions close to those found in true solar thermochemical environments.

The experiments helped prove the materials' abilities to split water and carbon dioxide and quantified the extent, products and kinetics of each reaction. Miller's findings may lead to a patent.

The practicum gave her experimental and data processing skills that will be useful in her thesis research under Scott Barnett. Working at both locations was strenuous, she added, but let her connect with a range of people and experience different lab environments.

It also "has shown me that even though my research focuses on a certain subsection of materials science, the skills I have developed will help me adapt to any career path," Miller wrote in her practicum review.

SHY NEUTRINOS ▸

In his 2012 **Livermore** practicum, **Walter Pettus** delved into the mystery of sterile neutrinos, a breed of particle hinted at in some experiments. They're sterile because, in theory, they don't interact with ordinary matter.

Working with Adam Bernstein of the lab's Advanced Detectors Group, Pettus improved a simulation that directly compares the physics of proposed source and reactor experiments to search for sterile neutrinos. Another graduate student wrote the simulation, but Pettus improved its flexibility. He added background models and detector and reactor geometries so the code handles more experimental setups. Pettus also focused simplified and unified simulation inputs to improve usability.

Pettus ran the simulation and worked with Bernstein to improve it based on the results. The model suggested reactors could be more important than sources in the search for sterile neutrinos.

Pettus also helped the group investigate synthesizing an experimental neutrino source – the isotope cerium-144 – from spent nuclear fuel or through target irradiation. He gathered and synthesized information, then calculated material quantities and assessed the feasibility. The group decided that developing a cerium-144 source wasn't currently feasible economically.

The projects meshed well with his thesis research on dark matter detection with Karsten Heeger at the **University of Wisconsin, Madison**, Pettus wrote. He also polished programming skills he used in his thesis research.

The practicum dispelled "the myth that the (National Nuclear Security Administration) labs are all about weapons and classified work," he wrote in his practicum review. "I saw first-hand how my group balances different demands and contributes significantly to large science collaborations and nonproliferation projects."

MESOPORE ACID TEST ▸

Jennifer Shusterman's 2013 **Livermore** practicum provided a nice addition to her **University of California, Berkeley**, research group's studies of materials designed for advanced separation in the nuclear fuel cycle.

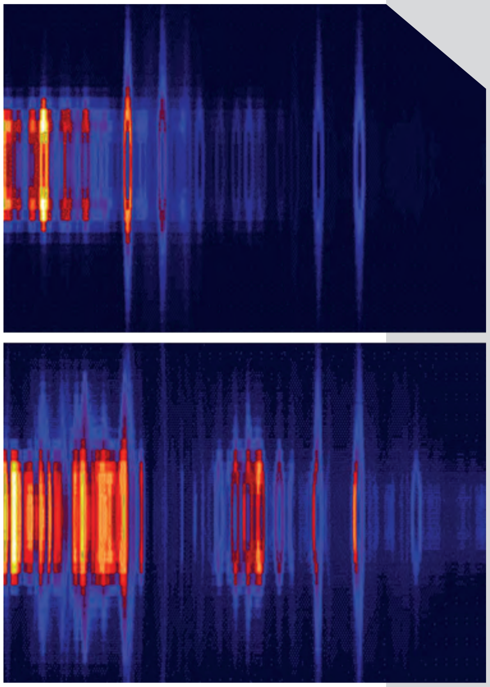
Working with Annie Kersting, director of Livermore's Glenn T. Seaborg Institute, Shusterman studied fundamental properties of functionalized mesoporous silica materials synthesized in the Berkeley research group John Arnold leads. After experimenting with the materials, Shusterman was curious about how stable they would be in acidic environments. She also wanted to see how the materials adsorb metals, especially as a function of ionic radius.

At Livermore, Shusterman learned to use nuclear magnetic resonance (NMR) spectroscopy to perform her experiments. She characterized the materials with solid-state silicon-29 and carbon-13 NMR. She applied various concentrations of nitric acid to them to monitor their degradation and collected new NMR spectra to compare with the pristine sample spectra.

Shusterman found the metal complexation studies especially interesting. She put aluminum(III) or scandium(III) in contact with the functionalized silica material to see how the metals sorbed to its surface. She used aluminum-27 or scandium-45 NMR to probe the metal nuclei and determine the metal coordination numbers and whether they were binding to the silica surface or the ligand. The results could provide insights into the binding mechanism and to improving the materials.

Apart from the data she gathered, Shusterman said in her practicum review that the opportunity to learn a new experimental technique might have been the experience's biggest benefit. "Sometimes it can be difficult to learn an instrument very thoroughly when only using it at a user facility, so this allowed me hands-on experience I could not have gotten otherwise."

– Thomas R. O'Donnell



Predicted brightness of X-rays emitted from an imploding plasma column. The vertical lines represent X-ray wavelengths created by specific transitions in the plasma ions. The lines split at the center (top), where Doppler shifts to the red and blue indicate plasma moving away from and toward the spectrometer at around 500 kilometers per second. Bottom: spectrum where lines from one plasma region can be absorbed and re-emitted in a different region. This redistribution results in a dimming of the red-shifted lines and a profound change in the spectral structure.

Spectral Paradise

When Stephanie Hansen came from Lawrence Livermore National Laboratory to Sandia National Laboratories in 2008 to work near the fabled Z machine, she knew she'd landed in a spectroscopist's paradise. Z routinely fields 10 or more spectrometers on most of roughly 200 annual experiments. "If a picture is worth a thousand words, one spectrum is worth a thousand pictures," she says.

The Z machine creates extreme conditions similar to those produced in a nuclear blast. The powerful energy pulses Z produces enable researchers to safely describe, define and delineate the state of our country's nuclear stockpile.

"In the Z machine," she says, "researchers create plasmas hotter than the sun, and they're now creating highly magnetized plasmas that are producing exciting numbers of fusion neutrons. For me, it's like being a kid in the candy store because I have a model and these experiments produce a lot of data."

Spectra inform physicists "what the plasma is made of, what materials are emitting, how hot and dense they are, and how fast they are moving. It gives you so much information about the detailed state of the plasma that is difficult to get any other way."

It's the kind of data researchers studying high energy density physics treasure, Hansen says.

Hansen won a 2014 Department of Energy Office of Science Early Career Research Program award to collaborate with researchers at Stanford's SLAC National Accelerator Laboratory, who use the most powerful X-ray free-electron laser in the world to create exotic plasmas. She also is on the proposal committee for SLAC's Linac Coherent Light Source (LCLS), with which researchers probe materials in unprecedented conditions.

"That laser is so powerful that it can preferentially ionize – or knock out of the atom – multiple inner-shell electrons, putting atoms in places they've never been studied before," she says.

Z is the world's largest X-ray producer, creating in a few nanoseconds beams more powerful than what the entire United States electrical grid can produce. These X-rays can drive iron samples into solar conditions, where Hansen's Sandia colleague, Jim Bailey, has measured their opacity. In results recently published in *Nature*, Bailey's measurements indicated that iron has a higher opacity than current solar models predict.

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Hansen has her own model, called SCRAM – for Spectroscopic Collisional-Radiative Atomic Model. In the *Nature* paper, Bailey compared his results with Hansen's model. "Those findings are important because opacity plays a key role in solar physics, and none of the models agree with the data," Hansen says. "My model did not have much better or worse agreement with his data than comparisons with any other model, and that's part of why his measurements are so exciting: No opacity model in the world can match it as well as they can match data taken at less extreme conditions. So it presents a challenge to the modeling community, myself included."

Hansen also works with Sandia physicist David Ampleford to design Z machine targets that produce high-energy X-rays from the interaction of fast electrons with materials like silver. And she supports data analysis for Sandia's Magnetized Liner Inertial Fusion (MagLIF) experiments. Performed on Z, these experiments produce neutron yields that benefit both nuclear fusion energy and stockpile stewardship programs.

Hansen's SCRAM code started when Alla Safronova, her advisor at the University of Nevada, Reno (where Hansen earned three degrees, all summa cum laude), encouraged her to write her own computer model. "It turns out that developing a model from the ground up is a really terrific exercise in computational science because you know where all the skeletons are. The code became the backbone of my dissertation and has improved substantially over the years as it has been tested against – and broken by – data from a variety of experiments. "

– Tony Fitzpatrick

Scientific Impact

Inside the 40-mm Impact Test Facility, a heavily instrumented gun – 40 millimeters in diameter – employs compressed helium or explosives like gunpowder to lob projectiles into small plutonium targets at impact velocities of up to 1.7 kilometers per second, all inside a protective steel glove box. At the ends of their brief trips, projectiles made of plastic or metals like aluminum or magnesium can generate pressures from thousands to hundreds of thousands of atmospheres as they smash their targets. After that, a stack of metal plates stops everything cold.

"It's how plutonium performs when the high explosives in a nuclear weapon go off and start shocking (the plutonium)," says William Anderson, a physicist and principal investigator of the Los Alamos National Laboratory test site, which gives researchers previews of plutonium-fueled nuclear blasts' first stages without having to set off real bombs.

The facility allows Anderson and other researchers' instruments to log how plutonium samples ranging from 1 to 1.25 inch in diameter – too scant to go critical – respond to the kind of shock waves bomb triggers could induce. Those data include the pressures and temperatures the material encountered, whether it melted or underwent other phase changes, how the process altered its strength and how it was structurally deformed or damaged as a result.

Measuring plutonium's properties under extreme pressure provides essential ground-truthing for the Stockpile Stewardship Program, under which computer modeling replaces actual weapons testing banned by international agreements.

Although used in bombs since the 1940s, toxic radioactive plutonium is a difficult material to evaluate. It can exist in six different phases before melting and has properties that can alter over time due to radiation-induced aging.

"For most of the nuclear weapons program's history," Anderson says, "the approach was to use fairly crude models for the way plutonium behaves, build something and then see if it worked. There was no scientific program to study how plutonium behaved at the high pressures we're talking about. There were almost no such studies before the 1980s."

His facility, opened in 1996, is located at Los Alamos' plutonium processing center, known as TA-55. Its glove box, where air pressure is reduced so no particles can escape, allows scientists and technicians access via rows of windows and protective gloves along its sides. The center of attention is the 11.5-foot smooth-bore gun barrel stretching along its middle.

In what are called "normal impact" experiments, technicians insert projectiles – lightweight for maximum speed – into the breech and targets into a holder near the barrel's end. Special transparent windows are glued to the targets to ensure that shock waves from the projectile-target collisions aren't reflected from the target surface, says Anderson, a shockwave expert.

Two kinds of electrical pin detectors are mounted around the targets. One measures velocity by shorting out as projectiles pass. Another uses pressure-sensitive piezoelectric crystals to detect projectile tilt. A laser velocity interferometer measures how shock waves interact with targets. Variations on this normal scenario can detect other information. And new instruments are being installed to further enhance these studies.

Meanwhile, the Joint Actinide Shock Physics Experimental Research (JASPER) Facility at the Nevada National Security Site (see "Gassing Up the Big Gun," *Stewardship Science* 2011-12) uses another high-energy shock gun to study plutonium under pressures from hundreds of thousands to millions of atmospheres. Anderson says modelers of advanced weapons simulation codes seek data from both facilities, as well as other sources, to support their work.

– Monte Basgall

Conversation

Materials Are Everywhere

'I always encourage people to ask questions – that's the best way to learn – but also to work across disciplines.'

Kathleen Alexander is assistant deputy administrator for the Office of Research, Development, Test and Evaluation in the National Nuclear Security Administration's Office of Defense Programs. She previously held posts at Los Alamos and Oak Ridge national laboratories.

You're a materials scientist. What about that subject interested you?

When I was in high school in Pittsburgh I was looking at different disciplines to pursue in college, primarily engineering. I had talked to a local (materials science) society, ASM International, and won a college fellowship award from them. When I began studying materials science, I liked the crosscutting nature of the discipline. It touched on physics and engineering and math, and it had broad applications to real-world problems. Look around you – materials are everywhere.

You have a long title. Just what is your job?

I oversee the portfolio in NNSA Defense Programs that has to do with experimental and computational sciences. Our facilities conduct experiments and tests, and we perform analysis and evaluation of those tests for stockpile stewardship. We are the core research, development, test and evaluation program that develops and validates these tools, which often are computer-based models and simulations. We also validate the models that go into these tools and how well the computer simulations perform compared to reality. We have a variety of experimental facilities that validate those simulations in appropriate conditions, which often involve extremes of pressure, temperature, strain rate, etc.

In the future, what will be the main science drivers in certifying the stockpile?

Primarily they're questions related to materials aging, safety and security. The bottom line is we're regularly assuring the safety, security and reliability of the stockpile.

What areas most need new researchers and scientists?

I mentioned materials aging, so obviously materials scientists, but also computational scientists. Distinct from that are computer scientists, in terms of ensuring that the high-performance computing hardware is appropriate for the kinds of codes we need to run. The technology of available computing hardware is evolving. Other key disciplines include high energy density physics, statistics, nuclear physics – it runs the gamut. We cross all disciplines.

Where do programs like the DOE NNSA SSGF fit into this?

They're key to the pipeline of researchers the program requires. These programs encourage developing the next generation of stockpile stewards. We train leaders in areas relevant to stockpile stewardship – high energy density physics, nuclear science, materials in extremes, hydrodynamics – and not necessarily on our problems per se. Fellows also get exposure to our national labs through a 12-week practicum, so they get to see the important work that's done, and they get to visit the NNSA national laboratories.

What's your advice for graduate students who are interested in stewardship science careers?

I always encourage people to ask questions – that's the best way to learn – but also to work across disciplines. Our problems are very crosscutting and learning to work across disciplines is very important. I think that's what also keeps our technical staff honed and fresh.

You're involved in efforts to cut across departments and disciplines. What motivates that?

Some of it is my background in materials science, which crosscuts physics and engineering. Another element is that the nature of challenges we have for stockpile stewardship is cross disciplinary. The cross-disciplinary focus I have stems from both those factors.

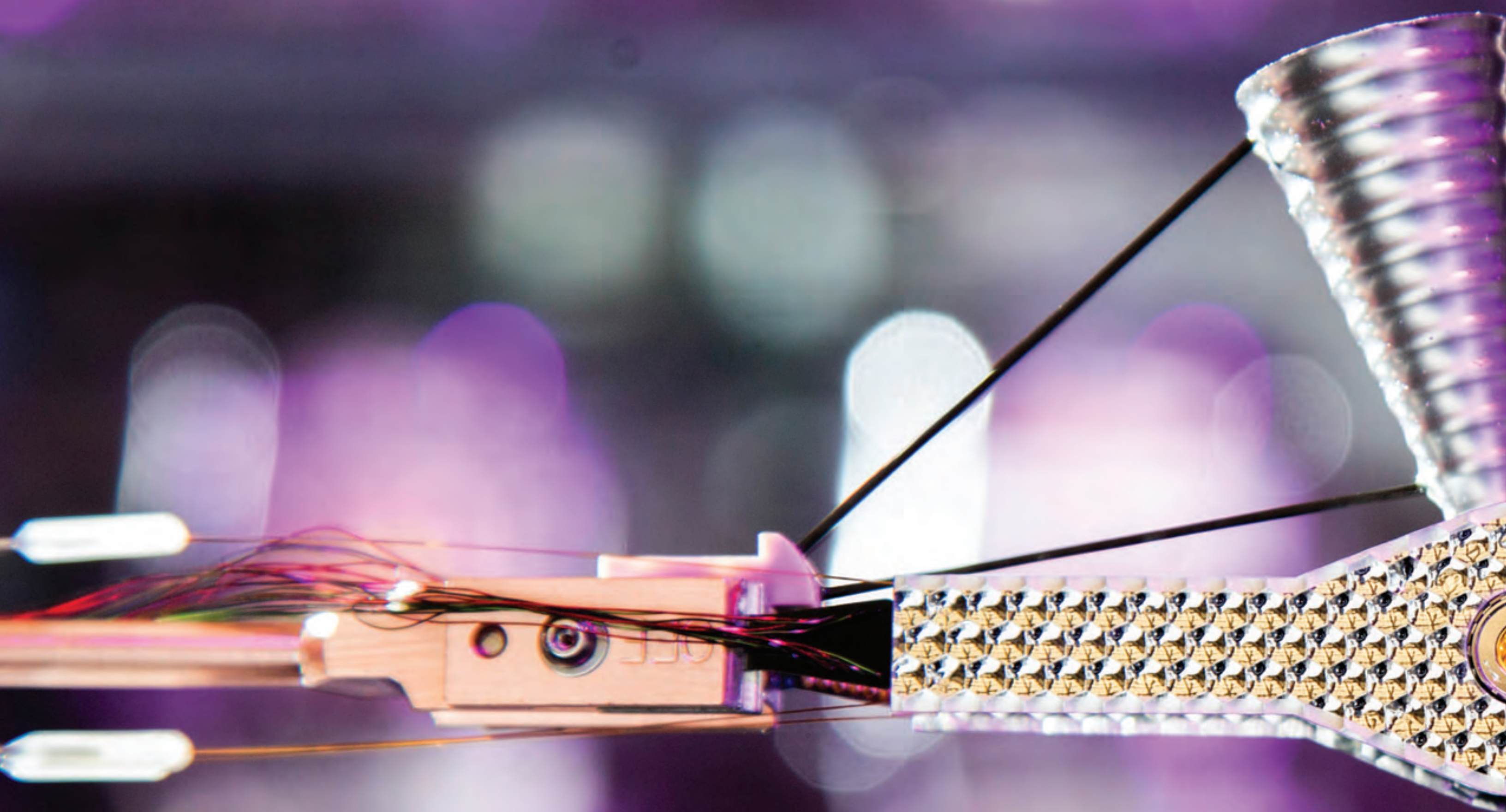
You've also studied the future of national laboratory facilities and infrastructure. What changes do you see ahead for them?

I think a renewed understanding of the role of FFRDCs – federally funded research and development centers. Our national labs are FFRDCs. It's important to the nation that we maintain laboratory capabilities for the long term. I also see more discussions across agencies, especially since budgets are constrained, on how to best utilize the capabilities of all national security laboratories.

You were a lab researcher and manager for 24 years. How do feel about no longer working at a lab or doing research?

Being a laboratory researcher and manager has been my identity for a long time, but I think it's important to have federal staff who understand the labs and understand how they really work. I tell people it takes a village to do the science we do and that involves having scientists in federal positions as well. I spent half of those years in a (DOE) Office of Science lab, so I coordinate on crosscutting programs with them.

COVER STORY



TARGETS OF INTEREST

Implosion targets no bigger than shoelace nibs have come of age, enabling researchers at Livermore and elsewhere to study fusion energy and weapons-related physics with unprecedented precision.

BY JACOB BERKOWITZ

An implosion target assembly up close.

IN THE FALL OF 2014, at a Lawrence Livermore National Laboratory (LLNL) ceremony, Alex Hamza and Abbas Nikroo celebrated a milestone they'd worked decades to achieve: the production of the 10,000th high energy density science target for the Omega Laser Facility at the University of Rochester and the 500th cryogenic target for LLNL's National Ignition Facility (NIF).

Not that either man could hoist a target in triumph like a showboating football player after a touchdown. Most of these implosion targets are about twice the size of a pen nib. Yet these itty-bitty bull's-eyes are a cornerstone of Stockpile Stewardship Program (SSP) science. Zapped by lasers or imploded by high-energy current, high-tech pellets are paving the way to fusion energy on Earth and enabling SSP scientists to simulate crucial weapons-related physics, from materials properties to radiation transport.

At Department of Energy (DOE) National Nuclear Security Administration (NNSA) labs and supported facilities, targets are essential to secondary assessment experiments – those that improve the scientific understanding of how a nuclear weapon's fusion component, called the secondary, performs.

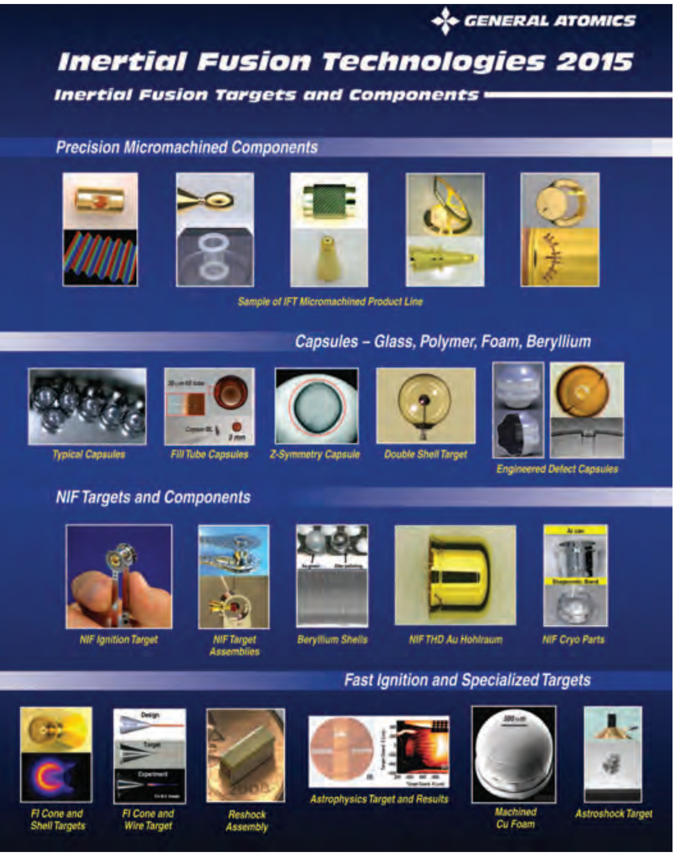
The LLNL ceremony was more than just a production benchmark. It signaled a coming-of-age moment for target design and fabrication. What 20 years ago was a largely artisanal effort has developed into a world-leading nanofabrication system, a highly streamlined, high-throughput, on-demand assembly-line process that, combined, annually produces more than 15,000 components and 1,000 targets for NIF, OMEGA and Sandia National Laboratories' Z machine. (See sidebar, "Building a Target.")

"The capacity we've developed to rapidly produce high-quality targets and to continually respond to feedback and design and engineer new targets is facilitating and driving a broad range of Stewardship science," says Hamza, manager of LLNL's Target Fabrication Group.

Hamza and Nikroo, director of the General Atomics (GA) company's Inertial Confinement Fusion Division, began their target-related careers a few years after the SSP kicked into high gear with the last U.S. underground atomic test in 1992.

General Atomics hired Nikroo in 1991 to help develop a DNA sequencing technology, but in 1994 he joined the company's nascent Target Fabrication Group. Here he worked with and learned from a small pioneering group of DOE/NNSA target fab researchers.

"The first-generation target fabricators told me stories from the 1970s," Nikroo says from his GA office in La Jolla, California. He leads 80 GA materials scientists, precision machinists and mechanical engineers there and at Livermore and other locations. "The glass capsules (the core of a target) were made at 3M and they'd buy a bucket of them, each one several hundred microns in diameter. They'd pour out a thousand shells and then methodically measure each one to find the single good one out of a thousand that met the specifications."



The cover of General Atomics' most recent target catalog.

Over the past two decades, Nikroo and Hamza have helped turn the art of target fabrication into an exacting industry. It's one that today boasts a 67-page GA full-color catalog of target components and capabilities available for scientists to leaf through while contemplating their experiments.

"We've had a focused effort and investment in making the components and then developing a real assembly line at Livermore," Nikroo says "It's really paid off."

You can see just how it's paid off by walking from Hamza's LLNL office to the 3,000-square-foot target-assembly cleanroom in a neighboring building. Here, 15 technicians in full-body suits use customized tooling at more than 40 assembly stations, where target components (mostly manufactured by GA) are inspected, assembled for NIF and tested to produce shot-ready targets.

"It is really cool in there," says Hamza, who joined LLNL in 1990 and the target fab group in 2001. "You're handling things that are millimeter size, with micron features, and they are just fabulous pieces of equipment that you get to put together. There's really a sense of awe in the room."

NO STANDARD TARGET

From the days of the first glass capsule targets, the collaboration now produces more than 100 varieties each year to support SSP science.

Targets come in two broad experimental categories: for high energy density (HED) physics and for fusion. Depending on the application, a target can range from a couple of components to dozens of them.

The HED targets are designed and built to test materials at weapons-related extreme temperatures and pressures.

"When it comes to the HED targets, there really isn't a standard target," Nikroo says. "There are many different types depending on the physics needs."

In many cases, an HED target consists of a micro-slab of precisely machined advanced materials, often with the addition, or doping, of a key element such as titanium that produces a diagnostic light signature to help instruments track the experiment. When lit by a laser, these HED targets provide unique, accurate data about material properties near or at thermonuclear conditions – information that's essential to improving the physics in DOE/NNSA weapon-performance simulation codes.

Whether HED or fusion targets, three aspects of target fab highlight

The clean room, a 3,600-square-foot plant at LLNL where technicians assemble cryogenic targets at a rate of one a day.

Inset: A technician assembles a cryogenic target from parts at the flexible final assembly machine in the clean room.

their diversification: new materials, new components and cryogenics, or deep freezing.

Capsules – millimeter-sized, pingpong-ball-like structures – are at the core of all fusion targets. The capsules are filled with a mix of the hydrogen isotopes deuterium and tritium that is compressed and heated to the temperatures inside a star. If all goes well, a fusion reaction results.

The Omega Laser Facility uses a direct-drive approach in which powerful lasers directly hit and heat 1 mm-diameter capsules.

For Sandia's SSP experiments, GA produces cylinder-shaped capsules imploded by the Z machine's 20-million ampere current.

When Hamza and Nikroo began their target careers in the early 1990s, all capsules were plastic. They were made through a process akin to industrial bubble-making, with little control over capsule dimensions such as diameter or shell thickness.

One of the key target fabrication turning points came when LLNL and GA scientists collaborated in the late 1990s to develop a mold-based process for making plastic capsules, providing much greater size and structural specificity.

Based on this success, GA and LLNL scientists then collaborated in a decade-long effort to develop diamond-shelled and beryllium-shelled capsules.

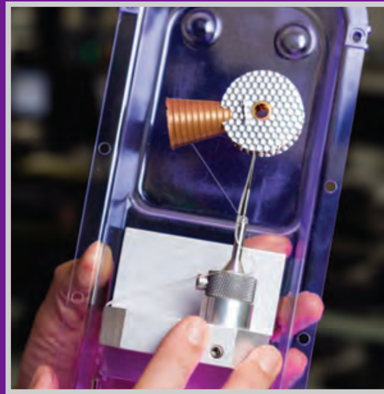
"Now diamond capsules are being shot regularly at NIF," says Hamza, who contributed to their development with scientists from Germany's Fraunhofer Institute.

A similar decade-long effort led to the development of cryogenic targets.

NIF shoots these targets cooled to 20 degrees Kelvin, or about minus 427 degrees Fahrenheit, cold enough for the deuterium-tritium fuel to form a solid layer on the inner side of the target capsule. Like air in a balloon, gas in a capsule pushes back when squeezed. This helps the solid fuel compress quickly and evenly, a characteristic considered essential for triggering fusion reactions.

These cryogenic NIF targets also involve a hohlraum, a multilayered can made of gold and depleted uranium in which the capsule is suspended. (The layer of gold, a few hundred nanometers thick, keeps the uranium from oxidizing, or rusting.) NIF's lasers hit the hohlraum, producing an X-ray burst that compresses the capsule, a technique termed indirect drive.

In 2005, the LLNL-GA partnership was able to manufacture just a few cryogenic indirect-drive targets a year. "Now we're making about five a week," Hamza says. About 200 are shot at NIF each year, providing SSP scientists with access to extreme temperatures and pressures.



Lawrence Livermore National Laboratory's Alex Hamza holds an assembled target.

Much of the remarkable progress in fabrication is due to development of the Thermo-Mechanical Package (TMP), a two-part, dual-egg-cup-like device that combines super-refrigeration with plug-and-play ease. The TMP was designed by LLNL's fab team, with components prototyped and now manufactured by GA's fab group.

"With the TMP, the connection between the hohlraum and the cooling unit, the cryostat, became much more systematic," Nikroo says, "and now this tremendously simplifies the assembly."

The TMP also greatly simplifies a process called "fielding" – mounting the target at NIF. "It lets you plug-and-play the hohlraum and the capsule because it assures the necessary alignments," Nikroo says.

Jacob Berkowitz is a science writer and, most recently, author of The Stardust Revolution: The New Story of Our Origin in the Stars *(Prometheus Books, 2012).*

BUILDING A TARGET

NEXT-GENERATION TARGET components require new nanofabrication production processes, many of which are at the leading edge of their respective technologies.

Technologists approach each new fabrication challenge by figuring out whether there's an existing method, tool or product they can use, or if it's "something that no one has done before and we need to develop," says Abbas Nikroo, director of the Inertial Confinement Fusion Division at General Atomics (GA).

In some cases, there's been remarkable cross-fertilization between disparate scientific disciplines.

For example, Nikroo's GA colleagues discovered they could use a micro-pipette, a tool used to dispense very precise amounts of biological samples, to deliver the five picoliters of glue needed to stick the fueling tube into a target capsule.

And the fueling tubes themselves?

"The tubes were originally developed for in-vitro fertilization," Nikroo says. "The company customizes the diameter and taper for us, and we just buy the tubes from them."

Other nanofabrication processes have required *de novo* approaches. A case in point: Many of the SSP-related HED experiments require slabs of customized materials just 10 microns thick.

"If you had this tiny slab free standing you couldn't pick it up," says Alex Hamza, manager of the Target Fabrication Group at Lawrence Livermore National Laboratory. "You couldn't handle it. Over the past decade, our machinists have developed techniques that enable us to handle, measure and machine these low-density nanomaterials and shape them into shapes the physics crowd has asked for."

Similarly, the LLNL fabrication team, along with GA, has developed a proprietary nano-polishing technique for the plastic target capsules.

"We're going to implode this thing by a factor of 40, from two millimeters to 10 microns in diameter," Hamza explains. "Any imperfection grows by a factor of a thousand."

The polishing technique produces a capsule with an almost perfectly even surface, one with a smoothness tolerance of one 100,000th the thickness of a human hair.

At both LLNL and GA, each component is thoroughly measured during and after fabrication.

"Half our work is measuring what we did," Hamza says. "The physics crowd needs to know exactly what they shot, so the precision to which we measure things is even more daunting than the precision to which we make them." The fab team's tools include X-ray imaging of overall features, atomic-force microscopy to measure surface features, and laser-ranging.

In the past decade, robots also have joined the target fab teams, increasing productivity and precision.

At GA, a technician used to manually measure eight capsules during each eight-hour work shift. Now a robot measures 100 every 24 hours.

At LLNL, a robot now performs the amazingly persnickety jobs of attaching a polymer membrane called "the tent" to a gold and depleted-uranium hohlraum and cutting off the excess membrane. The tent is the support structure which holds the capsule in place inside of the hohlraum. "This attaching is a hard step for the technicians to do," Hamza says, because the tent is about 10 nanometers thick. "That's only about 40 atoms," or "a hundred- to a thousand-times thinner than Saran Wrap. You can't even see it. We get a high-quality attachment from the robot."

AN ITERATIVE PROCESS

After two decades finessing target fabrication, Nikroo recalls one of the first questions he asked when he joined the group: Why not develop a warehouse of off-the-shelf components?

"We can't make them off-the-shelf because the design changes so often," he says. "And the design changes because this is an experimental program. They do the experiment, they shoot the target, they analyze it and then they say, 'We need to change these things.' Most of what we do in target development is driven by data collection and diagnostics. The experiment matures and the target matures with it."

At the LLNL fabrication clean room, Hamza concurs.

"When I'm in there I feel like a factory manager," he says. "But when you're outside you realize that these are research targets you're making."

That distinction captures the essence of today's target fabrication: a continually iterative process within a production context.

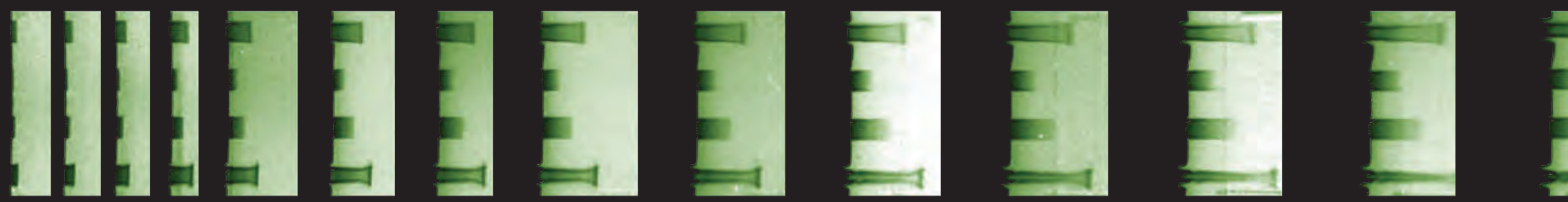
Hamza and Nikroo are now thinking about how to respond to the needs of SSP researchers over the next five to 10 years, the topic of a summer 2015 target fabrication meeting in Las Vegas.

Hamza's near- and long-term objectives include issues from developing targets that are boosted within a magnetic field and capsules of new materials, including boron, to new foams required to study weapons physics and ways to boost the now 80 percent energy coupling achieved with the gold-depleted uranium hohlraums.

Another, Hamza says, is developing what's been called nano-Velcro: "figuring out ways to make layered and multicomponent structures without gluing them, because the physicists want to be studying the material, not the glue." SS

A SHOCK TO THE SYSTEM

Using devices powerful as hand grenades, Los Alamos researchers track the path of ejecta – matter thrown off a shocked surface.



BY THOMAS R. O'DONNELL

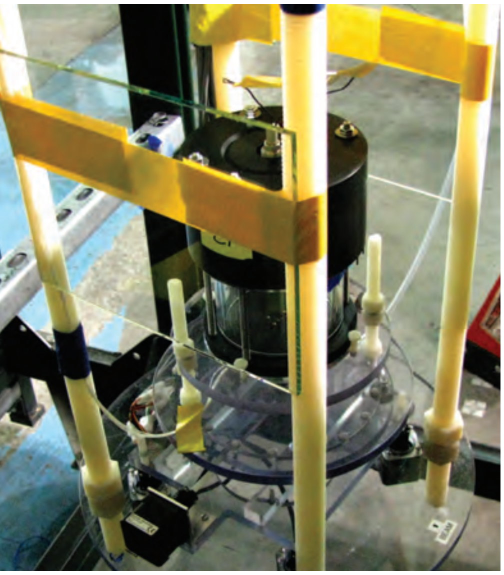
As a youth, William Buttler engaged in the kind of mostly harmless experimentation curious boys have tried for centuries. He blew up stuff. Toy airplanes and toy soldiers on miniature battlefields, usually with firecrackers. When he was a little older, it was milk cartons filled with oxygen and acetylene, tossed in large pipes and ignited by dripping molten metal onto the cartons.

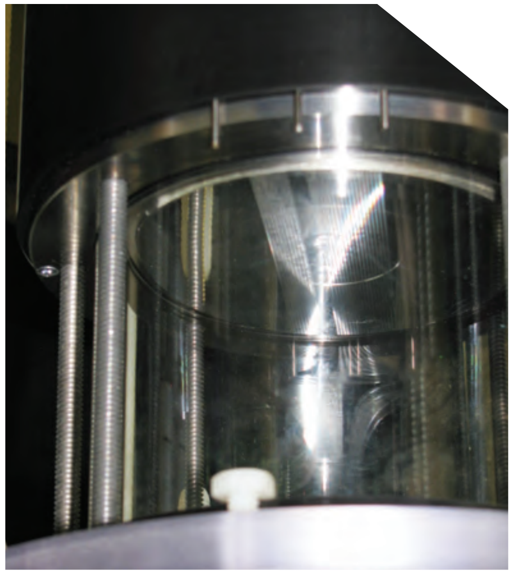
Now Buttler designs small bombs and blows them up for a living at Los Alamos National Laboratory (LANL) – albeit with scientific rigor. "And it is a lot of fun," he says.

There's still a let's-see-what-happens element to Buttler's blasts, but it's highly focused. He and his colleagues want to understand how materials fail under extreme conditions. Their current target is ejecta: the mass that flies from a surface when a shock hits.

It's important work at LANL, where Buttler is a scientist in the lab's Physics Division. A Los Almos research priority is stockpile stewardship – maintaining the nation's nuclear deterrent and ensuring its safety and security. Since the United States ceased nuclear weapons testing in the 1990s, scientists have relied on related experiments and complex computer simulations to help understand the materials and processes involved in such devices. "We would like to predict all the phenomena you might see occurring from start to finish," Buttler says, from explosion to shocked metal and ejecta.

Buttler's ejecta research is helping improve hydrodynamics codes in predictive computer models LANL researchers developed more than a decade ago and have been tweaking ever since. Such codes simulate what happens under the extreme conditions found in exploding weapons, inside giant planets or stars, and in other conditions.





Left: The assembled explosive ejecta experiment is shown in place. It's suspended on a stage that tilts, tips and rotates for precise alignment with the proton radiography beam. Glass on each side carries explosive energy away to minimize beam line damage.

Right: This view of the assembled ejecta experiment shows the tin target, including the lines of machined perturbations on its surface.

Scientists like Buttler have only recently developed experiments and diagnostic instruments that can generate data accurate enough to confidently develop and validate ejecta models.

The diagnostics include penetrating proton radiography, or pRad. At the lab's Los Alamos Neutron Science Center (LANSCE), a powerful accelerator generates a proton beam that captures images, similar to X-ray scans, of the ejecta experiments. Researchers can take as many as 20 high-resolution pRad images of evolving ejecta at intervals measured in millionths of a second. (For more on LANSCE and proton radiography, see "Molten Pictures" in *Stewardship Science* 2014-15.)

Before Buttler and his colleagues started their experiments, ejecta modeling was poor, says Malcolm Andrews, LANL national security fellow and, until recently, project lead for physics and engineering models. Other ejecta models were prescriptive – fitted to experimental data. That means they may work poorly when encountering conditions the data don't account for.

The LANL research could have applications in other fields, including modeling surface damage and fuel injection. Buttler says he's had interest from researchers in inertial confinement fusion, which seeks to squeeze capsules of hydrogen isotopes under such great temperature and pressure that the nuclei fuse, releasing great energy.

But getting there has been challenging. Buttler has worked on his explosive ejecta experiments for more than 10 years – including eight on a device to capture the effects of a second shock.

The difficulty: The process is intricate, Andrews says. "You are dealing with powerful shocks and the way in which they interact with surfaces. It's not something you can just look at." Things happen even faster than reactions in a car's engine, and "you have a lot of complicated processes taking place, all of which interact and interfere with one another."

EJECTA FROM THE SOURCE

Ejecta evolve through at least three phases: source, when a shock removes mass from a surface it passes through; transport, when the shocked mass moves through the surrounding atmosphere; and conversion, in which the shocked mass changes, either through recollection at the surface or some other means like evaporation.

Buttler and his colleagues focus on source since transport and conversion are considered less important. Their experiments systematically control and tweak one parameter at a time, building data to establish a mathematical model.

Ejecta researchers' favorite test material is tin. It has a stable, solid crystal configuration at room temperature,

Senior Science Editor Thomas R. O'Donnell has written extensively about research at the DOE national laboratories.

but under pressure changes to another, higher-density solid phase. Under exceptionally high pressures, tin also can change directly to a liquid. And tin can transform to a mixed solid-liquid phase or return to its original solid phase after pressure from a powerful shock passes and the material returns to ambient pressure, usually zero. Researchers know the approximate pressures at which these transitions occur and adjust experimental shocks to create the phase they want.

The experimental tool Buttler and other researchers developed packs two kinds of explosives into a conical container of stiff acetal plastic. When detonated, the cone-shaped explosives, about 3 inches in diameter at the wide end, deliver shocks at pressures in the billions of Pascals (GPa) – hundreds of thousands of times the pressure of Earth's atmosphere. The researchers can tweak the explosives to control the shock's strength.

At the cone's narrow end is a detonator. At the other end is a disc-shaped target, usually tin or copper, a few millimeters thick and glued to a buffer – a thin layer of material like titanium. Experiments typically take place in a vacuum to minimize an outside medium's influence on ejecta production.

Besides the shock's power, the researchers adjust another key factor: the shape of the target's back side – the surface facing away from the explosives. Early research found ejecta originate from imperfections on the shocked surface. Even exteriors that appear perfectly smooth, like metal casings, can have tiny imperfections – or damage like scratches and dings – that provide the seed for ejecta. To understand these defects' influence, researchers etch the targets with tiny perturbations: wave-shaped corrugations only a few millionths of a meter across. The researchers vary the troughs' widths (wavelengths) and heights (amplitudes) to see how those factors affect ejecta production.

THREE, TWO, ONE, BOOM

TYPICAL LABORATORIES can't handle the experiments William Buttler and his Los Alamos National Laboratory (LANL) colleagues often conduct.

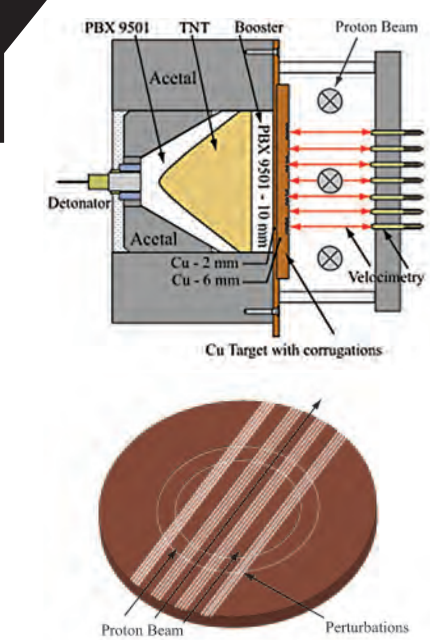
Each device they build carries at least as much explosive as a hand grenade, requiring containment facilities like Chamber 8 in LANL's Weapons Experiments Division: a piece of a submarine's hull.

Other experiments happen in a spherical chamber at the Los Alamos Neutron Science Center (LANSCE). There the researchers use a powerful proton beam to get images of fast-moving ejecta sprays. Some tests also have taken place at a California facility operated by National Security Technologies, a private firm.

The experiments are fairly simple. "We'll typically have three to four people involved," Buttler says. "We just build the (explosive) package, set it up and blow it up." The team uses a pre-detonation checklist to ensure diagnostics are hooked up, instruments are ready to gather data, and people are safe.

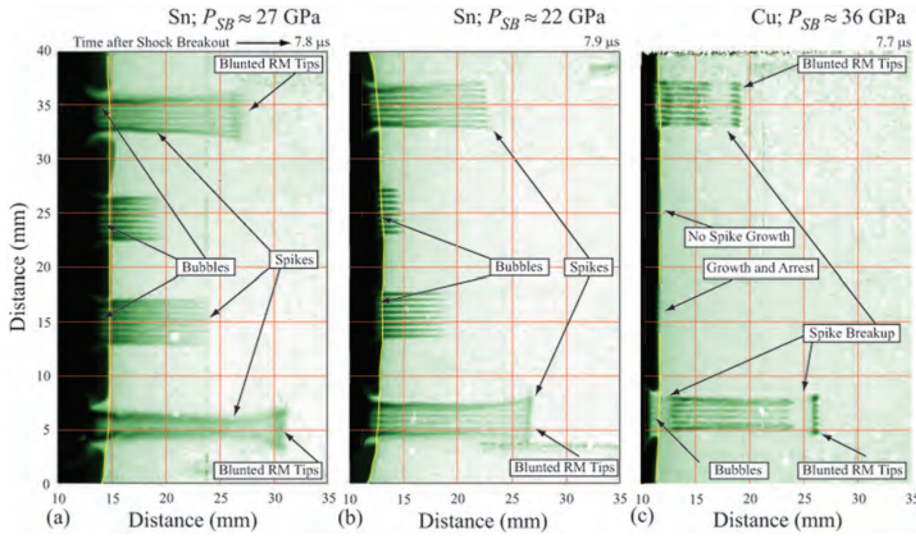
"Once everyone says 'Yeah, we're ready,' the firing site will say 'Three, two one,' boom." The researchers are either in an adjacent room or, at LANSCE, farther away in an area shielded from radiation. "But yeah, you can hear it. It's a fairly impressive explosion."

When it's done, Buttler says, "there's nothing left." Pumps evacuate toxic gases from the chambers. "Then you go in there with a shovel or a broom and you pick up the rest of it."



Top: This shows a typical single-shock ejecta experiment setup at Los Alamos National Laboratory's LANSCE proton radiography facility. A conical acetal plastic container holds a charge of explosive used to detonate a booster in contact with a buffer plate. A target of tin or (in this case) copper (Cu) is mounted on the buffer. Targets are machined with bands of wave-like perturbations, as at bottom, that provide the seeds for ejecta formation. When detonated, the explosives produce a tremendous shock that generates ejecta from the target surface. Probes to measure ejecta velocity during the shock are positioned over the target. The pRad proton beam is aligned into the page, parallel to the perturbations. *Based on* J. Fluid Mech., *(2012), vol. 703, pp 60-84.*

These penetrating proton radiography (pRad) images show ejecta microseconds after an explosively driven shockwave has passed through targets of tin (Sn, left and center) and copper (Cu, right). The shock pressure at breakout (P_{SB}), measured in billions of Pascals (GPa) is above each image. The time after shock breakout when the images were captured also is above each in microseconds (s). Each target had four regions of machined perturbations of varying wavelength and amplitude. The images show the effect of wavelength and amplitude on ejecta generation. *Based on* J. Fluid Mech., *(2012), vol. 703, pp 60-84.*



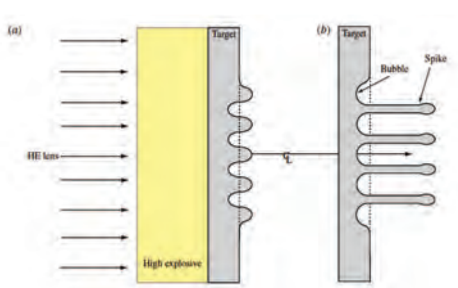
The detonating explosives create a flat, fast-moving shockwave that first hits the valleys – the minima – machined into the target. What happens is characteristic of Richtmyer-Meshkov instabilities (RMIs), which occur when an interface between two materials of different densities is accelerated, usually by a shock: The minima invert, becoming long spikes of mass stretching out from the surface.

By the time the shock hits the troughs' peaks – the maxima – the spikes have already stretched past them, becoming thin and distended. The maxima sink into the surface, forming divot-like bubbles that feed mass into the spikes. Eventually most of the spikes separate from the surface, spewing mass into the surrounding medium.

Data, including pRad images, from such experiments indicate that the key factor governing ejecta RMI physics is the mathematical relationship between the perturbation's wavelength and amplitude, expressed as *kh*. Ejecta are likely to contain more mass when *kh* is high than when it's low, researchers found.

To grasp how that works, it might help to think of the opposite situation: when a surface is smooth. In that case, "you have a very long wavelength and a very small amplitude," Buttler says, so the product of the two – kh – also is tiny. Even if the surface produces ejecta, "it's not much and it's running just ahead of the surface" as the shock hits.

Inertial confinement fusion researchers have contacted Buttler since he and his LANL colleagues published their RMI-fueled ejecta studies in the *Journal of Fluid Mechanics* in 2012. The fusion scientists want to predict and control ejecta in imploding fuel capsules, Buttler says. "Their question was 'How do I suppress ejecta?' because ejecta in the context of fusion tends to not be a good thing."



This shows a cross-section of the pre-shocked *(a)* and post-shocked *(b)* shapes of the target surface in an ejecta modeling experiment. The pre-shocked target surface includes trough-like perturbations that become sites for ejecta formation. Detonation of a high explosive (HE) drives a shockwave through the target. As the shockwave passes, the perturbations invert. Spikes form and grow and bubbles sink into the surface, feeding mass into the spikes. *Based on* J. Fluid Mech., *(2012), vol. 703, pp 60-84.*

What emerged from the explosive experiments, Buttler says, was a coherent picture of ejecta source, leading to a reliable mathematical model to predict it. That model of first-shock ejecta source now is in LANL hydrodynamics codes.

SHOCK TIMES TWO ▸

However, real-world situations are rarely as straightforward as a single shock moving through a material. In reality, "there are shocks rattling around in most explosive systems," Buttler says, and those reflected shocks affect ejecta. Besides predicting how much additional mass a second shock generates, researchers want to know its impact on the first-shock mass already flying away from the surface.

But a second shock's effects are tougher to predict than a first shock's – mostly because the first shock has drastically changed the target surface. "The tin has been damaged; it's distended; it's not at full density any more," Buttler says. A second shock recompresses that and moves on to influence the perturbations "in whatever state they're in after the first shock." Diagnostics have difficulty capturing what's happening in this fast, chaotic environment.

The LANL researchers think their first-shock model can predict the surface's shape after the initial shock, but the technique is imperfect, Buttler says. And to predict a second shock's effects, they must know the *kh* – the wavelength-amplitude relationship – of perturbations at the time it hits. To get at that, Buttler and his colleagues had to devise an effective second-shock experiment – a project that took eight years.

They first tried using a high-powered gas gun to fire a flyer plate at the target with tremendous force. But the researchers discovered that ejecta production is different with those methods than with explosives, and explosives were the chief concern.

The next problem was finding the right explosive technology to produce both a first and second shock. The researchers first considered launching a flyer plate that would detonate the explosive and then reflect the shock to create a second shock. Computer simulations suggested that would fail.

"It took a little bit of creativity to get where we wanted to go," Buttler says. The first idea came from Russell Olson, a LANL scientist who has since left the project. To create a second shock, the researchers chose to use a 2 mm thick anvil of tantalum, a strong metal used in high-temperature applications. Olson suggested putting explosives in contact with the anvil. In this setup, the anvil covers the wide end of the cone-shaped charge. Just beyond the anvil is a thin disc of booster explosive and just beyond that the buffer and target. The shock from the main explosive passes from the anvil to ignite the booster layer, which sends a first shockwave into the target. Part of the wave also reflects off the titanium buffer and back to the anvil. That shock bounces off the anvil and hits the target as a second shock.

Next the team had to find the best explosive for the thin booster sandwiched between the anvil and the target buffer. The booster had to deliver just the right initial shock – one below 18 to 19 GPa. Below that point, tin is solid when it releases to low pressure after the shock. One explosive the group tested, PBX 9501, was too powerful for tin. Another, PBX 9502, wouldn't detonate when the main explosive shock passed from the anvil into the booster. "So the second innovation was a composite booster, where I used a thin layer of 9501 followed by TNT or calcitol," another explosive, Buttler says.

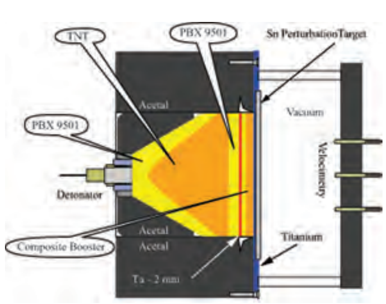
In a 2014 *Journal of Applied Physics* paper, Buttler and his colleagues describe three experiments using the two-shock tool. By using a different combination of booster explosives, they produced initial shocks of 18.5, 24.5 and 26.4 GPa. Under the two more powerful shocks, tin releases to a mix of solid and liquid. Calculations from diagnostics, meanwhile, estimated the strengths of the reflected second shocks at 5 to 10 GPa.

In devising their second-shock mathematical model, the researchers hypothesized that the first shock changes the corrugated perturbations' amplitudes but not their wavelengths. Wavelength, they postulated, remains the dominant factor in calculating the second shock's impact on ejecta. Knowing the wavelength part of *kh* would allow them to predict the perturbations' amplitude at the time the second shock hits.

The three explosive tests with Buttler's two-shock tool supported that hypothesis. "We got agreement between the predicted amplitude and the observed amplitude," Buttler says. That means the same mathematical model used to predict a first shock's effects on ejecta source also can be used to predict a second shock's effects.

Buttler and Andrews believe it's the first ejecta source model based on physics, rather than data-fitting. So far, however, it's only been tested on corrugated imperfections. Real surfaces usually don't follow that pattern, Buttler says; flaws may be irregular scratches, dents or divots.

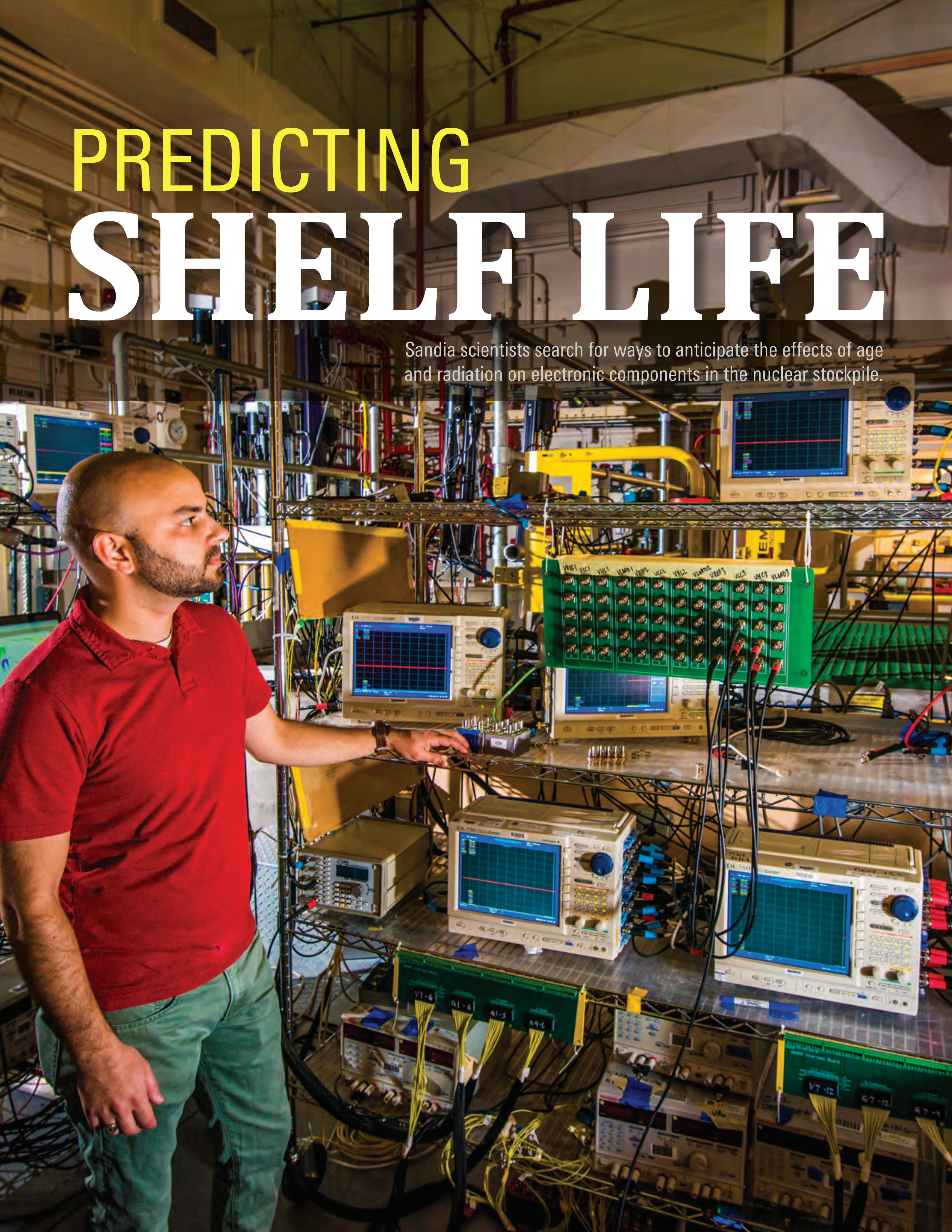
"We'll look at those to see if our model is generalized to different shapes," he says. He's also planning to study the transport and conversion ejecta phases. They're the next frontiers for Buttler's calculations – and his explosive experiments.

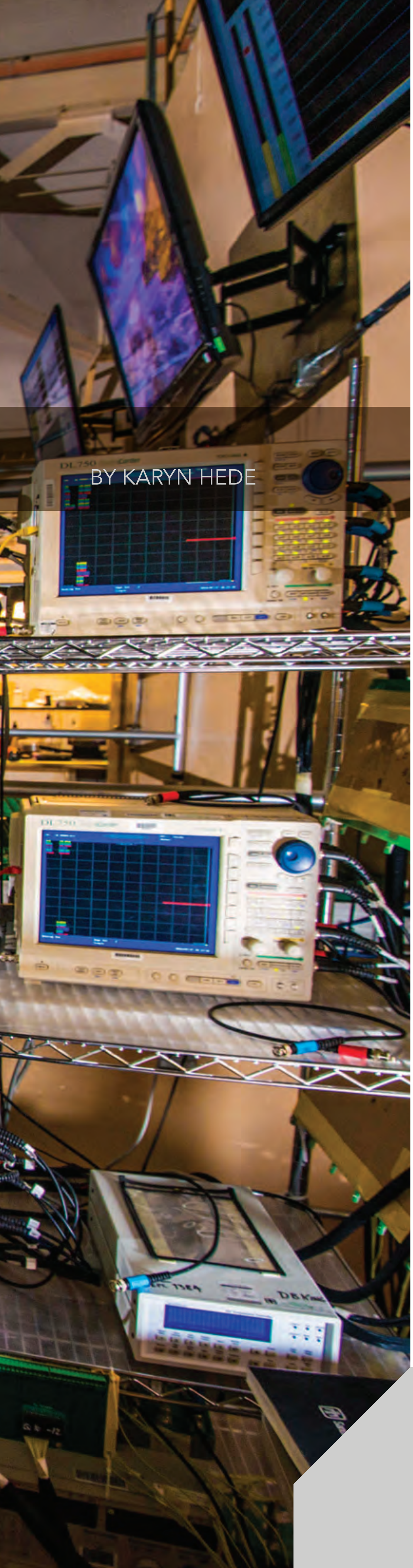


This shows the configuration of a two-shockwave experiment. The main charge is composed of TNT (orange) and PBX 9501 (yellow) encased in acetal plastic (dark gray). A tantalum anvil, in red, separates the main charge from a composite booster of PBX 9501 and TNT. The tin target (light gray) is mounted on a titanium buffer (blue). The tin is engraved with perturbations. *Based on W. T. Buttler et al.,* J. Phys.: Conf. Ser. *500, 112014 (2014) and W. T. Buttler et al, J. Appl. Phys.,* ***116****, 103519 (2014).*

PREDICTING SHELF LIFE

Sandia scientists search for ways to anticipate the effects of age and radiation on electronic components in the nuclear stockpile.





BY KARYN HEDE

Should an integrated circuit in your cell phone fail, you'd be inconvenienced. Should an electronic component in a nuclear warhead break down, the situation would be dire. Yet the circuits in cell phones and those in modernized nuclear warheads rely on the same basic technology. And unlike a cell phone, the electronic components in weapons are stored for long periods and sometimes exposed to low-level radiation. Under such extreme conditions, it's crucial to ensure nuclear components work if needed.

Scientists and engineers at Sandia National Laboratories, as part of their mission to preserve the nation's nuclear stockpile without underground testing, must ensure that every part of the weapons systems will operate properly. That's a high bar, and it includes tests and computer modeling that allow the nation to be confident that the parts going into weapons systems can handle the job.

Sandia's Electrical Sciences Group contributes knowledge that modern electronic parts placed in weapons systems will work as expected over their anticipated 30-year lifetimes. The fact that refurbishment includes combining new technology with Cold War-era technology complicates the task.

For more than a decade, the U.S. government has purchased electronic components from commercial vendors for military applications. These commercial off-the-shelf parts, or COTS, must meet all requirements for their designed applications. But in nuclear applications, COTS are combined with parts manufactured in Sandia's Microsystems & Engineering Science Applications (MESA) lab, which produces specialized radiation-resistant parts.

Sandia has embarked on a long-term project that combines environmental testing and computational modeling to predict performance of components as they age, "studying how aging and processing affect a material's microstructure and, in turn, how microstructure affects the material's bulk properties," says Steve Wix, manager of Sandia's Component Systems and Analysis department. "These are some of the fundamental building blocks of electronics. The devices, such as transistors, we are testing are used in components throughout the military and beyond."

Components are placed in precisely controlled environmental test chambers that mimic portions of typical operating conditions. Periodically, the group subjects a subset of the parts to more harsh conditions in a simulated radiation environment and analyzes the data for performance changes. "It doesn't take disassembly of a weapons system to understand the phenomenon," Wix says.

Sandia National Laboratories researcher Billy Martin looks over diagnostics that are part of the Qualification Alternative to Sandia Pulsed Reactor program. QASPR combines computer modeling and simulation, experiments and technology development for nuclear stockpile surveillance.

One particular area of interest is aging effects due to long-term storage in low-level radiation fields, he says. “Charge can actually be retained in a device due to radiation effects. This can cause threshold voltage shift, which means that some transistors may turn on sooner, some may turn on later.” The researchers now have a model that provides insights into the specific transistors they work with.

'The technology is continually changing in these devices.'

Most effects observed in testing can be fed into computational models that simulate a complete electrical circuit. This National Nuclear Security Administration-funded electrical circuit modeling capability, called Xyce Parallel Electronic Simulator, runs large-scale simulations to predict circuit performance in harsh environments. “These transistor models can be used within Xyce for specialized circuit simulations,” Wix says.

The group is now eight years into the 30-year project and has laid the foundation for making predictions about component aging, Wix says. Applications for the group’s research extend beyond nuclear to other extreme environments, such as deep space. For instance, NASA ordered parts for its Jupiter and Saturn probes from Sandia’s MESA lab because the lab could assure NASA its electronics are resistant to radiation such as X-rays found in deep space.

“Electrical simulation is still a young field,” Wix says. “There is a lot of area for growth. Plus the technology is continually changing in these devices. We are putting more semiconductor physics into our models to really understand these radiation effects.”

WHEN CHANGE COMES FAST ▸

The flip side of slow aging seen in transistors in storage is the threat that comes from exposure to extreme radiation produced by a nearby nuclear explosion either during deployment, an accident or a sabotage attempt.

In any of these scenarios, weapon components can be exposed to so-called fast neutrons produced by a nuclear reaction. In the past, Sandia used its on-site pulsed reactor to test radiation exposure, but when that was closed because of 9/11 security concerns, a new science-based project took its place: the Qualification Alternative to Sandia Pulsed Reactor (QASPR) project.

QASPR tests radiation-hardened microelectronics for high-voltage transistors used in weapons systems but without fast high-intensity neutron bombardment testing. The project relies on a combination of computational modeling and experimental testing, including the use of an ion beam, which creates damage similar to what would be expected in neutron radiation exposure.

QASPR manager Len Lorence says his team has devised the capability to explore a circuit’s “response under neutron radiation and to identify individual transistors that cause problems. Then we can reach back and look at what is happening on the material level inside the transistor.”

That inward glimpse is important, Lorence says, “because it allows you to make models that are more predictive, models that can predict things we didn’t anticipate. That’s where the true power of the models begins to happen. We begin to see things, to predict, and then to go ask our experimentalists to go verify that.”

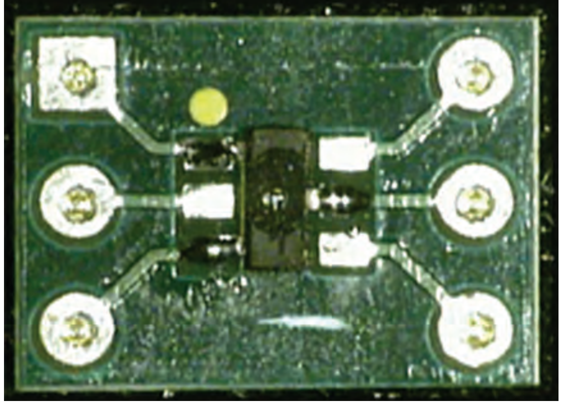
PERFECTING PREDICTIONS ▸

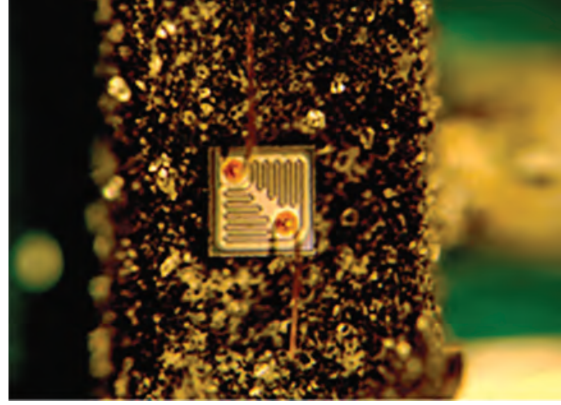
Semiconductor materials form stable lattices with the same basic cube structure as diamond. Of these materials, the alloy gallium arsenide has gained favor with electrical engineers for its stability and conducting properties. Electrons move freely among the atoms of its lattice; supplied with energy, this arrangement confers superior conducting properties. But no structure is perfect, and it’s the imperfections that garner the attention of Sandia engineers.

The environment in a nuclear explosion becomes saturated with fast neutrons that can enter the semiconductor material. This radiation can knock individual semiconductor atoms out of place, creating a vacancy. The effect of missing atoms ripples through the lattice, creating defects. In turn, these defects could alter components’ electronic characteristics.

Karyn Hede is a freelance journalist whose work has appeared in Science, Scientific American, New Scientist, Technology Review *and elsewhere.*

Near right: An exposed transistor die from a commercial off-the-shelf device, used to study the effects of radiation on nuclear stockpile components. Far right: Zoomed-in view of the exposed transistor that enables researchers to assay damage.





Countering these effects, which happen on the scale of microseconds to seconds, is critical to designing systems that can withstand nearby nuclear insults, including an adversary's nuclear-tipped anti-ballistic missile.

"The models help us understand the energy of activation you need to create certain kinds of defects," Lorence says. "They help us understand how defects change over time. That's important because we know that over time the lattice will anneal back to its original arrangement. We need to understand how quickly it does that under various conditions of temperature and operating current."

Sandia physicists are using density functional theory (DFT), which applies a quantum mechanical understanding of molecular systems to materials science, to model the defect properties in QASPR projects.

"We've advanced density functional theory to tackle materials that have complex arrangements of many elements in an alloy," Lorence says. "To do that we had to increase the number of atoms that we simulate."

DEFT USE OF DFT

Peter Schultz of the Multiscale Science Group recently used DFT to resolve previously unexplained experimental data on the structure of displaced atoms in irradiated gallium arsenide semiconductors. The work used a new method to calculate accurate defect energy levels to show that an arsenic atom replaces a gallium atom in the crystal lattice and forms a voltage pair, a phenomenon not previously thought possible.

Much of the previous theoretical work focused on modeling silicon semiconductors and comparing them to newer gallium arsenide devices. The new work, published January 2015 in the *Journal of Physics: Condensed Matter*, showed that the assumptions made from extrapolating results in silicon to gallium arsenide have not held up and must be reexamined.

These new models evaluate performance under conditions that would be difficult to replicate via experiment. RAMSES – the Radiation Analysis Modeling and Simulation of Electrical Systems computational simulation program – models a combination of radiation, electrical and electromagnetic effects. Using this system, modelers are approaching the ability to predict how weapon systems and components would react if exposed to extreme radiation environments or natural disaster, including lightning strikes. These large-scale calculations run on Cielo, a 1.37-petaflops supercomputer run by Sandia and Los Alamos national laboratories as part of the NNSA Advanced Computing at Extreme Scale (ACES) partnership.

On the experimental side, Robert Fleming, a principal researcher in semiconductor material and device sciences, worked with colleagues to conduct tests using deep-level transient spectroscopy at the Little Mountain Test Facility linear accelerator in Ogden, Utah. The results provided data on radiation-damaged semiconductors over a range of temperature and electric field conditions. The researchers then used this data to inform their computational model and enable future predictions. They found their experimental results and theoretical framework agreed, providing a foundation for predictive modeling. The team reported its findings in the *Journal of Applied Physics* in 2014.

Lorence says "we are looking toward predicting – not simply monitoring – any identified age-induced changes in materials through the use of models. There is no way to test every part in every device. Modeling can help us be ready for the next wave of advanced electronics."

"Electronic technologies never stay static," he adds. "Whenever we replace electronics, we are going to be introducing new types of technology. We've put together the technology that cannot only respond to the electronics of today but also of tomorrow, so that 20 or 40 years from now, when new electronics are introduced, we have the infrastructure in place and we will be ready." SS

Remembering Heino

BY JENNIFER SHUSTERMAN

It was a quiet Sunday afternoon and I was working alone in my office at Lawrence Berkeley National Laboratory. Suddenly, my advisor, Heino Nitsche, jumped out from the adjacent office and yelled, "Boo!"

I, of course, nearly fell out of my chair. Heino turned to the visiting scientist he was showing around the lab and boasted, "I told you she would be here and that would work!"

Heino was delighted with himself – he had been trying for ages to prank me. Then he sat down, said he was glad I was working on the weekend but that I should be having fun instead and to go home.

This is precisely the type of person Heino was: He enjoyed science, but he also loved life and doing things outside of work. As leader of the Heavy Element Nuclear and Radiochemistry Group at Berkeley Lab and a chemistry professor at the University of California, Berkeley, Heino always tried to instill this in his students. He wanted us to be more than just good scientists; he wanted us to be good, well-rounded people.

Heino's research encompassed a range of nuclear and radiochemistry topics but focused on two main areas: the production and chemistry of the heaviest elements, and chemistry of the actinide elements. His work earned him the 2014 Hevesy Medal. Shortly before his passing, Heino also learned he would receive the 2015 Glenn T. Seaborg Award in Nuclear Chemistry.

Though Heino took great pride in his research, he often seemed even more proud of the success of students he taught and mentored. In the UC Berkeley College of Chemistry, he taught Chem 1A, a general course for non-majors, and Chem 146, the introductory nuclear and radiochemistry class. He had a passion for teaching and loved interacting with students. Chem 1A office hours would find undergraduate students (looking oddly chipper for people consulting a professor) overflowing into the hallway. When the Chem 146 lab was redesigned with new experiments, I was Heino's graduate student instructor. He insisted on doing the experiments himself to see where the students would hit pitfalls. Each week, Heino and I would stay in the lab a few days before running experiments in the class, troubleshooting and optimizing each procedure. Then he would stick around for the lab with students, put on a lab coat and help out. He wanted students to get the best experience they could from their time at Cal.

Heino Nitsche was a chemistry professor at the University of California, Berkeley, and senior research scientist at Lawrence Berkeley National Laboratory. He died unexpectedly on July 15, 2014. Nitsche, a native of Germany, mentored two Department of Energy National Nuclear Security Administration Stewardship Science Graduate Fellowship (DOE NNSA SSGF) recipients, including Jennifer Shusterman.

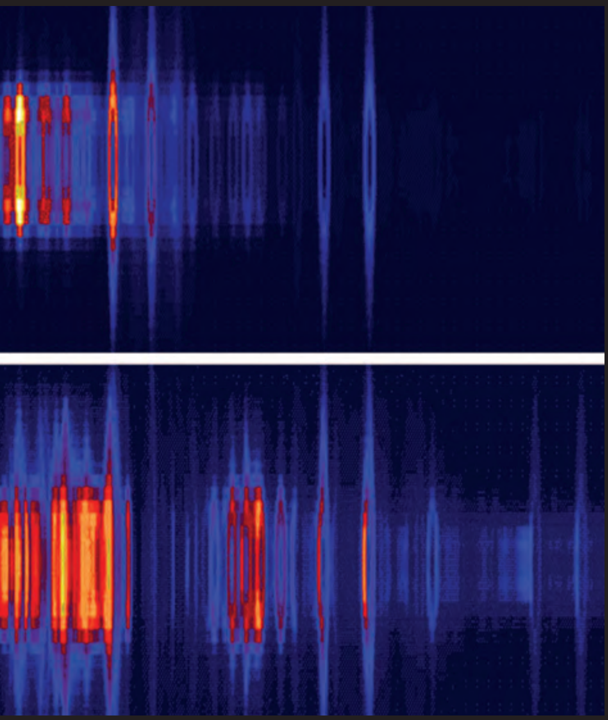
The author and her mentor in Berkelely, California, 2014.

As a Ph.D. advisor, Heino encouraged us graduate students to solve our own problems and pushed us to try methods even if he was fairly sure they would fail. (He was a big fan of these so-called teaching moments.) He always encouraged us to do more than even we thought we were capable of, saying later that he never doubted we would get there. We were always slightly suspicious of that statement.

Success or failure, Heino was there. He would celebrate our triumphs and help us through our more challenging times. When I learned I was awarded the DOE NNSA SSGF, he sent an email from Germany – at 1:45 a.m. his time – primarily consisting of exclamation points. (Heino wasn't one to conceal his excitement. The Monday before his death, he was bouncing off the walls because Germany had just won soccer's World Cup.)

Heino loved advising DOE NNSA SSGF recipients, starting with Paul Ellison. Heino looked forward to attending the fellowship's annual program review, including one in Berkeley just weeks before his death. He enjoyed the social events because he got to spend time with fellows, fellowship staff and DOE lab staff who attended. For many years, he judged the fellows' poster session, telling me how impressive and interesting he found the presentations. Heino genuinely enjoyed belonging to the SSGF family. He is truly missed by many.

SPECTRAL PROSPECTING



Sandia National Laboratories' Stephanie Hansen says "one spectrum is worth a thousand words." Enlisting Sandia's abundant tools for performing high energy density physics, Hansen has, among other accomplishments, modeled the predicted brightness of X-rays emitted from an imploding plasma column. Read more about her work starting on page 7.

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