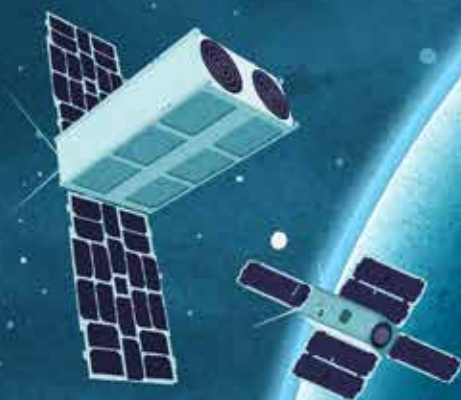
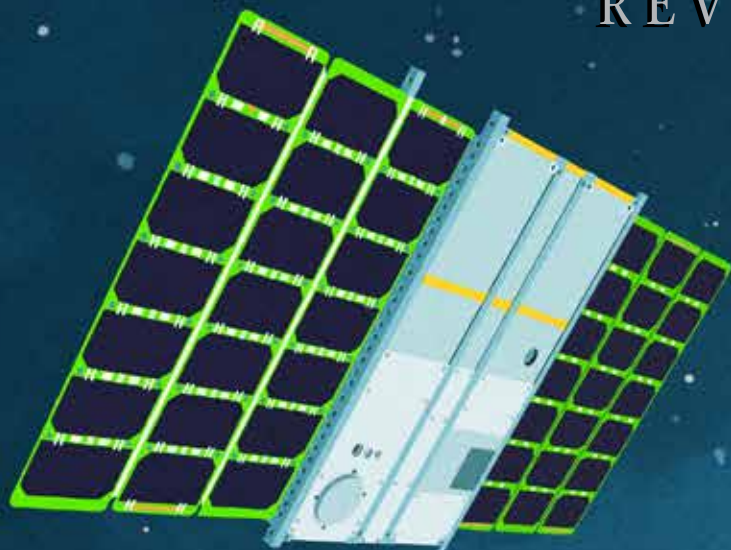


April 2019

Science & Technology

REVIEW



LIVERMORE'S CUBE SATELLITE EVOLUTION

Also in this issue:

Record-Breaking Neutron Yield

A Wolter Optic for X-Ray Imaging

Military Education and Outreach

About the Cover

The Laboratory's work developing small modular cube satellites, called CubeSats, applies innovative new technologies and is boosting the institution's space program. As the article beginning on p. 4 describes, Lawrence Livermore has been involved with CubeSat development for nearly a decade, which has resulted in enhanced optics and telescope designs and, more recently, the implementation of its own bus platform. Depicted on the cover is an artist's rendering of three Livermore-developed CubeSats in low-Earth orbit: (from top to bottom) MiniCarb, GEOSTARE-2, and STARE-A.



Cover design: Alexandria Diaz; Rendering: Ryan Goldsberry

About S&TR

At Lawrence Livermore National Laboratory, we focus on science and technology research to ensure our nation's security. We also apply that expertise to solve other important national problems in energy, bioscience, and the environment. *Science & Technology Review* is published eight times a year to communicate, to a broad audience, the Laboratory's scientific and technological accomplishments in fulfilling its primary missions. The publication's goal is to help readers understand these accomplishments and appreciate their value to the individual citizen, the nation, and the world.

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Prepared by LLNL under contract
DE-AC52-07NA27344

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S&TR, a Director's Office publication,
is produced by the Technical Information
Department under the direction of the
Office of Planning and Special Studies.

S&TR is available on the Web
at str.llnl.gov

Printed in the United States of America

Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

UCRL-TR-52000-19-4
Distribution Category UC-99
April 2019

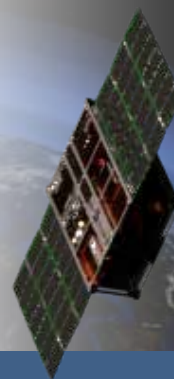
Feature

3 A Rich Heritage of Space Science Innovation

Commentary by Bruce E. Warner

4 Space Program Innovation, One Small Satellite at a Time

A fleet of innovative small satellites builds on the capabilities of Lawrence Livermore's long-standing space program.



Research Highlights

12 On the Threshold of a Critical Milestone

Results of recent experiments at the National Ignition Facility have yielded record numbers of fusion neutrons.

16 An Optical Revolution for X-Ray Imaging

Researchers are developing a Wolter microscope to enable sharper images of radiation sources inside high-energy-density experiments.

20 Military Education Programs: A Two-Way Street

Outreach programs give service members insight into crucial national security issues and support Laboratory research efforts.



Departments

2 The Laboratory in the News

24 Patents and Awards

25 Abstract

Ancient Meteorite Tells Tales of Mars Topography

Lawrence Livermore scientists and collaborators have analyzed a Martian meteorite (see image below) and determined that a significant topographic and geophysical feature of Mars—its crustal dichotomy, or divide, that separates the northern hemisphere lowlands and southern hemisphere highlands of the planet—likely formed within the first hundred million years of planetary history. The study was published in the May 23, 2018, issue of the journal *Science Advances*.

Northwest Africa (NWA) 7034, discovered in the Sahara Desert, is the oldest Martian meteorite that has been discovered to date. The sample is a breccia, containing a variety of crustal rocks that were mixed together and sintered during a meteoroid impact on Mars.

Using radioisotopic dating techniques and other data, the team determined that the crustal rocks incorporated into NWA 7034 were emplaced near the Martian surface more than 4.4 billion years ago in a regional terrain spanning hundreds of square kilometers, and that this terrain remained relatively undisturbed throughout the planet's history. The rocks were brought together by a small impact event 2 to 3 million years ago.

The retention of ancient volcanic terrains near Mars' surface indicated to the researchers that the Martian crustal dichotomy likely formed within the first 100 million years of planetary formation—a time when many planetesimals were impacting the inner planets. The data are consistent with a giant impact hypothesis for its formation, although other mechanisms cannot be dismissed.

The results of this research have important implications for understanding when and how one of the oldest, and most distinctive, global geologic features on Mars was formed. Cassata says, "This study demonstrates that multiple radioisotopic dating systems that are reset by different metamorphic processes can be used to tease out the thermal history of a sample over billions of years."

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Researchers Discover Cause of Radiation Defects

Scientists from Lawrence Livermore and Texas A&M University have made significant progress in understanding the formation of radiation defects. The team's research, which appears in the May 25, 2018, issue of the journal *Physical Review Letters*, explains how the density of collision cascades—collisions of atoms induced by energetic particles—significantly affects defect interaction dynamics in silicon.

The team calculated cascade densities with a computer model that accounted for the fractal nature of collision cascades and, using a

novel pulse ion-beam method, systematically studied the temperature dependencies of the rate of defect interaction in silicon bombarded with ions in a wide range of masses, creating collision cascades with vastly different densities. The results demonstrate that the complex dependence of defect dynamics on irradiation conditions can be reduced to a deterministic effect of collision cascade density.

The density determines the lifetime of point defects, which is the time it takes for them to annihilate or interact to form stable damage. Defects in denser cascades take longer to decay, and a change in the dominant process of defect interaction occurs at higher temperatures.

"The new results can be used to predict radiation defect dynamics in silicon and provide a blueprint for future studies of radiation defect dynamics in other technologically relevant materials," says Sergei Kucheyev, the Livermore project lead and co-author of the paper. Understanding radiation damage is important for nuclear materials performance and for electronic materials. The results from this study can be used to predict the ranges of process conditions where the dynamic defect interaction phenomena are pronounced or less important.

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Simulations Capture Life and Death of a Neutron

A team of scientists from Lawrence Livermore and Lawrence Berkeley national laboratories as well as from the University of California at Berkeley and other institutions have calculated, with unprecedented precision, a quantity that is central to the understanding of a neutron's lifetime, nucleon axial coupling (g_A). The research appears in the June 7, 2018, issue of the journal *Nature*.

The complex theory of quantum chromodynamics (QCD) describes the strong interaction between quarks and gluons—the building blocks for larger particles, such as neutrons and protons. Using supercomputers from Lawrence Livermore and Oak Ridge national laboratories, the research team numerically simulated QCD on a four-dimensional grid of points called a lattice. The simulation method, called Lattice QCD, helps to determine the mass of a neutron and proton as well as the value of g_A . The team's theoretical determination of g_A was based on a simulation that represented only a tiny piece of the universe—the size of a few neutrons in each direction. They effectively simulated a neutron transitioning to a proton inside this section of the universe to predict what happens in nature. Livermore scientist Pavlos Vranas, who co-led the research, says, "Our study indicates that Lattice QCD is now capable of calculating g_A with high precision, opening the door for a wealth of Lattice QCD calculations of importance to nuclear physics."

The scientists' work builds upon decades of research and advances in computational resources by the Lattice QCD community. The team is the first to calculate g_A to a precision within 1 percent and aims to drive the uncertainty margin down to approximately 0.3 percent.

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(Image courtesy of Carl Agee/University of New Mexico.)



A Rich Heritage of Space Science Innovation

LAWRENCE Livermore is renowned for its pioneering accomplishments in national and global security, but it's perhaps less well known for its rich history in advancing space science. In fact, the Laboratory's first contribution to space exploration coincided with the start of the space age. On October 4, 1957, the Soviet Union placed in orbit Sputnik I, the world's first artificial satellite. Soon after the launch, the Smithsonian Astrophysical Observatory, charged with tracking Sputnik in orbit, contacted the Laboratory (then called the University of California Radiation Laboratory at Livermore) for help. In response, Livermore scientists turned to their THEMIS code, the only software available that could accurately track Sputnik's orbit. The code ran on the Laboratory's two IBM 704 computers for three days.

Over the following decades, Lawrence Livermore researchers continued to make important contributions to the nation's growing capability in space for both basic science and as an increasingly important element to national security. For example, a major element of President Ronald Reagan's Strategic Defense Initiative (SDI) in the 1980s was a Livermore concept called Brilliant Pebbles: a constellation of small, lightweight spacecraft that could stop ballistic missiles by colliding with them at high speeds. Although the Laboratory's work on SDI was discontinued following the end of the Cold War, sensors and cameras developed for Brilliant Pebbles became components of the Clementine Deep Space Experiment in 1994.

Clementine was the first U.S. spacecraft to visit the moon in more than two decades. Using six cameras designed and built at Livermore, Clementine mapped the entire lunar surface in 14 discrete spectral bands and at resolutions never before attained. Clementine represented a new class of small, low-cost spacecraft. In addition, a wide variety of Laboratory advances in state-of-the-art sensors have built on Clementine's success.

More recently, Livermore has made seminal contributions to space science with x-ray optics for various NASA missions and laser guide star technology that eliminates the twinkles caused by atmospheric distortions in ground-based telescopes. Livermore engineers played a central role in the design of the Large Synoptic Survey Telescope (LSST), under construction in the Chilean Andes. One Livermore innovation combined two of LSST's three

massive mirrors into a single monolithic surface, thereby saving construction costs and weight.

As described in the article beginning on p. 4, an important new focus for Livermore is a class of nanosatellites called cube satellites, or CubeSats. These miniature spacecraft get their name from a design based on one or more cubes measuring 10 centimeters on a side. Their modular architecture allows scientists to "plug and play" different sensors on a standardized framework. These remarkably small spacecraft are beginning to transform space operations, in particular data collection. NASA tested the concept last year when it sent the first CubeSats into deep space for relaying communications to Earth from the InSight Mars lander.


CubeSats offer several benefits over traditional satellite technology. Rather than one large satellite costing hundreds of millions of dollars and taking many years to build, CubeSats can be designed and built for a few million dollars (or much less) in several months. The reduced cost and shorter development cycle and production time means technology can become viable more quickly. A less expensive fleet of smaller satellites also means the demise of one CubeSat in a fleet would not jeopardize an entire mission, as would the loss of a much larger one-of-a-kind spacecraft.

Although early CubeSat efforts at Livermore incorporated conventional telescope designs, later GEOstare spacecraft used a visible light telescope fabricated from a single piece of fused silica, a design inspired by LSST. A fleet of these probes could vastly improve our space-based situational awareness capability. Our latest CubeSat design, dubbed MiniCarb, will monitor atmospheric gases.

Livermore's many space science efforts are made possible by an outstanding team with multidisciplinary expertise in astrophysics, instrumentation, x-ray and visible-light optics, physics-based high-performance modeling and simulation, advanced manufacturing, and innovative spacecraft architectures. We are pushing the boundaries of space technology to meet challenges in space security, space exploration, and basic science.

■ Bruce E. Warner is principal associate director for Global Security.

SPACE PROGRAM ONE SMALL

A photograph showing three engineers in a cleanroom environment working on a MiniCarb cube satellite. The engineer in the foreground is wearing a white lab coat, a face mask, and safety glasses, and is focused on a component. The engineer in the background is also wearing a white lab coat and safety glasses, and is looking at the same component. The engineer on the right is wearing safety glasses and is looking at the component. The satellite is a small, rectangular device with a green frame and various electronic components. The background is a dark, starry space scene.

Engineers and scientists complete the installation of the laser heterodyne radiometer (LHR) into the MiniCarb cube satellite, or CubeSat. Clockwise from bottom left is Lance Simms from Lawrence Livermore and AJ DiGregorio, Guru Ramu, and Jenny Young from NASA. (Not pictured: Emily Wilson, Darrell Carter, and Vincent Riot.) (Photo by Randy Wong.)

INNOVATION SATELLITE AT A TIME

The Laboratory's "out-of-this-world" technologies are enabling development of small modular cube satellites for space applications.

THE population of human-made satellites orbiting Earth has skyrocketed over the past 60 years. Launches nearly doubled from 2016 to 2017, and a significant contributor to this growth has been the development and implementation of small satellites that are easier and less expensive to build and more cost efficient to launch than conventional ones. Today, the hottest destination for these spacecraft is low-Earth orbit (LEO)—in the range of a few hundred kilometers above the planet's surface.

Nanosatellites, a class of small satellites weighing between 1 and 10 kilograms (kg), have become increasingly popular because of their lower cost and ease of construction—made possible through standardization. Cube satellites, called CubeSats, are a common type of nanosatellite comprising a modular framework of cube-shaped building block units (U) that measure 10 centimeters (cm) per side, about twice the size of a Rubik's cube. For comparison, the spherical Sputnik—the first artificial satellite in orbit—measured 58 cm in diameter and weighed 83.6 kg.

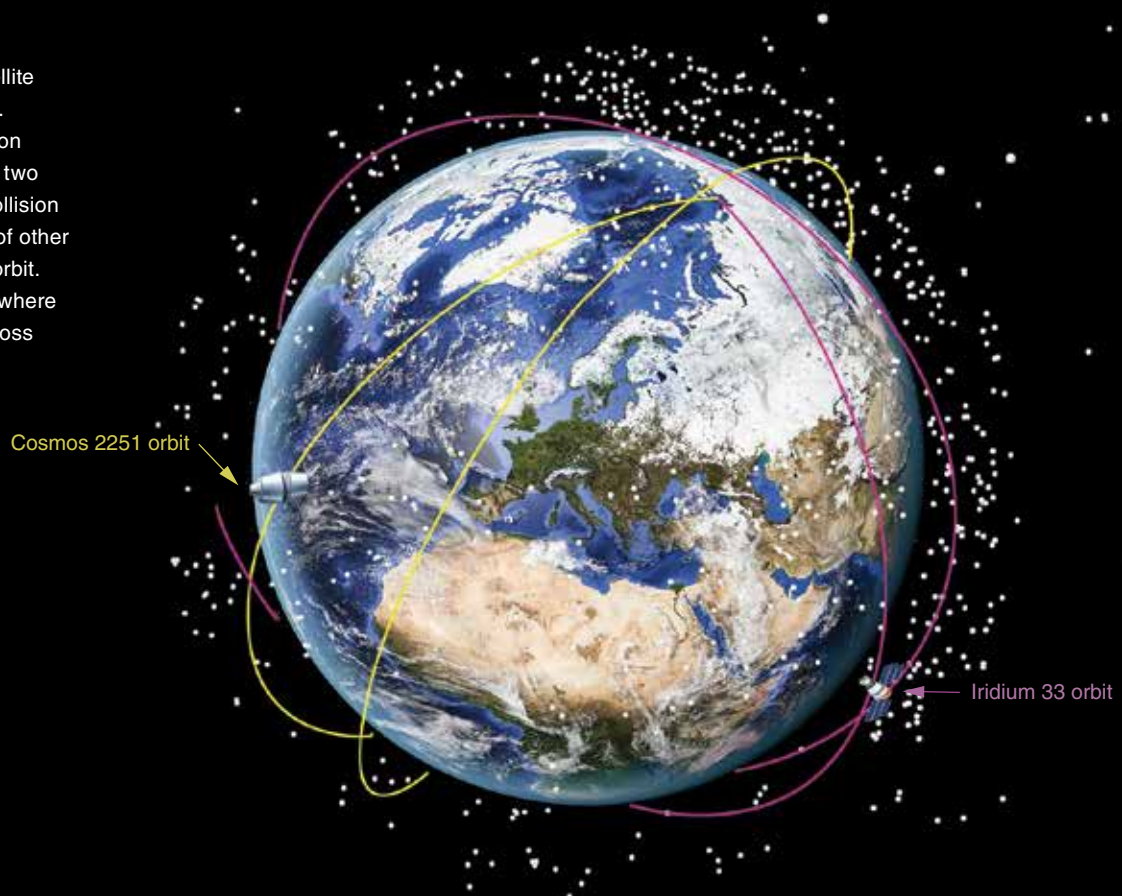
CubeSats typically comprise two main parts: a payload and a bus, the latter of which provides the structure, command and control, communication, power, navigation, and maneuvering systems for the spacecraft. Lawrence Livermore's first involvement with CubeSats was developing optical imaging payloads for the Space-Based Telescopes for the Actionable Refinement of Ephemeris (STARE) project to monitor space debris. (See *S&TR* April/May 2012, pp. 4–10.) Since then, the Laboratory has continued to advance CubeSat technology and strengthen the institution's space program. Through this work, Lawrence Livermore is embarking on new technological frontiers, from enhancing sophisticated optics and telescope designs to developing its own bus platform.

STARE-ing into Space

Consisting of derelict satellites, rocket boosters, and parts from spacecraft, pieces of space debris range in size from too small to be tracked to larger than a softball and can travel at speeds exceeding 25,000 kilometers per hour. Tens of thousands of these objects are tracked and considered lethal, and collisions, intercepts, and catastrophic failures continually increase the amount of debris. In 2009, for example, the inoperable Cosmos 2251 satellite collided with the privately owned Iridium 33 satellite over the Arctic at a closing speed of 12 km per second, breaking into more than 2,000 pieces of trackable debris. More recently, in 2015, astronauts aboard the International Space Station nearly collided with a fragment from a defunct weather satellite.

Although simple laws of physics govern the path of an orbiting object, variations in solar radiation and perturbations from the gravitational pull of the Sun, Moon, and Earth make determining the exact positions of any single object, let alone thousands, rather tricky. Satellites in LEO also experience drag from Earth's upper atmosphere. Ten years ago, a team from Livermore, consisting of engineers, physicists, and computer scientists, began studying how to improve detecting and tracking objects that threaten space operations. Funded by the Laboratory Directed Research and Development (LDRD) Program, their approach to space situational awareness (SSA) included using high-performance computing to analyze and simulate the trajectories of space debris and

In 2009, the defunct Cosmos 2251 satellite and the Iridium 33 satellite collided in Earth's orbit. A Livermore visualization shows the orbits of the two satellites prior to the collision among the thousands of other satellites in low-Earth orbit. The collision occurred where the two orbital paths cross near the North Pole.



the results of hypervelocity collisions between satellites. The team applied improved orbital predictions with optical and radiofrequency observations to develop their model.

Building on this modeling effort, Livermore began a partnership to build a series of three CubeSats (STARE-A, -B, and -C) and launch them into LEO at approximately 700 km. The CubeSats were designed to investigate methods for better protecting operational satellites from fates similar to Iridium 33. Livermore was responsible for developing the telescopes as part of the optical imaging payloads. Each CubeSat telescope had a diameter of 8.5 cm, weighed less than 1 kg, and took up about 1U of space.

Whereas STARE-A and -B used a conventional telescope design with independent primary and secondary mirrors for viewing distant objects, the (unlaunched) STARE-C configuration was the first to feature a new monolithic optic, an approach that combines the primary and secondary mirrors into a single element. The idea stemmed from the dual-surface monolith that Livermore scientists helped develop for the Large Synoptic Survey Telescope. (See *S&TR*, September 2017, pp. 4–11.)

In 2014, a team led by Livermore physicist Wim de Vries partnered with the U.S. Air Force and commercial bus provider Tyvak to develop the 3U GEOstare-1 CubeSat. This satellite, and the subsequent GEOstare-2, also incorporated a monolithic telescope design and tested new concepts for SSA missions. Imagery of Earth and the Moon collected by GEOstare-1 during checkout operations validated the telescope's performance.



GEOstare CubeSats use monolithic telescopes, which combine the primary and secondary mirrors into a single optical element (left). The entire telescope assembly (below) also includes the baffle (black component) to reduce stray light.

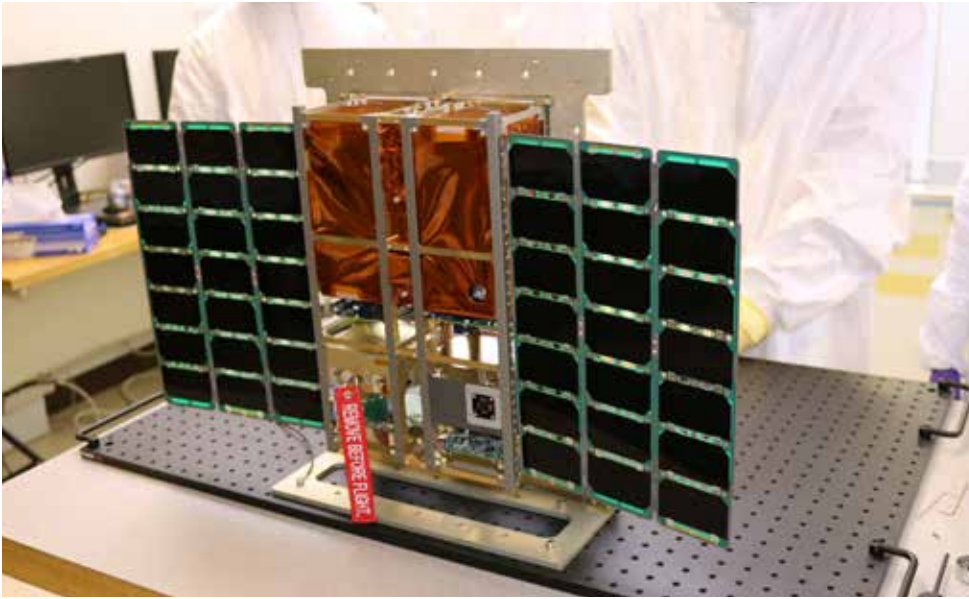


“GEOstare-1 launched in January of 2018,” says De Vries. “We’re already done with the experiment, which produced beautiful data and validated all the ideas that we had.” Scheduled to launch in 2019, GEOstare-2 is twice the size of its predecessor. The 6U CubeSat will carry a narrow-field-of-view color imager and a wide-field-of-view panchromatic imager mounted side-by-side to fulfill its SSA mission.

Building a Next-Generation Bus

Once in orbit, bus failures prevented both STARE-A and STARE-B from becoming operational, so neither could be evaluated in space. Instead of launching STARE-C, the partners moved in new directions. Livermore again focused on telescope payloads but also began work on a new bus design. In 2014, a team led by Livermore engineer Vincent Riot, in collaboration with colleagues at the Naval

Postgraduate School and under sponsorship from the National Reconnaissance Office, created the CubeSat Next Generation Bus (CNGB) architecture. The bus design featured flexibility; transparency; and mechanical, electrical, and software standardization. Although initially defined for a 3U CubeSat, CNGB is scalable to larger configurations. Darrell Carter, lead Livermore mechanical designer for CNGB, notes, “We used the lessons learned from STARE-A and STARE-B to guide our designs and ensure we could easily and reliably mount, test, and unmount components as needed.”



MiniCarb combines NASA's LHR (seen in orange) and Livermore's CubeSat Next-Generation Bus, which consists of all the other components. (Photo by Dan Linehan.)



During a telemetry verification test of MiniCarb's satellite radio, physicist and engineer Lance Simms (right) and engineering summer student Nicholas Hsiao send a communication signal to the Iridium satellite network in space. The signal is relayed back to them via a ground station. (Photo by Dan Linehan.)

To provide the most design flexibility and efficient integration of payloads, the framelike structure—a lattice reminiscent of an Erector Set toy—was designed with 4 perforated rails running the length of the CNGB structure. The rails are fastened together by 16 crossbars, and the payload and other components mount to these rails. The widely used vehicle Controller Area Network (CAN) interface handles the electricity and data signals. To support a broad range of computing platforms, the bus includes the Space Plug-and-Play Avionics (SPA) software interface.

“This work represents the building blocks for one sector of the Laboratory’s space program,” says Bill Bruner, a senior advisor for Livermore’s Space Science and Security Program (SSSP). “For years we have built instruments and optics for others. Now, thanks to a boost from our work with the National Reconnaissance Office, we are also providing bus platforms that can deliver different services for sponsors depending upon their needs.”

Introducing MiniCarb

With the new Livermore bus design in place, in 2016 the team began partnering with NASA Goddard Space Flight Center to develop the payload and the U.S. Air Force to provide a way to launch the spacecraft. Using CNGB, the final size of the CubeSat, called MiniCarb, is 6U. Once in orbit at 500 km, MiniCarb will be used to monitor atmospheric gases. “This work represents the first time that we are launching a Livermore-developed spacecraft,” says Riot, who also leads Livermore’s MiniCarb team. “It’s a proof of concept for our bus design, but we are also conducting important science with a NASA payload.”

Building satellites inexpensively requires an innovative approach. MiniCarb was built for only \$500,000 by using commercial parts that have limited lifespans in the harsh environment of space. Costs were further managed by

assembling the satellite under a clean hood as opposed to in a clean room. Some of the prelaunch testing even occurred outdoors. Says Riot, “It’s a cost–schedule–performance tradeoff.” CNGB has realized the goal of cost efficiency whereby a second one would only cost a few hundred thousand dollars more to produce, take a year to build with minor modifications, and incorporate upgraded technologies and capabilities. Quick iteration of the “design–build–test–fly” cycle is the key to obtaining performance and reliability.

As with other CubeSats, MiniCarb relies on GPS and star tracking to determine its exact location and orientation. Similar to other modern satellites, MiniCarb rotates around and refines its aim using three continuously spinning reaction wheels.

Power is generated by two trifold solar panels, stored in 6 lithium batteries, and delivered by a software-controlled distribution system. This entire power system is one of Lawrence Livermore’s key innovations for CubeSats. For data transmission and other telemetry, MiniCarb uses a modem from Iridium Communications, Inc., to connect to the company’s network of satellites in orbit. In seconds, the network relays communications back and forth to an Iridium ground station linked to Livermore’s spaceflight control center.

To ensure MiniCarb can withstand the various hazards in orbit and promote its successful operation, all systems are tested and verified prior to launch as part of NASA’s Technical Standards Program. To help the satellite survive the harsh space environment, a bright, coppery-orange thermal blanket regulates the payload’s temperature as MiniCarb’s orbit causes a swing from 5°C to 45°C.

MiniCarb on a Mission

On May 8, 2018, NASA installed a 4U laser heterodyne radiometer (LHR)

A Spacefaring Coast Guard

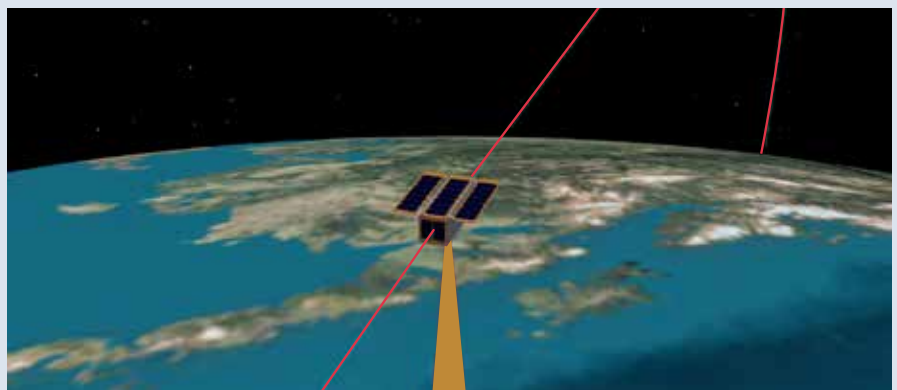
Nanosatellite technology, in particular, small cube satellites, are finding purpose in the most extraordinary places. Known as CubeSats, these miniature versions of conventional satellites can be used for applications that range from tracking space debris to monitoring atmospheric gas concentrations. Now, Lawrence Livermore scientists and engineers are turning their expertise in CubeSat development toward assisting the U.S. Coast Guard in becoming a spacefaring agency.

Shawn Higbee, an associate program leader in the Laboratory’s Space Science and Security Program, leads the project. He says, “The Coast Guard came to us because they were excited by the promise of space and wanted to refine their strategy on where to start. So, we helped develop a strategy and technical roadmap for how small satellites could help Coast Guard missions.”

With more than a dozen mission objectives, which include search and rescue activities, iceberg monitoring operations, law enforcement, fishery protection, and homeland defense, the Coast Guard operates over vast areas of the Arctic, Pacific, and Atlantic oceans. The rigorous demands across this remote expanse present many challenges for the Coast Guard. For example, the melting of the Arctic ice sheet and the opening of the Northwest passage have provided an avenue by which ships can now travel ocean to ocean. The lack of infrastructure in the Arctic and the increasing risks have the Coast Guard looking to CubeSats as a way of protecting these new waterways.

In 2018, two 3U CubeSat payload prototypes were developed at the Laboratory and delivered to the Coast Guard Academy for education and training. The devices are to be used by academy cadets for instructional purposes on dry land as the Coast Guard begins its journey with space technology. The prototypes are designed for maritime domain awareness missions, but one specializes in searching for life rafts adrift in the ocean. The distinct orange color of life rafts makes it easy for the CubeSat to identify them against a backdrop of seawater.

The Coast Guard is interested in CubeSats as a cost-effective approach to improving the performance of many missions. Another advantage of having its own fleet is that it allows the Coast Guard to more easily share information with international partners and use it for law enforcement proceedings.



This simulation shows a U.S. Coast Guard CubeSat in orbit over Alaska’s Aleutian Peninsula searching for life rafts after a storm.

into Livermore's CNGB to complete the MiniCarb CubeSat. By collecting sunlight that has passed through slices of Earth's upper troposphere and lower stratosphere, LHR can detect the amount of sunlight absorbed by methane (CH_4) and carbon dioxide (CO_2). Absorption spectra are then used by scientists to measure the concentrations of these greenhouse gases.

For LHR to work, it must mix the incoming sunlight with laser light of a wavelength that corresponds to the absorption peaks of the gases. Advancements in technology and the increasing availability of laser components enabled the design of an existing ground-based LHR to be miniaturized for use in MiniCarb. The key to the LHR instrument development was finding the solid-state, distributive feedback laser tunable to around 1,640 nanometers.

Unlike typical ground-based LHRs that cannot distinguish between gas concentrations at different altitudes, or current remote-sensing, atmospheric satellites that point directly to the ground,

MiniCarb will have a better vantage point. With the atmosphere positioned between a direct line of sight from the Sun to MiniCarb, the orbiting LHR can take multiple measurements as the CubeSat orbits. Each measurement slices through a different altitude, providing key details about the concentrations of greenhouse gases within the atmosphere.

The launch of MiniCarb will mark the first time an LHR enters space and the first use of a CubeSat to measure CH_4 and CO_2 simultaneously. NASA scientist Emily Wilson leads the LHR design and MiniCarb's science mission. She says, "Compared to other types of commercial instruments, LHR gives a better-quality measurement because of its higher spectral resolution." Favorable angles occur twice per orbit—the best measurement positions occur during sunrise and sunset from the CubeSat's point of view. MiniCarb must rotate between observations at these two positions. MiniCarb records two series of scans each time it circles Earth. Up

to five scans are completed per position, with each scan lasting about a minute and collecting approximately a hundred data points.

After MiniCarb's three-month mission, its orbit will naturally decay over about two years and then burn up in Earth's atmosphere so as not to add to the collection of already defunct satellites in space. Of the approximately 4,800 satellites in orbit, less than half of them are operational.

Small Satellites, Big Potential

The successful launch of MiniCarb will mark the first time a CubeSat bus built by the Laboratory is delivered to space. It will also represent the maiden voyage and operation of NASA's innovative LHR instrument. Scheduled for no earlier than May 2019, MiniCarb will be put into space as part of an Earth-to-orbit rideshare. It will be a Department of Defense Space Test Program mission launched by VOX Space on a Virgin Orbit LauncherOne vehicle. Such partnerships make splitting

This artist's rendering shows the direct line of sight between the Sun and MiniCarb, which will be used to monitor atmospheric gases. (Rendering by Jacob Long.)





MiniCarb will be put into space as part of an Earth-to-orbit rideshare. It will be a Department of Defense Space Test Program mission launched by VOX Space on a Virgin Orbit LauncherOne vehicle. (Image courtesy of Virgin Orbit.)

the cost for a ride to space much more affordable.

Branching out with new mission concepts, improved optical payloads, and other technological advances, CubeSat projects contribute to both basic science and national security endeavors and have helped shape the broader Laboratory space program and mission. (See the box on p. 9.) Mike Pivovarov, the program leader for SSSP, adds, “The Laboratory’s strength is looking at a sponsor’s mission, separating it into basic requirements, and then doing the architectural studies, which regularly require high-performance computing. The focus of our integrated team is to provide a cost-effective solution for getting the best data for the sponsor.”

The research and development efforts have also enabled Livermore to expand its space technology expertise, which can be further applied to existing programs at the Laboratory. “For example, what if our additive manufacturing group produces a breakthrough structural element that can be used as an antenna, and scientists want to fly the element to space because it supports underlying missions,” says Pivovarov. “We are now in a position to bring these efforts together in a vertically integrated way.”

Through a strong understanding of the principles that guide operations in orbit, development of innovative instruments, and research and design that promotes the realization of more cost-effective spacecraft, Livermore’s space program is

embarking on something extraordinary. CubeSat by CubeSat, the Laboratory is demonstrating that small modular satellites are just the beginning of big scientific breakthroughs.

—Dan Linehan

Key Words: bus, cube satellite, CubeSat, CubeSat Next Generation Bus (CNGB), GEOstare, Large Synoptic Survey Telescope, laser heterodyne radiometer (LHR), LauncherOne, MiniCarb, monolithic telescope, nanosatellite, payload, Space-Based Telescopes for the Actionable Refinement of Ephemeris (STARE), space debris, Space Science and Security Program (SSSP), space situational awareness (SSA), telescope.

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ON THE THRESHOLD OF A CRITICAL MILESTONE

THE 192-beam National Ignition Facility (NIF), the world's largest and most energetic laser, supports the National Nuclear Security Administration's Stockpile Stewardship Program and is a powerhouse for a broad range of scientific research. For decades, scientists have pursued inertial confinement fusion (ICF) as a means for achieving ignition—a fusion process by which self-heating generates more fusion heating than is lost to all cooling processes in the target's fusion fuel. Recent experiments at NIF have shown that the “burning plasma” stage needed to reach this challenging goal may be within reach.

In ICF experiments, a deuterium–tritium (DT) fuel capsule is seated inside a gold or depleted uranium hohlraum, a cylindrically shaped device with open ends. NIF's laser light striking the hohlraum walls generates a bath of x rays that causes the capsule to implode, heating and compressing the DT fuel into a central hot spot. Fusion reactions within the hotspot produce

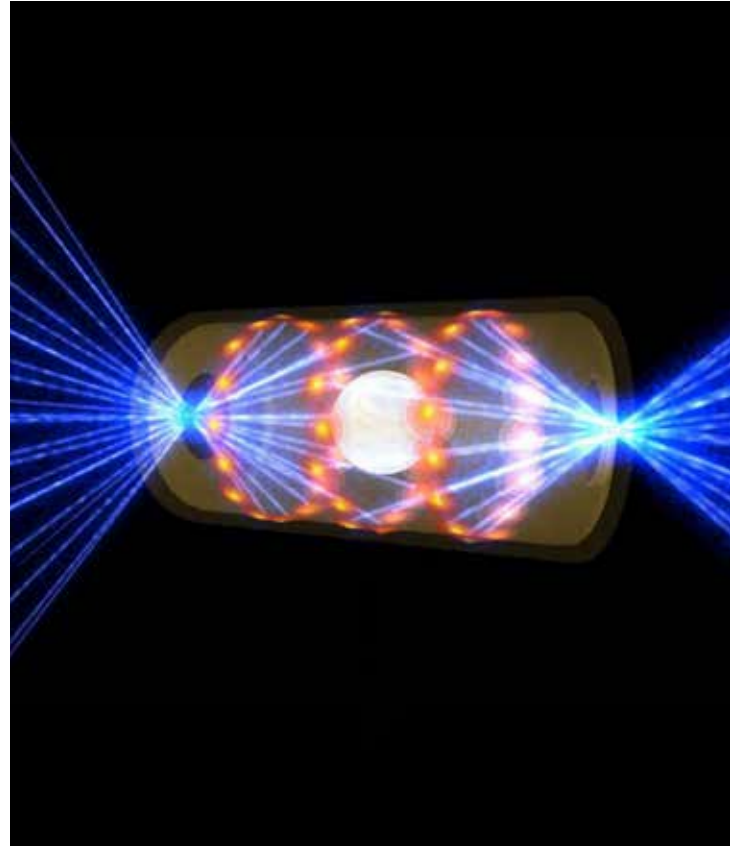
an alpha particle (helium nucleus) and a neutron. The number of neutrons generated characterizes the extent of the fusion process. For ignition to occur, enough alpha particles must be present to generate the heat needed to initiate further fusion reactions in the hot spot, creating a thermal runaway effect.

As part of a successful experimental campaign that took place over several months in 2017 and 2018, scientists at NIF successively produced record numbers of fusion neutrons. One of the experiments, conducted in August 2017, delivered 1.9×10^{16} neutrons—the highest yield to that point—and generated about 53 kilojoules (kJ) of energy (nearly double the previous performance). A subsequent shot in January 2018 further increased the output, producing 2.0×10^{16} neutrons and 55 kJ of energy.

The shots used an experimental platform aimed at controlling implosion asymmetries and hydrodynamic instabilities, thereby



(below) During inertial confinement fusion (ICF) experiments, laser light entering through either end of a hohlraum strikes the cylinder's walls and generates a bath of x rays that causes the target capsule to implode. Recent experiments feature target capsules made of high-density carbon (HDC) and a thin layer of deuterium–tritium (DT) fuel located just inside the outer shell.



increasing the transfer of energy from the implosion to the DT fuel. Performance of the fuel capsules has improved to such a degree that scientists may be able to create a reaction in which the alpha energy deposited in the hot spot is the dominant source of heating the implosion—known as the “burning plasma” stage. Omar Hurricane, chief scientist for Livermore’s ICF program, says, “The people in magnetic fusion research have been working towards this achievement for 50 years.”

Velocities All-Important

The highly successful experimental campaign incorporated a number of promising features, including a shortened laser pulse for initiating the reaction, an improved fuel capsule material, modifications to the fill tube (used to transfer the DT fuel to the capsule), and a lower concentration of helium gas within the hohlraum (for controlling the plasma expansion). These changes

enhanced the delivery of laser energy to the fuel capsule with better implosion symmetry and unprecedented implosion velocities, resulting in record pressures and temperatures, as well as neutron yields.

According to Hurricane, the experiments demonstrated that increasing the fusion fuel’s adiabat—that is, resistance to compression—yields a more controlled implosion that is closer to the calculations obtained from supercomputer simulations. However, the lack of compression was more than offset by higher implosion velocity—400 to 430 kilometers per second. “Increasing implosion velocity proved more important than changes to lower the adiabat, as codes had predicted,” says Hurricane. NIF physicist Cliff Thomas says, “Historically, we aimed for low adiabat to preserve the compressibility of the fuel, but the experimental data suggest that velocity provides the highest return on investment.” Thomas also notes that

with greater laser energy, velocities of 500 to 550 kilometers per second are possible, but the implosion might then become unstable.

At the start of NIF ICF experiments in 2010, researchers adopted a “low-foot” laser pulse to try to obtain maximum compression. However, the low-foot pulse made the implosion more susceptible to instabilities that decreased neutron yield. Experiments beginning in 2013 used a high-foot laser pulse to create more stable implosions. (See *S&TR*, June 2014, pp. 4–10.) The high-foot pulse lasted 15 nanoseconds (instead of the 20 nanoseconds used in low-foot shots) and featured three main shocks instead of four. It also used a higher power initial pulse, called the “picket,” and a lower peak power, creating a stronger first shock in the foot, or trough period, of the pulse (hence the name high-foot pulse). These experiments proved more forgiving of imperfections in the fuel capsule and less susceptible to implosion instabilities that decrease fusion reactions. The result was improved understanding of implosion physics and important progress in addressing Rayleigh–Taylor instabilities that can tear apart material interfaces.

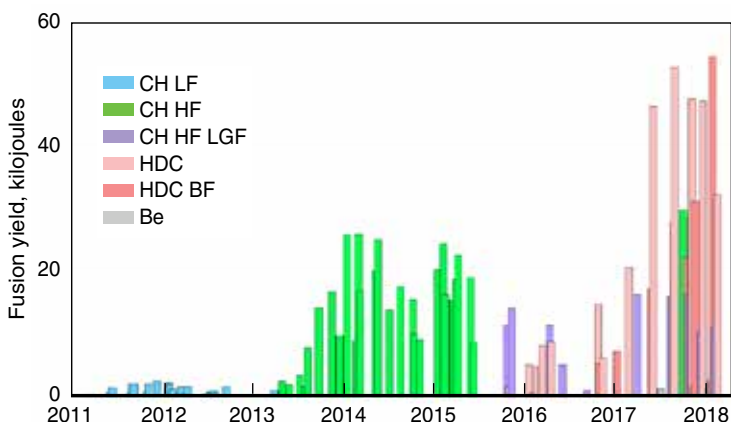
Applying this knowledge to the more recent ICF experiments, the research team fired a three-shock laser pulse (less than half the duration of pulses used in the high-foot campaign) lasting about 7 nanoseconds at the target. The precisely timed series of shocks propagated through the fuel capsule as it imploded. Some experiments adopted a strong initial shock, deemed the big-foot pulse, to drive a high-velocity implosion. A somewhat different strategy, called the HDC low gas-fill platform, used a more

traditional pulse shape, similar to that implemented in the high-foot experimental series.

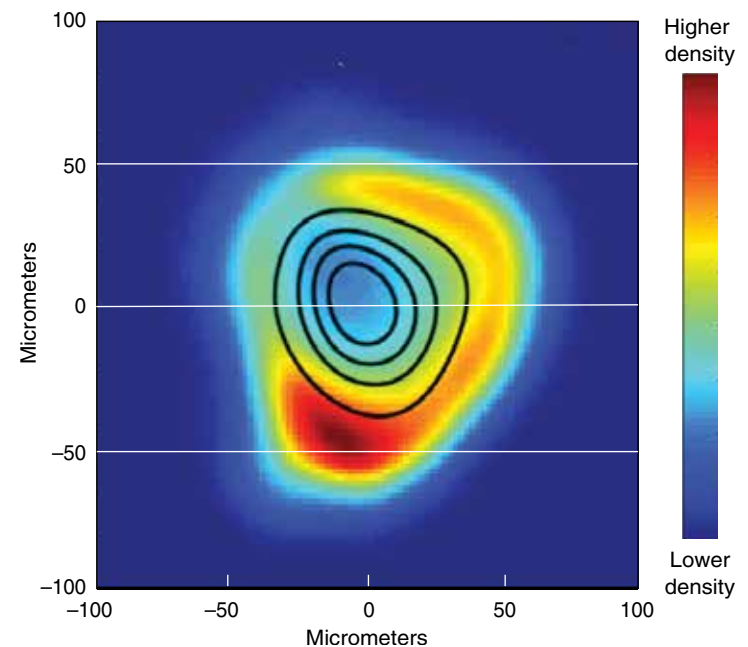
Diamond Outperforms

The 2017 experiments used an ultrathin, roughly 2-millimeter-diameter, high-density carbon (HDC) capsule that contained a thin layer of DT fuel located just inside the outer shell. HDC, or diamond, has a higher density than the plastic and beryllium shells previously used in ICF experiments. HDC allows for a shorter pulse that still reaches the same kinetic energy. “Material properties matter,” says Hurricane. “Diamond is the highest ablation pressure capsule material that we can make at this time and offers the best chance to control symmetry.” HDC capsules are currently produced by Diamond Materials in Germany and then shipped to General Atomics in San Diego, California, for additional work before being forwarded to Lawrence Livermore for final preparations.

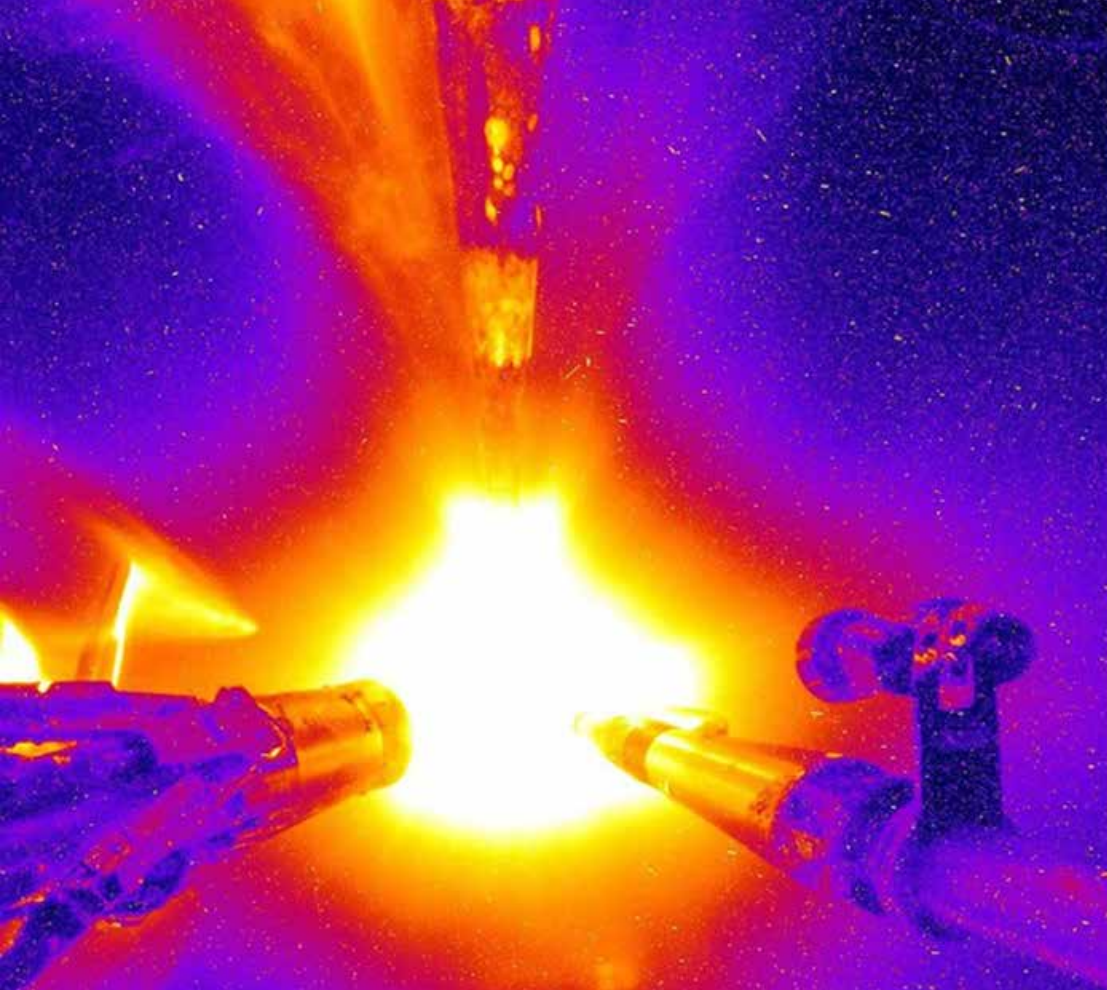
Changes to the helium gas concentration inside the hohlraum also contributed to the success of the neutron-producing experiments. During the high-foot campaign, helium gas was used to slow the expansion of plasma from the hohlraum’s wall that interferes with the laser beams and contributes to implosion asymmetry. However, the high gas concentration increased



The ICF experimental campaign, which has included the low-foot (LF), high-foot (HF), big-foot (BF), and low gas-fill (LGF) platforms, has made steady progress by addressing challenges systematically. The recent record neutron yields stem from the use of HDC capsules rather than plastic (CH) or beryllium (Be), a shortened laser pulse, a lower concentration of helium gas fill, and a thinner fill tube, as well as enhanced understanding of the implosion process.



Data analysis of scattered neutrons in the hot spot of an ICF experiment yield images similar to this one. This image shows data from the January 2018 ICF experiment that produced a record 2.0×10^{16} neutrons and 55 kilojoules of energy. Color gradient indicates the level of neutron scattering.



This colorized image shows the ICF program's first layered DT fusion implosion using the big-foot pulse strategy in a subscale HDC ablator. The big-foot platform uses a shortened three-shock pulse and a thinner DT ice layer that puts the fuel and the diamond ablator on a higher adiabat (resistance to compression) than previous designs.

laser-plasma instabilities (LPI), which induced time-varying asymmetries. Sharply lowering the helium gas concentration reduced LPI, increasing the conversion efficiency from laser energy to x rays by 20 to 25 percent. The change also improved the symmetry of the x rays driving the capsule inward.

To ultimately achieve ignition, NIF's ICF team has made great progress in identifying performance-degrading factors and is developing the tools to mitigate them. For example, the diameter of the fill tube has been decreased from 10 to 5 micrometers to help reduce perturbations. "Our focus has been on systematically identifying limiting factors and then exploring ways to overcome them," says Hurricane. "We are making important progress."

Learning an Incredible Amount

Major scientific breakthroughs often stem from perseverance and building on discoveries made through the investigative process. NIF physicist Laura Berzak Hopkins says, "We have learned an incredible amount and are translating that knowledge into increased capsule performance. ICF experiments are a balance

of different factors, but we have many 'knobs' we can turn for adjusting symmetry, and we have made substantial progress."

Only a limited number of ICF shots are available annually, yet experimenters can run hundreds of simulations on the Laboratory's family of powerful supercomputers to complement the tests. These simulations are continually refined as new experimental data are acquired.

For the upcoming experimental campaign, researchers are adopting many of the strategies that made the record-breaking 2017 experiments so successful. One focus is exploring the advantage offered by larger fuel capsules, which absorb more x-ray energy, allowing them to concentrate more energy into the hot spot and generate more fusion reactions.

The 2017 experimental campaign used capsules with radii about 8 to 12 percent larger than their predecessors. Future experiments will feature fuel capsules with 25 percent larger radii.

The team is also investigating new hohlraum shapes. For example, researchers are studying the potential of an I-Raum, whose design features outward pockets to counteract the effect of hohlraum walls interacting with the incoming laser beams. In addition, they are testing alternatives to the ultrathin membranes that suspend the fuel capsule inside the hohlraum as well as shrinking the size of the fill tube even more to further improve implosion symmetry.

"Our focus has been on identifying and then overcoming limitations to chart the path forward toward ignition," says Hurricane. "For a burning plasma, we need about 70 kilojoules and we now have 55 kilojoules. Six years ago, we attained only 2 kilojoules." As researchers work to achieve a key milestone, they continue to obtain a deeper understanding of what is required for ignition, one of the most challenging scientific goals of the past 50 years.

—Arnie Heller

Key Words: adiabat, alpha particle, burning plasma, deuterium-tritium (DT) fuel, fill tube, high-density carbon (HDC), hohlraum, hotspot, I-Raum, ignition, inertial confinement fusion (ICF), laser-plasma instabilities (LPI), National Ignition Facility (NIF).

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AN OPTICAL REVOLUTION FOR X-RAY IMAGING



WEIGHING nearly 4 kilograms, the first portable digital camera was built in 1975 and offered photographers the ability to capture black-and-white images with a resolution of .01 megapixels. Today, technological advancements have made it possible for people to carry much smaller, lighter, and significantly higher resolution cameras in their pockets (a standard smartphone camera is 8 megapixels). Such a remarkable jump in capability is what scientists at Livermore are aiming to achieve for x-ray imaging.

In a research project spearheaded by Livermore astrophysicist Julia Vogel, Livermore scientists in collaboration with the Harvard-Smithsonian Center for Astrophysics, NASA Marshall Space Flight Center (MSFC), and Sandia National Laboratories have designed, built, and characterized an optical instrument intended specifically for imaging pulsed-power x-ray sources. Known as a Wolter x-ray microscope, the optic significantly improves image resolution and throughput compared to conventional imaging systems. The new instrument has been fitted to Sandia's Z machine—the world's

Livermore scientist Julia Vogel examines the Wolter x-ray microscope developed for pulsed-power x-ray sources.

strongest pulsed-power facility—to help researchers gain a better understanding of the x-ray sources under observation during high-energy-density experiments.

Working with Wolter

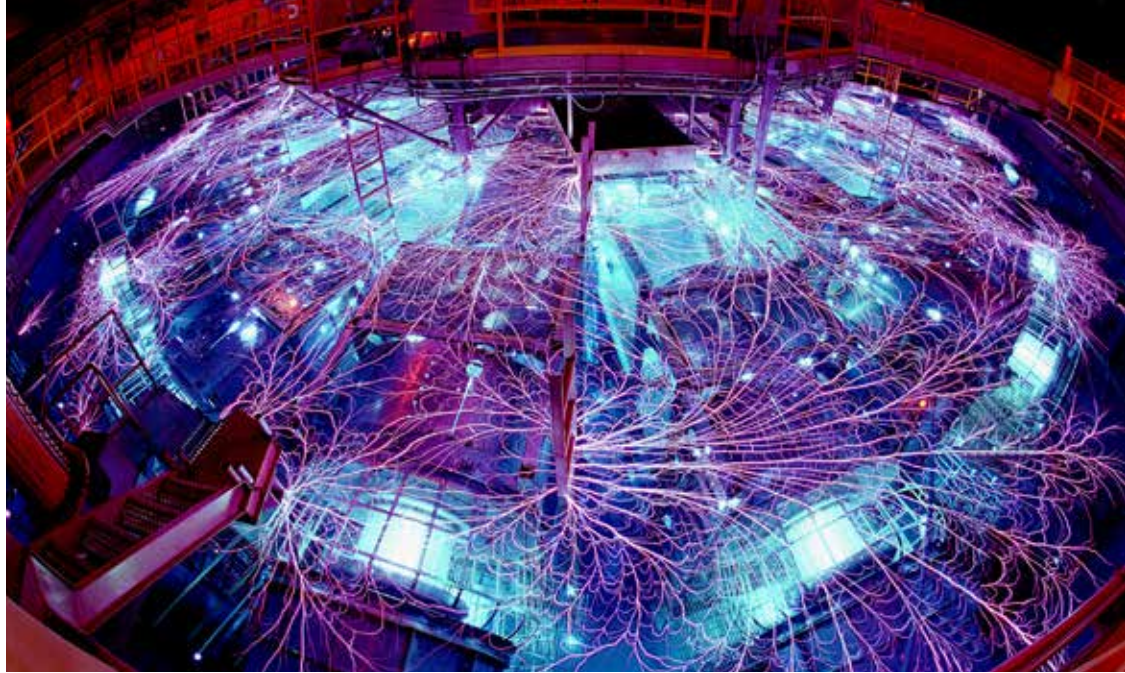
Wolter optics were first developed by the German physicist Hans Wolter in the mid-20th century. Characterized by two conical grazing incidence mirrors, the optics reflect x rays at shallow angles, allowing the image of an object under observation to be focused as a sharp image onto a detector. Originally designed for implementation in x-ray microscopes, the optics were ultimately realized in a more accessible telescope design for applications in astronomy. However, recent advances

in fabrication techniques have allowed the optic to be adapted for microscopes as Wolter initially intended.

Wolter's innovation—joining together two mirror surfaces with different curvatures—makes the optic's field of view considerably wider and also suppresses several intrinsic optical effects that degrade the image quality, allowing for a larger margin of error when pointing at an object. Says Vogel, "The Wolter setup provides a sharp image even if the source is not located right on the system's optical axis." Out of three potential Wolter designs (called Wolter types I, II, and III), scientists have primarily used Wolter type I, which has properties similar to a thin lens. With this design, multiple mirrors could be "nested" inside one another, similar to a Russian matryoshka doll, to increase the reflective surface area of the optic. This design is also the most suitable for use in the Z machine.

Recipe for Success

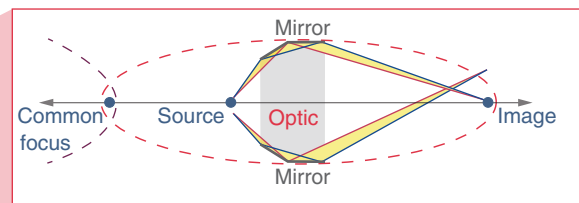
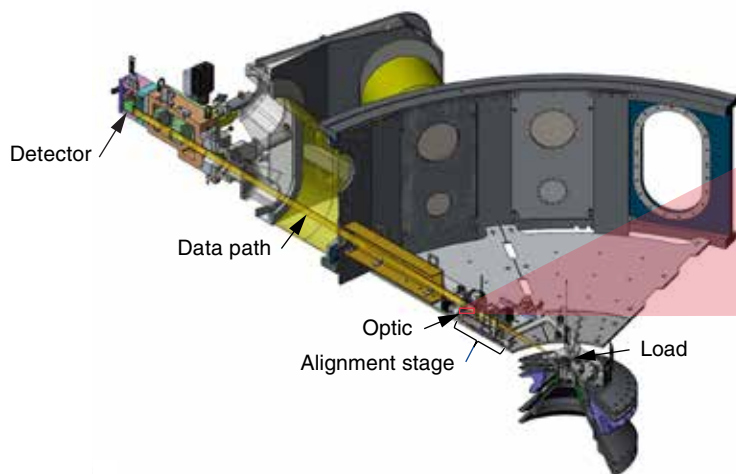
During previous experiments using the Z machine, a traditional time-integrated pinhole camera funneled x rays through a tiny aperture to create two-dimensional (2D) images of the x-ray sources under investigation. However, these images were usually low-resolution approximations, inhibiting scientists' ability to capture key details from the tests. When developing the Wolter microscope, Vogel's team first had to ensure that the optical requirements determined by Sandia scientists were met. For example, spatial resolution had to be better than 100 micrometers over a field of view that is 5 by 5 by 5 millimeters cubed. Other considerations included



Sandia National Laboratories' Z machine is the world's strongest pulsed-power facility. It produces intense x rays and extremely high temperatures and pressures for high-energy-density experiments. (Image courtesy of Sandia National Laboratories.)

the spectral response of the optic and its efficiency, which was tailored to the photon energies present in the experiment. Space constraints within the facility were also a factor. Using these criteria, the team defined the conic parameters of the optic to achieve the desired field of view, spatial resolution, and energy response, and then created hyperboloidal and ellipsoidal mirrors with those parameters using replication—a fabrication technology advanced by NASA MSFC.

Although the geometric design of the Wolter optic largely determines its spatial resolution and field of view, spectral response and throughput (the number of photons that pass through it) can be enhanced by depositing multilayer coatings onto the mirrors' surfaces. "The resolution of traditional pinholes can be improved by making them smaller, but that means fewer photons can pass



This diagram shows the Wolter microscope fielded on the Z machine. (inset) The optic consists of hyperboloidal and ellipsoidal mirrors that enable a wider field of view and help focus the x rays onto an image plane. Multilayer coatings on the mirrors' surfaces improve their performance.

through the aperture,” says Vogel. “Wolter optics decouple these two quantities.”

To increase the throughput and tailor the energy response to experimental needs, scientists deposit alternating thin layers of high-mass (reflector) and low-mass (spacer) materials onto a mirror to enhance its reflectivity. Vogel explains, “Essentially, x rays are not reflected with normal mirrors, and metallic coatings do not work well at energies greater than approximately 10–12 kiloelectronvolts. Multilayers enhance reflection using constructive interference, allowing more reflectivity at higher energies.” Vogel and the Livermore team ultimately decided on multilayers made of tungsten and silicon based on the materials’ well-studied properties.

The multilayers can also be customized for an experiment to study a particular energy range. “You can apply the multilayer coating to the Wolter optic to control the photon energy spectrum under examination,” says Louisa Pickworth, leader of the X-ray Measurement and Diagnostic Science group at Livermore’s National Ignition Facility (NIF). “The result is an energy-banded image—similar to a color-coded filter—rather than a broad range of spectral content,” she explains.

A key innovation for this project was developing a method for depositing the multilayer film onto the inner surface of

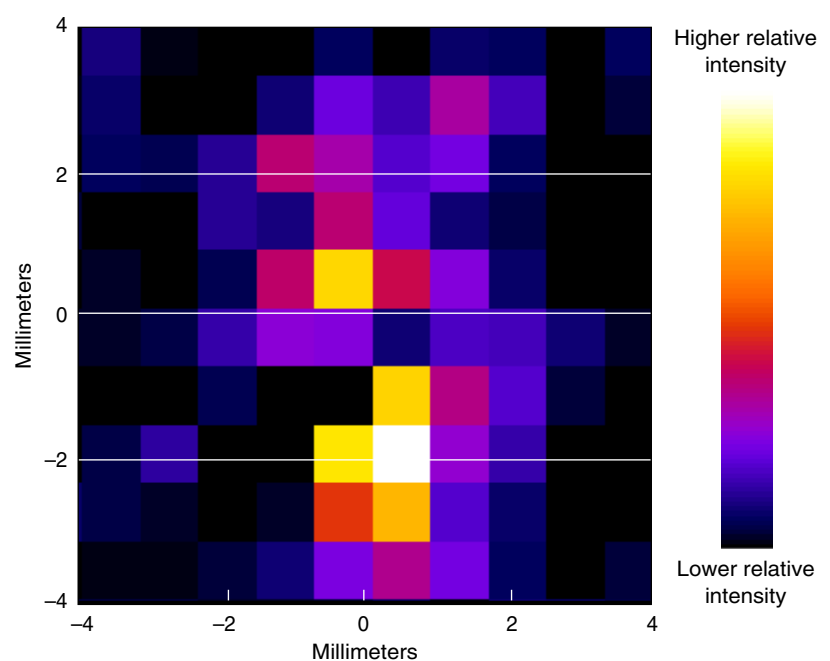
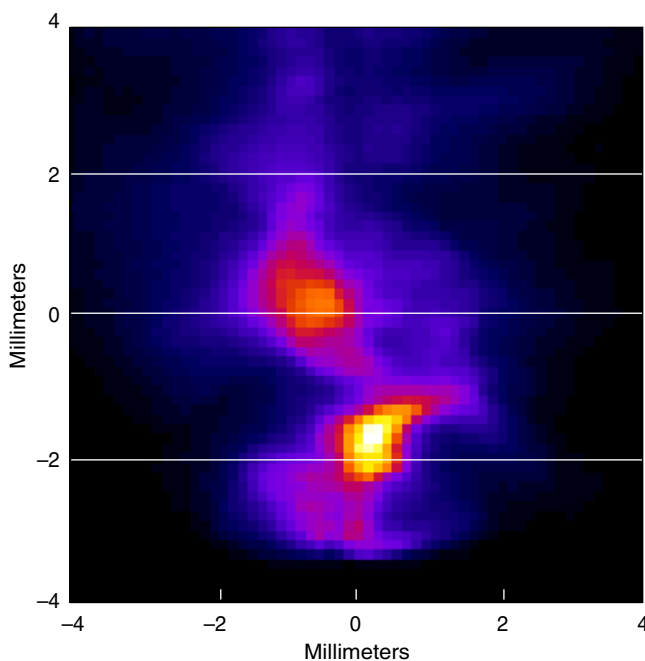
the small-sized optic needed for the Z machine. The Harvard-Smithsonian Center solved this problem by innovating an indirect coating technique. Rather than replicating a mirror shell directly on a mandrel and then coating it—the standard process for larger optics—the new process coats the mandrel with the multilayer first, and then the optic shell is electroformed on top. The mandrel, with optic shell and multilayer in place, is then placed into a cold bath, wherein the shell and the multilayer are released together from the mandrel as a result of thermal expansion. Using this technique, the team could create an optic with the right amount of reflectivity.

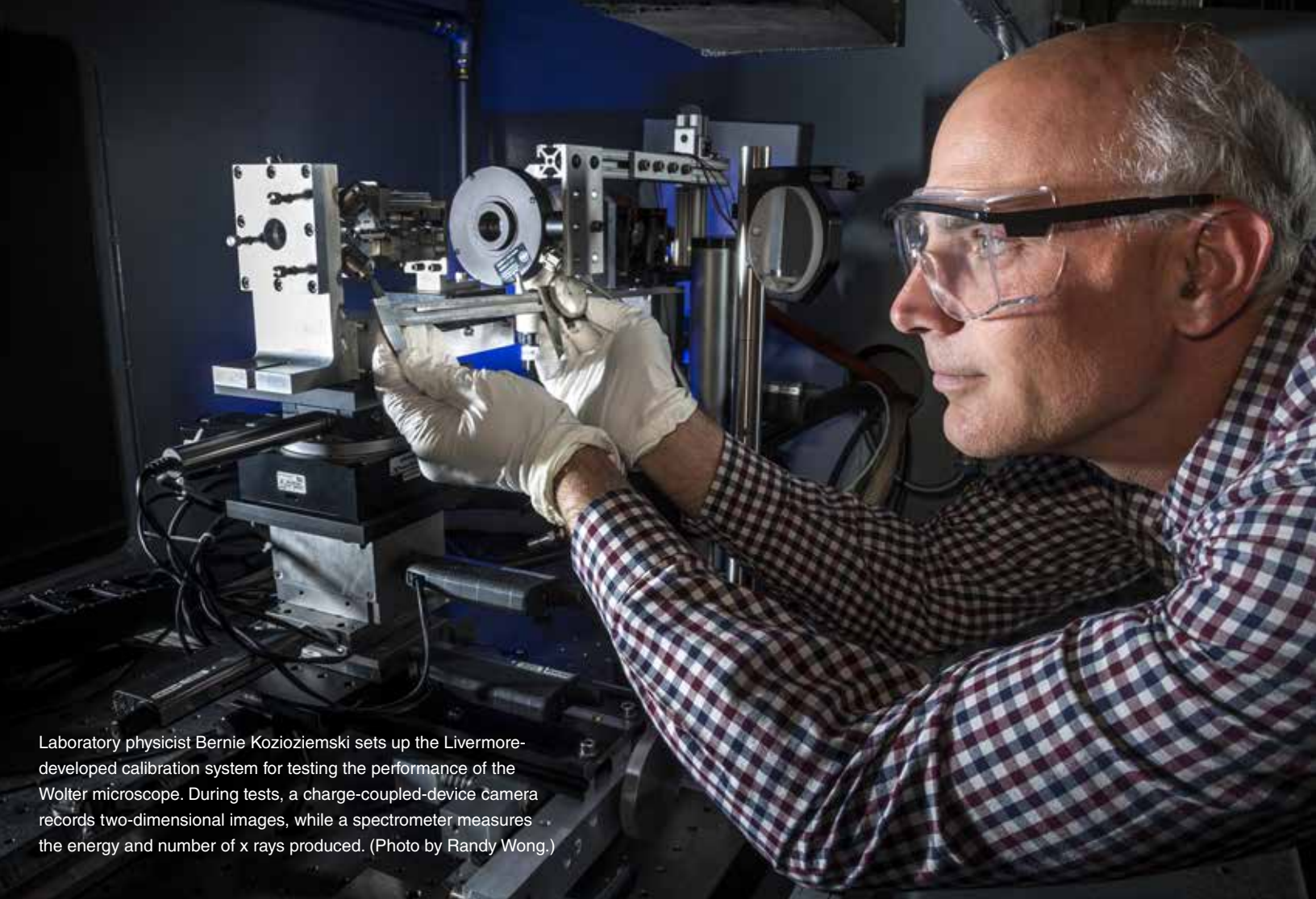
Calibration and Installation

The calibration process verifies that an optic works as expected and allows scientists to characterize its performance. During this time, scientists study the system’s spatial resolution and throughput, as well as determine the ideal distance from the source to the optic and the detector.

At Livermore, scientists created a calibration system in which the Wolter optic, an x-ray point source, and a charge-coupled-device (CCD) camera are placed on stages inside a lead-lined box. Each element can be precisely aligned and adjusted as needed. During calibration tests, the CCD camera records 2D images, while a spectrometer measures the energy and number of x rays produced. The x-ray source is moved around to sample different points in the optic’s field of view, and scientists use both the CCD images and spectrometer output to evaluate the Wolter optic’s performance. “We want to sample the most points possible with a

Initial tests at Sandia’s Z machine have shown that the spatial resolution of x-ray images achieved with the Wolter microscope (left) is significantly better than that produced using a traditional pinhole camera (right).





Laboratory physicist Bernie Kozioziemski sets up the Livermore-developed calibration system for testing the performance of the Wolter microscope. During tests, a charge-coupled-device camera records two-dimensional images, while a spectrometer measures the energy and number of x rays produced. (Photo by Randy Wong.)

known x-ray source to produce a map of the optic's performance over its field of view," says Livermore x-ray physicist Bernie Kozioziemski, lead designer of the calibration system. "We are essentially simulating the source for the Z machine."

Sandia scientists use the calibration information to precisely position the optic within the full instrument system they designed and built for experiments on the Z machine. Initial tests have demonstrated x-ray results that surpass the performance of conventional diagnostics at the high energies studied. The next iteration of the Wolter optic is expected to achieve resolutions down to the desired 100 micrometers.

Next Steps

Vogel and the team eventually plan to integrate the Wolter optic into NIF, where the imaging specifications are much more stringent—better than 5 micrometers. "A challenge at NIF is detecting hard x rays greater than 50 kiloelectronvolts," says Pickworth. "Hard x rays tend not to interact with detectors—so many photons must be collected to sense them. We can improve detectors by either making them more sensitive or by channeling more photons their way with more efficient imaging systems." The first reflective optics developed for NIF (a

Kirkpatrick–Baez microscope) can achieve a spatial resolution better than 5 micrometers, but this system collects fewer photons than a Wolter system would, limiting the highest energies it can view to approximately 13 kiloelectronvolts.

With a Wolter microscope, NIF could achieve the large collection efficiency and spatial resolution needed to image hard x rays. Pickworth says, "The ability to look at hard x rays would open experimental schemes that are inaccessible today. This capability could also be coupled with more advanced detector technology under development." The team's efforts for adapting the Wolter microscope to NIF include further fine-tuning the optic fabrication method and the multilayer coating. Pickworth emphasizes the importance of the optic for NIF in a way that only a scientist can. She says, "It will be a transformative technology."

—Lauren Casonhua

Key Words: calibration system, grazing incidence mirror, multilayer coating, National Ignition Facility (NIF), pulsed-power x-ray source, Wolter microscope, Wolter optic, x-ray imaging, Z machine.

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MILITARY EDUCATION PROGRAMS A TWO-WAY STREET

LAURENCE Livermore's connection with the U.S. military goes back to its very inception. Shortly after its founding in 1952, the Laboratory began hosting officers from the branches of the Armed Services with nuclear warfighting responsibilities (Army, Navy, and Air Force). These officers came to the Laboratory as military research associates, and their assignments lasted 2.5 years, on average. Over the course of the program, which the Department of Defense (DOD) concluded at the end of the Cold War, approximately 350 officers completed tours of duty in various scientific and engineering assignments.

Military education and outreach made a resurgence in the late 1990s, when Livermore human resources specialist Barry Goldman helped institute the Military Academic Research

Associates program, with the mission of funding cadets and midshipmen from the service academies. In the same timeframe, the Laboratory implemented Reserve Officers Training Corps (ROTC) internships, wherein cadets and midshipmen are recruited nationally and brought on as summer hires for 12 weeks. The Newly Commissioned Officer program also offers three- to nine-month appointments for second lieutenants, as they await their first military assignments.

Today, new links continue to be forged through these and other military education and outreach programs offered by the Laboratory's Office of Defense Coordination (ODC), which provides a unified point-of-contact to DOD. Annually, as part of the Air Force Fellows program, up to four participants

(Photo by Carrie Martin.)

come to the Laboratory for one year to familiarize themselves with Lawrence Livermore and the National Nuclear Security Administration (NNSA) and exchange ideas with Laboratory scientists. This exchange helps direct Livermore's research efforts to be more applicable "in the field" and provides the fellows with insights into diverse national security issues.

Fulfilling a Need

The Air Force Fellows program dates back to 2004, when the military branch became concerned over the loss of nuclear expertise among its officers. At that time, Air Force Brigadier General Bob Smolen reached out to Livermore's George Sakaldasis, a retired Air Force colonel then in the National Security Office, and together they established the fellows program. Holly Franz, who oversees military education programs for ODC, says, "The fellows act as translators from scientists to operators and back. They help ensure that the capabilities delivered by the Laboratory meet operational needs in the field."

Fellows provide critical operational insight into various national defense research efforts, ensuring key emerging technologies are provided to the warfighter. Their input and participation in programmatic activities reinforces the Laboratory's commitment to strengthening national security through research, development, and application of world-class science and technology. Fellows arrive for their yearlong stints in August. Their assignments begin with a week-long nuclear expertise course, a visit to the Nevada National Security Site, and the "Survey of Weapons Development and Technology" course offered by Sandia National Laboratories in Livermore, California. "The fellows get credit for intermediate development courses, just as if they were attending the Air Command and Staff College," explains Sakaldasis, who now assists the ODC director, Chuck Lutes, on military affairs.

Over the years, the fellows have contributed to a range of Laboratory initiatives and programs, including counterproliferation, advanced conventional weapons, and life-extension programs (LEPs). "We provide them with assignments in their areas of expertise and interest that support Air Force missions," says Franz. The Laboratory looks for officers with proficiency in technologies such as radar, photonics, laser systems, and software that focuses on modernization and optimization of the stockpile as well as cyber-warfare and technologies related to nuclear command, control, and communication.



The BLU-129B warhead was developed at Livermore for the U.S. Air Force. The highly effective, low-collateral-damage munition allows troops to maneuver in tight, often densely populated areas while minimizing inadvertent casualties or destruction of infrastructure.

A Breadth of Experience

Majors Chris Coleman and Andrew Paulsen, both B-52 weapons officers from the Air Force Global Strike Command, were fellows from 2017 to 2018. They found their time at Livermore to be educational and eye-opening. Paulsen says, "Instead of focusing on a single project, I chose to spend most of my fellowship interacting with different individuals in as many areas as I could. Taking this approach allowed me to build a foundation for a spectrum of projects ranging from conventional low-collateral-damage weapons, advancements in additive manufacturing, ongoing projects within the nuclear enterprise, and more." Coleman adds, "To be honest, I was largely an active sponge during my time at Livermore, trying to understand and experience as much as I could in that year." He was initially drawn to the weapons program, with distinct interests in warhead survivability and LEPs. "However, what really made my experience valuable was the flexibility provided by the ODC program," he says.

Through Coleman's initial contact, he met others who worked in multiple or branching programs ranging from high-powered computing applications, conventional weapons design, advanced manufacturing, and the Laboratory's intelligence program. "Although I am sure I did not even scratch the surface of Lawrence Livermore's capabilities, the breadth of experience I was given during my limited time at the site demonstrated to me the tremendous scope of the Stockpile Stewardship Program and how Livermore capitalizes on the science and technologies that result from the program to provide potential cost-effective



Air Force Fellows (from left to right) Major Daniel Gebhardt, Major Michael Valdivia, civilian Cara Jones, and Major Bryan Kelly spent a week at the Nevada National Security Site as part of their Laboratory assignment. The building in the background is a bank vault (designed by the Mosler Safe Company, San Francisco, California). The vault was constructed for the Priscilla test, conducted in June 1957.

modernization technologies relevant to both civilian and military applications,” he says. Coleman also worked with Paulsen and Livermore’s Matthew Weingart in ongoing efforts to educate the warfighter on the capabilities of the Livermore-designed, low-collateral-damage BLU-129B munition and to expand current DOD modeling and simulation capabilities regarding the weapon. (See *S&TR*, March 2013, pp. 4–9.)

For this program year, the Laboratory is hosting Major Daniel Gebhardt, Major Bryan Kelly, Major Michael C. Valdivia, and Air Force civilian Cara Jones. Kelly, working alongside members of Livermore’s science and technology community, is eager to learn about the various key emerging technologies at Livermore and to share his DOD perspective, where applicable. “I am researching the role of testing in aircraft software development,”

he explains. “As such, I converse weekly with Livermore’s software development teams to further my knowledge of modern test tools and where they best fit into various aircraft software development frameworks.” He also wants to learn more about the Laboratory’s light-field directing array technology and ultimately contribute to its test planning.

Jones anticipates broadening her knowledge on the science and technology aspects of the nuclear enterprise and ultimately returning to the Air Force with a deeper understanding of, and appreciation for, how the Laboratory contributes to nuclear deterrence. She adds, “I am excited to provide an Air Force perspective and contribute to Laboratory projects.” Jones, Gebhardt, and Valdivia are working on a joint project to explore the progression of the nuclear weapons testing program from its earliest post–World War II origins to the present, from a scientific and geopolitical perspective. The goal is to gain insights from the past into what the next possible “abrupt change” might be that could trigger a shift in how the nation’s stockpile readiness is evaluated.

Connections Lead to Deeper Understanding

Laboratory support for military education and active duty personnel continues to expand, notes Franz. For instance, the



Laboratory offers a monthly NNSA Nuclear Enterprise course for the professional development programs given to personnel in the 20th Air Force ICBM (intercontinental ballistic missile) Center of Excellence and the 8th Air Force. This 3-day course is attended by 10 to 20 senior enlisted personnel and junior to mid-level officers. ODC also hosts students from the Naval Postgraduate School (NPS) in Monterey, California, who come to Livermore to perform research. In addition, the Laboratory sponsors an annual ROTC Day, which is an opportunity for ROTC cadets, midshipmen, and cadre to learn about Laboratory programs supporting DOD, the military, and national security.

Lawrence Livermore recognizes the importance of education and supporting current and future military leaders as they advance throughout their careers. Toward this goal, the Laboratory takes steps to understand trends in science and technology as it applies to the institution's national security missions, and makes connections, fosters relationships, and enhances communication between members of the armed forces and Laboratory staff. Notes Major Paulsen, "One of the most valuable aspects of my time at Livermore was the interactions and relationships I formed throughout the year. The chance

The annual Reserve Officers Training Corps (ROTC) Day is sponsored by Livermore's Office of Defense Coordination and the Strategic Human Resources Management Directorate. During the event, attendees learn about the Laboratory as well as internship and career opportunities offered through the ROTC internship program and the Newly Commissioned Officer program. (Photo by Julie Russell.)

to work alongside many of the Laboratory's experts was a tremendous opportunity that helped shape my own perspectives and understanding of some of the most difficult national security problems the nation faces today."

—Ann Parker

Key Words: Air Force Fellows program, Armed Forces, BLU-129B, life-extension program (LEP), military, Military Academic Research Associates program, Newly Commissioned Officer program, Office of Defense Coordination (ODC), Reserve Officers Training Corp (ROTC), stockpile stewardship.

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In this section, we list recent patents issued to and awards received by Laboratory employees. Our goal is to showcase the distinguished scientific and technical achievements of our employees as well as to indicate the scale and scope of the work done at the Laboratory. For the full text of a patent, enter the seven- or eight-digit number in the search box at the U.S. Patent and Trademark Office's website (<http://www.uspto.gov>).

Patents

High Temperature Oxygen Treated Carbon Aerogels

Michael Stadermann, Theodore F. Baumann, Alexander E. Gash, Alex P. Parra

U.S. Patent 10,008,338 B2
June 26, 2018

Three-Dimensional Electronic Scaffold for Cardiac Applications

Fang Qian, Mihail Bora, Eric Duoss, Christopher Spadaccini, Cheng Zhu

U.S. Patent 10,018,615 B2
July 10, 2018

Separation of a Target Substance from a Fluid or Mixture Using Encapsulated Sorbents

Roger D. Aines, Christopher M. Spadaccini, Joshua K. Stolaroff, William L. Bourcier, Jennifer A. Lewis, Eric B. Duoss, John J. Vericella

U.S. Patent 10,029,206 B2
July 24, 2018

Waveguide Design for Line Selection in Fiber Lasers and Amplifiers

Paul H. Pax, Graham S. Allen, Jay W. Dawson, Derrek Reginald Drachenberg, Victor V. Khitrov, Michael J. Messerly, Nick Schenkel

U.S. Patent 10,033,148 B2
July 24, 2018

Architected Materials and Structures to Control Shock Output Characteristics

Alexander E. Gash, Eric B. Duoss, Joshua D. Kuntz, Kyle T. Sullivan, John Vericella, Bradley W. White

U.S. Patent 10,036,616 B2
July 31, 2018

Stent with Expandable Foam

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U.S. Patent 10,080,642 B2
September 25, 2018

Awards

Tammy Ma, an experimental plasma physicist in inertial confinement fusion (ICF) and high-energy-density (HED) physics at Lawrence Livermore, has been named a recipient of the prestigious **Department of Energy (DOE) Office of Science Early Career Research Program**. The program, now in its 9th year, is designed to bolster the nation's scientific workforce by providing support to exceptional researchers during the crucial early career years, when many scientists do their most formative work. Awardees are selected from a large pool of university and national laboratory-based applicants according to a peer review by outside scientific experts.

Under the program, Ma will receive a total of \$2.5 million in research funding over five years for her proposal, "Multi-ps short-pulse laser-driven particle acceleration for novel HED and ICF applications." Ma currently serves as chair of the Laboratory Directed Research and Development Program's Labwide committee and also as the X-Ray Analysis Group lead for the Laboratory's ICF Program at the National Ignition Facility.

Lawrence Livermore magnetic fusion physicist **Max Fenstermacher** has been awarded the **2018 John Dawson Award for Excellence in Plasma Physics Research** from the **American Physical Society**. He is cited jointly with Todd Evans of General Atomics and Richard Moyer of the University of California at San Diego for "the first experimental demonstration of the stabilization of edge localized modes in high-confinement

diverted discharges, by application of very small edge-resonant magnetic perturbations, leading to the adoption of suppression coils in the ITER design." ITER is an international nuclear fusion research and engineering megaproject, which will be the world's largest magnetic confinement plasma physics experiment.

The Dawson Award recognizes a particular recent outstanding achievement in plasma physics research. The award consists of \$5,000 to be divided equally in the case of multiple recipients, and includes a certificate citing the contributions made by the recipient(s).

Lawrence Livermore retiree **Bruce Cohen** has been selected as the recipient of the **2018 Charles K. Birdsall Award** from the **IEEE Nuclear and Plasma Sciences Society**. He was cited for "contributions to the numerical simulation of plasmas, particularly multiple time-scale methods and to their application to diverse plasma physics problems, from laser-plasma interactions to tokamaks."

The Birdsall Award recognizes outstanding contributions in computational nuclear and plasma science, with preference given to areas within the broadest scope of plasma physics encompassing the interaction of charged particles and electromagnetic fields. Cohen's achievement marks the fourth year this award has been presented and the second time a Lawrence Livermore researcher has won.

Space Program Innovation, One Small Satellite at a Time

Cube satellites, called CubeSats, are a common type of nanosatellite comprising a modular framework of cube-shaped building block units that measure 10 centimeters per side. Their lower cost and ease of construction compared to large, conventional satellites have made them a popular choice for modern space applications. Lawrence Livermore's first involvement with CubeSats began nearly a decade ago when scientists developed optical imaging payloads for the Space-Based Telescopes for the Actionable Refinement of Ephemeris project to monitor space debris. More recently, as part of a collaboration with NASA Goddard Space Flight Center, the Laboratory has helped develop the MiniCarb CubeSat for measuring atmospheric greenhouse gases. MiniCarb will be the first to use the innovative, Laboratory-developed CubeSat Next Generation Bus platform, ushering in a new era for the institution's Space Science and Security Program.

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A Small Chip Promises Big Payoffs



Livermore's brain-on-a-chip could advance understanding of how the brain functions, as well as aid the development of antidotes to toxic compounds, including chemical warfare agents.

Also in May

- *A gamma-ray spectrometer being sent to space will provide insights into the formation of Earth and other rocky planetary bodies.*
- *Preparations for isotope harvesting at an advanced radioactive beam facility yield a surprising result.*
- *Using the National Ignition Facility, researchers create extreme x-ray and neutron conditions to test the nation's nuclear stockpile.*

Science & Technology Review
Lawrence Livermore National Laboratory
P.O. Box 808, L-664
Livermore, California 94551

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