EXTENDING THE LIFE OF A **WORKHORSE WARHEAD**

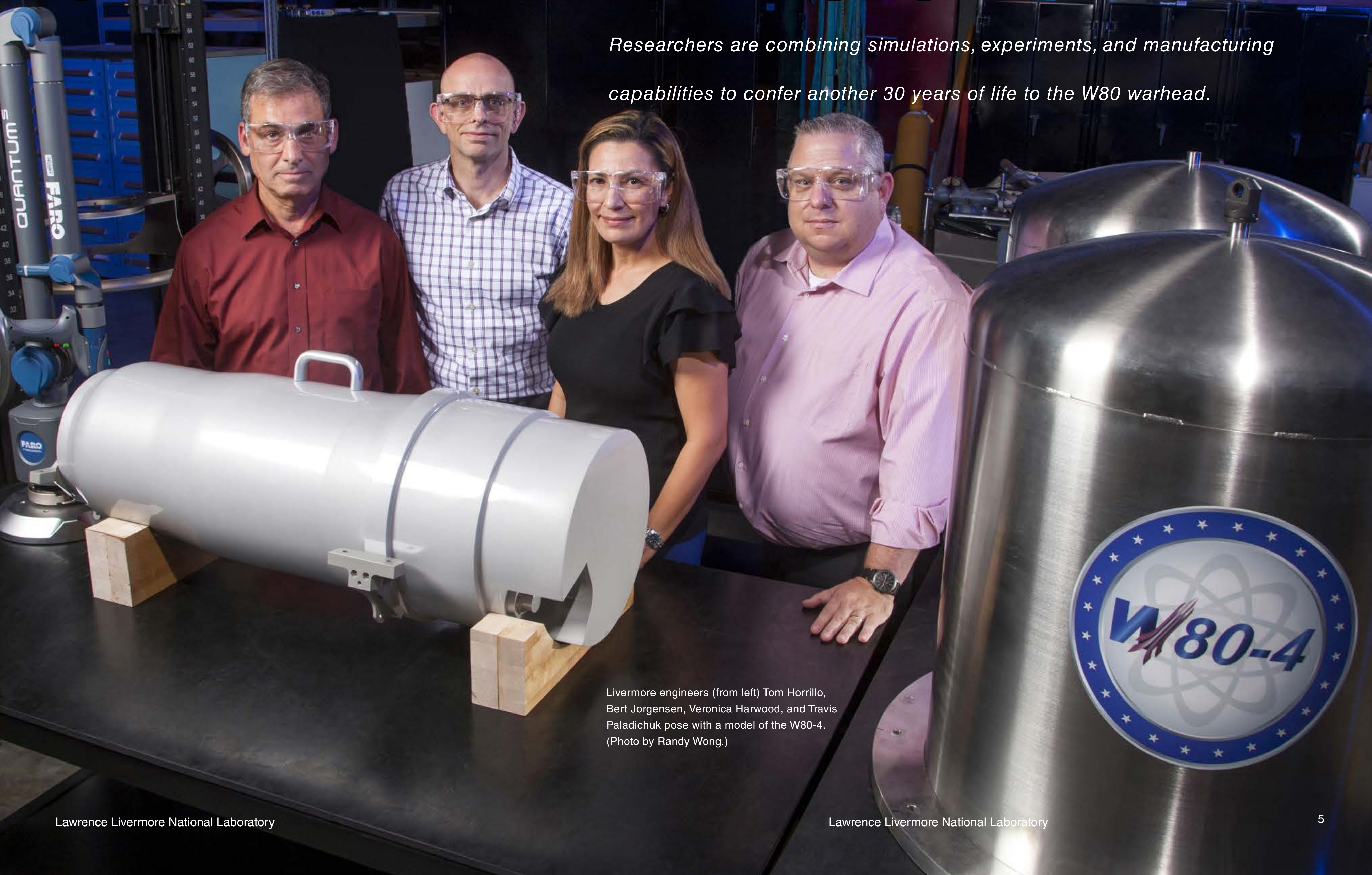
Researchers are combining simulations, experiments, and manufacturing capabilities to confer another 30 years of life to the W80 warhead.

IN today's era of stockpile stewardship, no effort focuses the Laboratory's technical resources as much as a life-extension program (LEP) aimed at adding 30 years of service life to an aging nuclear warhead. In 2014, the National Nuclear Security Administration (NNSA) selected Lawrence Livermore as the lead nuclear design agency for refurbishing the W80-1 nuclear explosives package as the W80-4 LEP, setting in motion the most significant weapons development program at the Laboratory since the end of the Cold War.

The W80-1 warhead, originally developed by Los Alamos and Sandia national laboratories, is carried on the Air-Launched Cruise Missile (ACLM), which entered service in 1982. Thirty-six years later, both the missile and its warhead are well past their planned lives. The Long-Range Standoff (LRSO) missile, currently under design, will be the ALCM's replacement. LRSO, coupled with the W80-4, will be carried on the U.S. Air Force B-52 and B-21 aircraft.

Six Decades of Experience

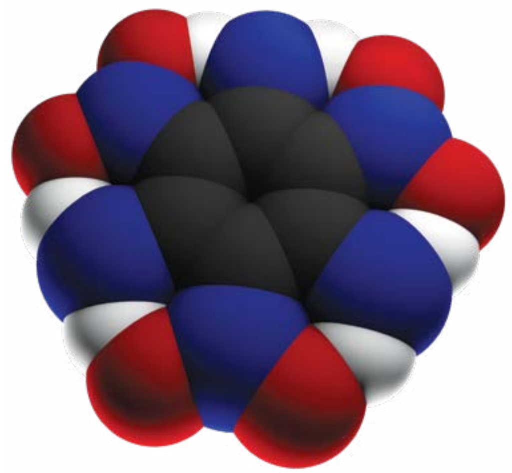
The full array of NNSA's computational, experimental, and manufacturing capabilities are needed for all prototyping, proof-of-concept design testing, certification, and surveillance activities required by an LEP. In particular, the program takes advantage of Livermore's high-performance computing (HPC) and experimental tools developed through the NNSA's science-based Stockpile Stewardship Program, which ensures the safety, security, and effectiveness of the nation's nuclear arsenal without resorting to nuclear explosive tests. Key capabilities also include the Contained Firing Facility (CFF), the largest



Livermore engineers (from left) Tom Horrillo, Bert Jorgensen, Veronica Harwood, and Travis Paladichuk pose with a model of the W80-4. (Photo by Randy Wong.)

indoor firing chamber in the United States; the National Ignition Facility (NIF), the world's largest and most energetic laser; and the High Explosives Applications Facility (HEAF), a Department of Energy–NNSA Center of Excellence for high explosives (HE) research and development.

Tom Horrillo is the Livermore program manager for the LEP effort and serves as the principal liaison with NNSA, other NNSA sites, and the Department of Defense. "We have a very good and close working relationship with Sandia National Laboratories, NNSA, and the U.S. Air Force," says Horrillo. He notes that other sites across the NNSA complex will participate in production of the W80-4 warhead. Livermore scientists and engineers are



Triaminotrinitrobenzene (TATB) is an insensitive high explosive that will be used for the warhead's main charge. Livermore engineers and chemists are helping to restart the TATB production process after 30 years of dormancy. (Rendering by Adam Connell.)

Anatomy of a Life-Extension Program

After nuclear testing ended in 1992, the United States began extending the life of existing warheads rather than developing new ones. The science-based Stockpile Stewardship Program, established in 1994, is based on advanced simulations and experiments conducted at the National Ignition Facility and elsewhere within the National Nuclear Security Administration complex to provide improved knowledge of the underlying physics and engineering of modern U.S. nuclear weapons in the stockpile.

A critical part of stockpile stewardship is the life-extension program (LEP), which aims to reuse, replace, or redesign aging components that are reaching the end of their service life and therefore require modernization to ensure they remain safe, secure, and effective. Reused components are requalified to go back into a weapon without change. Components determined to be past their original service lives are remanufactured to their original specifications, and if they cannot be remade to those specifications (because the materials are no longer available), they are redesigned using modern materials and manufacturing technologies. LEPs may also use advanced technologies to enhance safety and security characteristics.

Lawrence Livermore scientists and engineers are responsible for the nuclear explosives package for LEPs and must certify the life-extended warheads as they enter the stockpile. Certification of the life-extended warhead is accomplished by extensive component testing, warhead simulations that model the integration of the warhead into the missile, and high-fidelity flight tests. LEPs typically extend the operational lives of weapons by 20 to 30 years.

In the 1990s, Lawrence Livermore scientists, engineers, and technicians began the first LEP, which was undertaken for the W87 ballistic missile warhead. In addition to the current W80-4 LEP effort, Livermore has been assigned to the replacement program for the W78 warhead deployed on the Minuteman III ballistic missile. That effort will resume in the 2019 fiscal year following a five-year hiatus. As with the W80-4 LEP, the planned replacement program for the W78 represents an important opportunity to extend the warhead's service life and incorporate modern safety and security features.

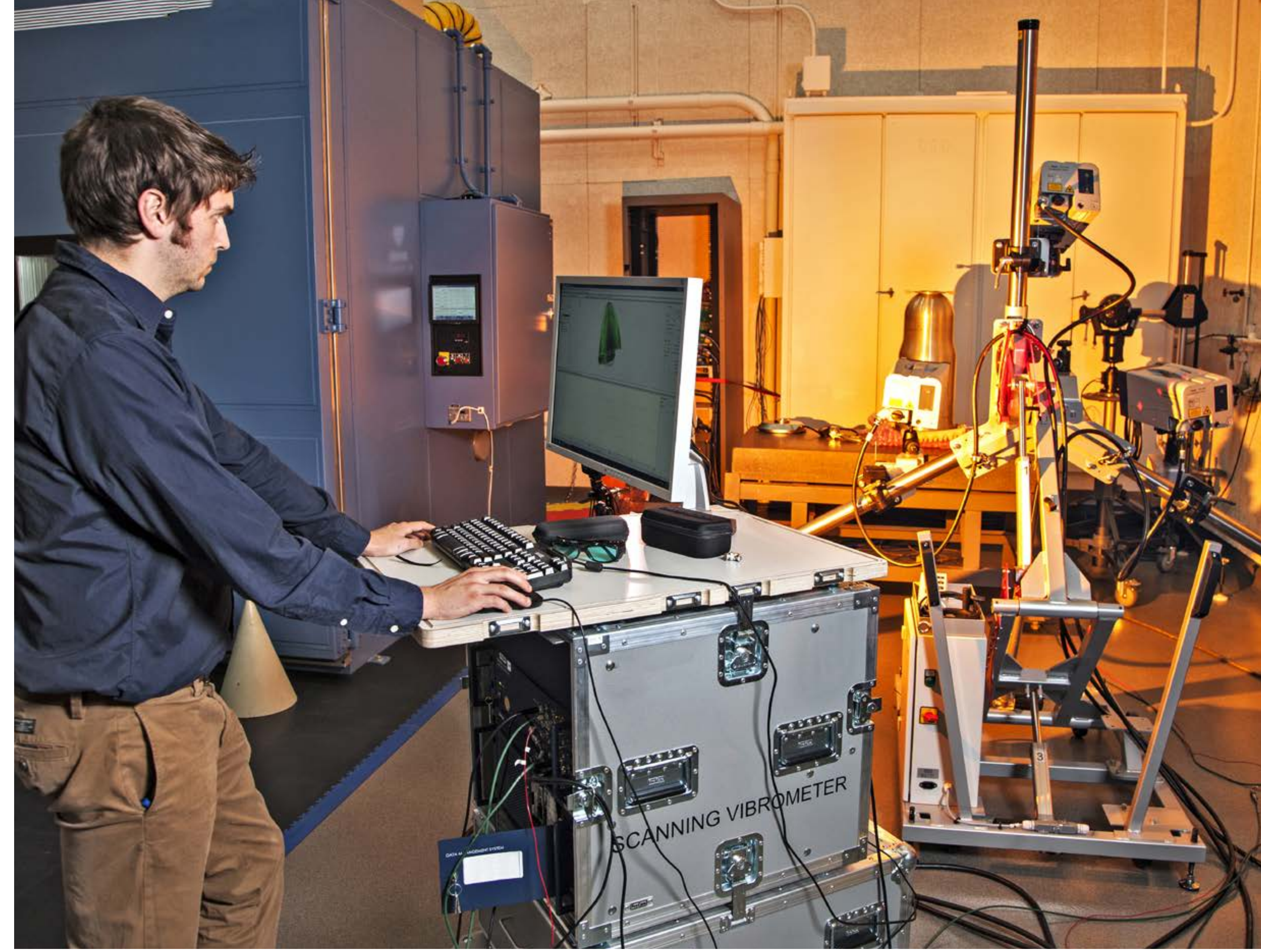
collaborating with Sandia, the lead (nonnuclear) engineering laboratory for the LEP, and the NNSA production plants to develop options for replacing aging components and materials, including new manufacturing methods that minimize costs, increase throughput, and reduce the use of environmentally sensitive materials and processes.

Horrillo notes the refurbished warhead will not introduce any capabilities that do not already exist in the nuclear stockpile. However, the W80-4 warhead will incorporate modern electronics and safety features and use nonnuclear component technologies and designs developed for other LEPs to limit costs and risks. The effort also involves developing a booster that supports safety enhancements and restarting production of triaminotrinitrobenzene (TATB) for the warhead's main charge. "The W80-4 is projected to go out of service in the 2060s," says Horrillo. "Since some warhead parts will be in use for about 80 years, we will need to assess them every year to ensure they meet their original specifications."

Missile Interface Is Critical

The W80-4 is the first U.S. warhead designed for use with a new carrier since nuclear testing ended in 1992. As a result,

The W80-4 warhead (depicted in this artist's rendering) is being developed in partnership with the Department of Defense and will serve the nation into the second half of the century. (Rendering by Adam Connell.)



At Site 300, several facilities subject prototype components to vibration, shock, impact, acceleration, and extreme temperatures. Shown here, an engineer prepares for a laser vibrometer to measure noncontact vibration of a W80-1 test component. (Photo by George Kitrinos.)

an important aspect of the LEP effort is adapting the refurbished warhead to the LRSO missile. The complexities of designing a new missile in parallel with extending the life of the warhead demand close cooperation with the Air Force. Two U.S. contractors, Lockheed Martin and Raytheon, are competing for the contract to build the LRSO missile—the Air Force will decide the winner during the 2022 fiscal year (FY). Says Horrillo, "Lawrence Livermore and Sandia have the responsibility for defining and validating the interface between the warhead and missile." Livermore and Sandia engineers meet regularly with representatives from the Air Force and both contractors to review interface issues.

One aspect of the W80-4 LEP is a program management process that closely tracks costs and technical progress. The process is an outgrowth of findings from previous LEPs, recommendations of multiple NNSA reviews, and industry best practices. Called the Earned Value Management system, the process is designed to ensure more accurate cost estimation and timely delivery of LEP milestones through the "6.X" process, which includes design, development, systems integration, testing, production, and surveillance.

The LEP process begins with Phase 6.1 (concept assessment), which for the W80-4 program commenced in 2014. The following year, the team started Phase 6.2 (feasibility study and design options). In October 2017, the program transitioned to Phase 6.2A (design definition and cost study) to establish detailed cost estimates for all design options. This phase is scheduled to conclude during FY 2019, when program representatives present the team's final design recommendations to the Nuclear Weapons Council. During Phase 6.3 (design engineering),

Technicians know as "ramrods" set up an experiment inside the Contained Firing Facility (CFF), the nation's largest indoor firing chamber. Hydrodynamic experiments at CFF create extreme temperature and pressure conditions to assess the performance of nonnuclear weapon components for life-extension programs (LEPs). (Photo by George Kitrinos.)

scientists and engineers will ensure the warhead meets military requirements. Phases 6.4 (production engineering) and 6.5 (first production) will begin in FY 2022 and FY 2025, respectively, and Phase 6.6 (quantity production and stockpile) will begin in FY 2026.

Facility Modernization Is Key

The experimental campaign for the W80-4 requires robust part and material testing to meet manufacturing and inspection requirements. To support the timely execution of LEP activities, NNSA's Capabilities-Based Investment (CBI) Program has funded a wide range of programmatic equipment recapitalization worth about $75 million. In addition, NNSA's Office of Safety, Infrastructure, and Operations has funded an array of facility improvements worth more than $100 million over the last five years. These investments are aimed at modernizing both the equipment and buildings at Livermore's main site and its remote Site 300, which is located some 32 kilometers away. (Many Lawrence Livermore facilities are 50 years old—or older.) Travis Paladichuk, who leads a large group of engineers assigned to the LEP effort, says that the infrastructure supporting the W80-4 LEP is in high demand. He adds, "We do not have much capacity to spare. Our machine shops are extremely busy."

The LEP effort uses most of Site 300's testing and engineering facilities. The extensive range of tests conducted at the site provide confidence in the performance of W80-4 LEP design options. One type of test simulates the potential environmental conditions a weapon may experience. Prototype HEs, detonators, and other nonnuclear components are subjected to vibration, shock, impact, acceleration, and extreme heat and cold. Other investments in advanced diagnostics provide enhanced data from experiments. For example, CFF hydrodynamic tests combined with the high-energy diagnostic known as the Flash X Ray provide data to assess the science and operation of nonnuclear weapon components for LEPs. (See *S&TR*, July/August 2018, pp. 20–23.) These tests use surrogate metals in place of nuclear materials and create temperatures and pressures so great that solids behave similarly to liquids. Results of hydrodynamic tests help scientists refine computational models that simulate nuclear weapon performance.

At Livermore's main site, investments have been focused at HEAF—incorporating computed tomography and other advanced diagnostics—and at several key engineering facilities. In addition, a 31-ton, state-of-the-art hydraulic press, called a hydroform, was brought online in 2016 as part of the CBI Program. The hydroform is used to build nonnuclear parts for LEP-related experiments. The computer-controlled machine replaces a manually operated hydroform and offers higher part throughput and improved repeatability with reduced material waste.

Analysis of Aging Materials

The W80-4 must be effective for three decades, thus a critical task of the LEP is understanding how the warhead's constituent parts will age and assuring that those aging processes will not significantly degrade performance of a particular component or one located nearby. "We will be putting old and new parts together in the refurbished warhead," says lead materials scientist Pat Allen. "In particular, new materials, especially those produced with advanced manufacturing processes not available two decades ago, require careful accelerated aging and compatibility testing." Allen explains that a polymer, for example, may emit low levels of residual water over time as it ages. He says, "We need to know whether the water could affect other parts of the system, or if a very small amount of water proves harmless."

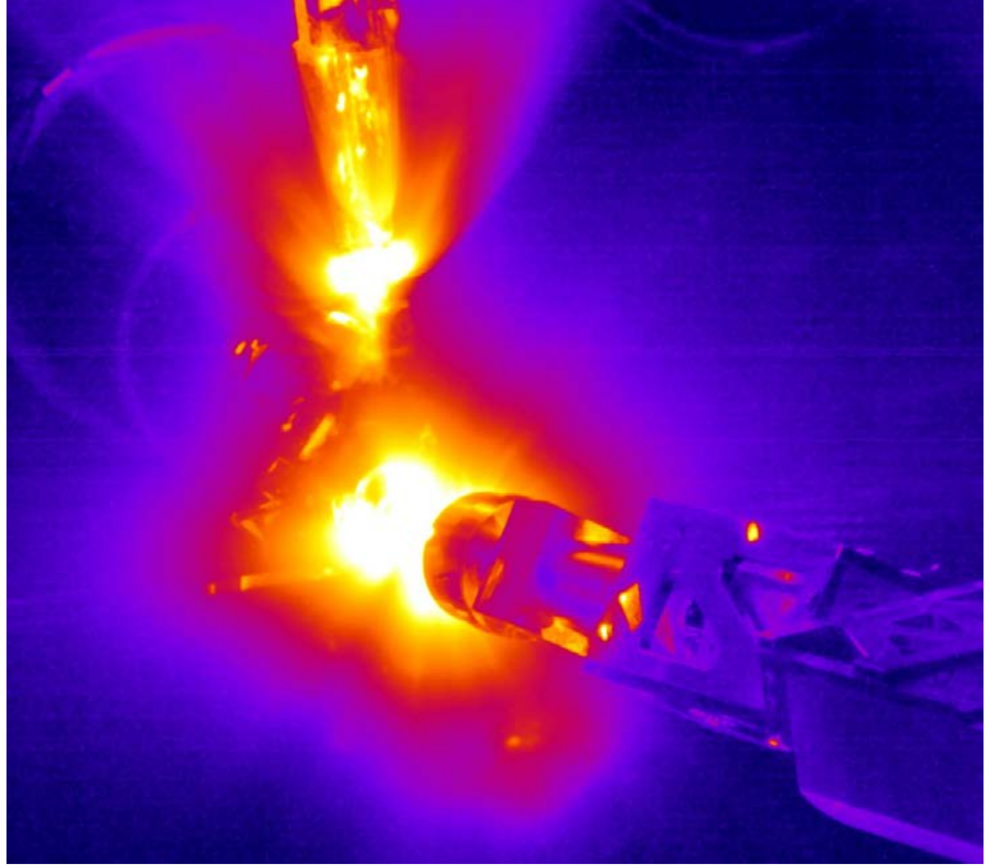
Researchers have at their disposal two types of controls for accelerated aging tests. The first is temperature, to accelerate chemical reactions by "cooking" materials at elevated levels. The second is radiation, for approximating the exposure effects to parts over their 30 years in close proximity to special nuclear materials. Allen notes that data gathered from accelerated aging tests are supplemented with computer models, which through the years have helped scientists predict the behavior of aging materials and mitigate potential aging issues.

Starting Up HE Production

For added safety, the W80-4 will use a modern initiation train to set off the HEs that ultimately lead to nuclear detonation. This system includes a detonator, booster, and the main HE charge, each of which uses different HE formulations (explosive molecule and inert binder). Veronica Harwood, lead HE engineer for the LEP, notes that once the W80-1 warheads are disassembled, the legacy HE cannot be reused.

The main charge uses PBX 9502, which consists of TATB and binder. TATB is an insensitive high explosive (IHE), which means it has greatly lessened the possibility of accidental initiation from heat, shock, bullet impact, electrostatic discharge, or other unplanned stimuli. Livermore engineers and chemists have been working to restart the TATB production process after 30 years of dormancy because not enough of the material exists in reserves for the forthcoming W80-4 warheads. The goal is to manufacture TATB with the same performance characteristics as the W80-1. Unfortunately, many of the production details from three decades ago have been lost.

Machinists Wes Scoggins (left) and Ron Cabeceiras examine a steel sheet before pressing it into a test part with a new hydroform, the key tool for building experimental parts for the W80-4 LEP. (Photo by Julie Russell.)



Experiments conducted at the National Ignition Facility (NIF) are uniquely capable of informing and validating three-dimensional weapons-simulation computer codes that support the W80-4 LEP effort. This NIF experiment was aimed at developing a high-pressure strength measurement capability for plutonium.

Livermore chemists have analyzed more than 50 pilot-scale batches of TATB to establish a reproducible set of manufacturing conditions. "We want to understand how the physics performance relates to synthesis parameters," says Harwood. Conditions such as different stirring rates and the scaleup to 1,000-gallon production equipment can affect the size and morphology of TATB particles. Harwood notes that subsequent LEPs will also rely on PBX 9502 formulated using the newly produced process. As a result, the Livermore team has been diligently documenting how the newly synthesized TATB's manufacturing details affect its performance.

Separately, a research team is preparing a new HE booster with improved safety performance. The LX-21 booster is an IHE "candidate" and consists of LLM-105, an energetic molecule developed at Livermore. In another effort, the detonator will use the explosive LX-16, a Livermore formulation. Paramount to the HE research and development program are HEAF and Site 300 facilities that support synthesis, formulation, processing, testing, and evaluation of newly manufactured HEs. A small plant for producing TATB and LLM-105 is planned for Site 300.

Simulating by the Nanosecond

As the nation's weapons age long past the point at which the designers assumed they would be replaced, Livermore scientists must assess their performance with the highest possible level of confidence. Simulations conducted as part of NNSA's Advanced Simulation and Computing Program offer a computational surrogate for informing judgment on weapons behavior, which was historically done via simulations combined with nuclear testing. Simulations model much of the complexities of nuclear weapon systems and provide a clearer understanding of the factors affecting weapons performance. Three-dimensional (3D), high-fidelity simulations allow physicists to more clearly observe phenomena at nanosecond-scale resolution.

Scientists combine extensive experimental data with computer simulations to understand and assess the safety and performance of refurbished and new components. For example, a family of increasingly accurate computer codes predicts the performance of new energetic material formulations, as validated with experiments. In addition, accurate simulations help reduce design iterations compared to building and testing prototypes. The large number of simulations is also driven by the requirement that the refurbished warhead be compatible with the LRSO missile.

In all, LEP-affiliated simulations consume about 40 percent of Livermore's enormous classified supercomputer capacity. Sierra, the Laboratory's next-generation supercomputer, with a peak speed of 125 floating-point operations per second, will play an important role in assessing W80-4 performance and LEP certification.

192 Beams of Light

NIF experiments strengthen the technical foundation of the W80-4 LEP and inform design and material options. The most extreme conditions that can be created in a laboratory are in the high-energy-density (HED) regime, where materials often behave in unexpected ways. NIF makes it possible to test materials in HED regimes formerly inaccessible to scientists.

Physicist Seran Gibbard conducts HED experiments at NIF that focus on determining materials' equation of state (EOS)—that is, the relationship between pressure, temperature, and density. Data from these experiments help advance scientific understanding and refine supercomputer models. Gibbard notes that the LEP efforts involve replacing legacy materials with counterparts made using new processes. "With EOS experiments, we heat the material, run a

shock wave through it, and see how the material responds. We test legacy and new materials simultaneously, so we can directly compare the two."

Gibbard also conducts a second type of NIF experiment that studies the behavior of new materials exposed to radiation for determining whether the inevitable impurities found in every material could affect performance. In both EOS and radiation experiments, NIF laser beams typically strike the inside of a hollow gold-lined cylinder called a hohlraum and produce x rays. For EOS tests, the x rays heat the material and create a shock, and for radiation experiments, the x rays penetrate the materials under study.

Approximately a dozen NIF tests are conducted yearly that support the W80-4 LEP. Together, data generated from NIF experiments and accelerated aging tests help to inform and validate 3D weapons-simulation computer codes and facilitate a broader understanding of important weapons physics. Says Gibbard, "In the absence of nuclear testing, NIF is the only experimental facility that can produce the energy levels we require for capturing the necessary data."

Where Art and Necessity Meet

The physicists and engineers working on the W80-4 LEP are presented with a formidable challenge. They must be able to confidently certify that the myriad parts of the life-extended warhead will have the desired performance. The key to addressing this difficult task is what Livermore design physicists call "the art of design." Mike Dunning, acting principal associate director for Livermore's Weapons and Complex Integration Principal Directorate, says, "The designer must fully grasp the objectives of the LEP effort and make them happen."

Dunning explains that the art of design is knowing how to differentiate between needing to solve a problem directly and getting around it without compromising performance or safety. "Sometimes we have to understand the chemistry or physics in exquisite detail. Other times we can design around a particular challenge by avoiding areas we do not comprehend as well as we would like." In addition, designers must also be mindful of what can be accomplished within the NNSA production complex.

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According to Dunning, experienced designers know how to navigate this complicated landscape. A particular necessity is training new people to be "navigation" experts, especially the hundreds of scientists and engineers hired in the past few years to help meet the Laboratory's growing national security responsibilities. In this respect, the W80-4 LEP affords people an opportunity to exercise existing skills and learn new ones by conducting experiments at NIF and other one-of-a-kind facilities at the Laboratory.

Dunning observes that many members of the W80-4 team have been at Lawrence Livermore for less than a decade and are working alongside more experienced staff on the program. "Very few people at the Laboratory have LEP experience," says Horrillo. "We are training a whole new generation." Lead program engineer Paladichuk notes that almost all engineers working on the W80-4 are participating in their first LEP. "We have a lot of learning and training to do," he says. Toward this end, the engineering team has been reviewing lessons learned from other stockpile stewardship efforts and previous LEP activities.

Lead HE engineer Harwood notes that when the LEP started three years ago, the Laboratory had to hire much more staff—from chemists to machinists—in support of the HE effort. She says, "These are truly stellar people," who nevertheless must be trained in new skills and taught the technical knowledge that was not offered in academia. "We are exercising every aspect of our HE capabilities in training the next generation. We want to lay a strong foundation for the next LEP."

From infrastructure investment to research and development and workforce management, the W80-4 is no small undertaking. Horrillo notes that the fiscal and staff resources required to support the LEP are significant. However, the payoffs are equally significant: ensuring the nation's nuclear deterrent force remains safe, secure, and effective; enhancing scientific understanding of materials under extreme conditions; advancing new manufacturing processes; and ultimately ensuring the next generation of stockpile stewards is ready and waiting in service to the nation.

—Arnie Heller

Key Words: air-launched cruise missile (ALCM), Capabilities-Based Investment (CBI) Program, Contained Firing Facility (CFF), Earned Value Management system, High Explosives Applications Facility (HEAF), life-extension program (LEP), long-range standoff (LRSO) missile, National Ignition Facility (NIF), National Nuclear Security Administration (NNSA), Sierra, Site 300, Stockpile Stewardship Program, triaminotrinitrobenzene (TATB), W80-1, W80-4.

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