W87-1

The Modification that Invigorated an Enterprise

Lawrence Livermore will deliver the first newly manufactured nuclear warhead in three decades, which will replace the aging W78, meet military requirements, improve safety and security, and transform the Nuclear Security Enterprise through innovative collaborations.

WHEN the Cold War ended, so too did nuclear testing and the need for ongoing nuclear weapon design and production. In the ensuing decades, the U.S. stockpile of nuclear weapons aged beyond its designed service life, and the national laboratories were tasked with conducting Life-Extension Programs (LEPs) to refurbish existing designs and reuse existing parts to the maximum extent possible. Because of the nature of LEPs, key production technologies were allowed to atrophy or disappear completely from the Nuclear Security Enterprise (NSE). The W87-1 Modification Program is reinvigorating and transforming the production complex such that NSE can once again produce all of the components typically required for modern nuclear warheads. This work will give the nation expanded options for maintaining an effective nuclear deterrence posture for decades to come.

The W87-1 Modification Program marks the first time since the end of the Cold War that the nation's NSE will be putting a 100 percent newly manufactured nuclear warhead into the stockpile. "For decades, nuclear deterrence has been foundational to U.S. national security,

enabled by our ability to field innovative solutions on relevant timescales," says Laboratory Director Kimberly Budil. "Over the last two decades, our adversaries have rapidly modernized and expanded their nuclear capabilities, while the U.S. lost its ability to manufacture critical warhead components as facilities aged and capabilities atrophied without a consensus on the path forward. The W87-1 Modification Program changes that. Relearning to design, engineer, and produce a warhead presents a tremendous challenge, but we are working side-by-side with our partners to deliver for the nation and transform the Nuclear Security Enterprise in multiple critical areas."

As the design agency for the nuclear explosive package for the W87-1, Lawrence Livermore researchers are spearheading new partnerships to innovate materials development and manufacturing techniques. They are leveraging decades of advances in science and engineering to certify the first newly manufactured warhead without conducting a nuclear test. Laboratory researchers benefit from concurrent work on the W80-4 LEP, which began before the W87-1. "The W80-4 LEP kick-started the modernization process and has had significant ramifications in terms of skills, materials development, workforce training. It's been challenging, but we've learned a lot and developed first-of-its-kind protocols and standards. The W87-1 came in right behind, and thanks to the W80-4, we're hitting the road running," says Derek Wapman, deputy principal associate director for stockpile modernization. "U.S. warheads were designed and manufactured until the late 1980s and early 1990s," says Juliana Hsu, Livermore physicist and W87-1 program manager. "Since then, we have not designed any new nuclear components. When the warheads needed repair, we remanufactured the existing designs and reused components that we were not able to manufacture. That's no longer an option. For the W87-1, every part will be newly manufactured using well-established design knowledge. W87-1 requires different thinking, different problem solving, and close collaboration with the production agencies to construct entirely new components. W87-1 also requires training a new generation of weapons designers and engineers."

Subject matter experts from the Kansas City National Security Campus and Lawrence Livermore work together to hone production processes at the Polymer Production Enclave in Livermore. (Photo by Garry McLeod.)

Rewriting the Playbook

Building on the progress of past LEPs, the design and production agencies—Lawrence Livermore and Sandia National Laboratories (SNL)—and the production agencies—Los Alamos National Laboratory (LANL), Savannah River Site (SRS), Kansas City National Security Campus (KCNSC), Y-12 National Security Complex, Pantex Plant, and key NNSA material supplier—Holston Army Ammunition Plant—are collaborating more closely than ever. This includes enhancing the integration across National Nuclear Security Administration (NNSA) to establish appropriate project controls. Strong partnerships with the U.S. Air Force, Lockheed Martin, and Northrop Grumman are key to having a reliable deterrent based on the Sentinel intercontinental ballistic missile and the Mk21A reentry vehicle that will deliver the W87-1 warhead.

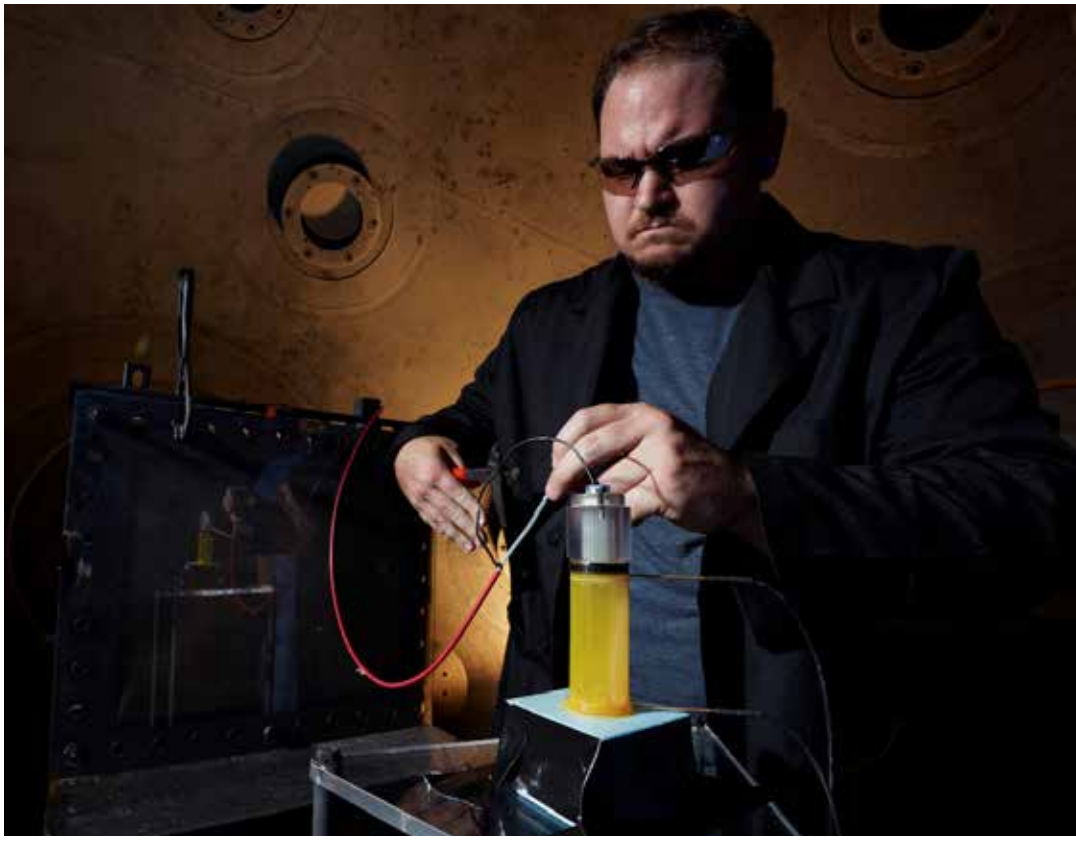
"As the design agency for the W87-1 nuclear explosive package, our responsibility is to make sure our designs meet the Department of Defense (DOD) requirements for safety, security, reliability, and nuclear yield. The production agencies are responsible for making the

parts. Lawrence Livermore could design amazing parts, but if the production agencies can't make them, it's moot, so we work collaboratively with the production agencies to ensure our designs are manufacturable so that we can ultimately deliver the system," says Alicia Williams, W87-1 project engineer.

Over the past few decades, scientific and engineering communities have made significant progress in the area of materials science and technology. The Laboratory has been at the forefront of some of these advances and has been actively leveraging new materials science and associated engineering know-how to develop new materials and production methods to support the NSE. "In the past, design agencies might throw drawings over the fence to the production agencies and assume they could manufacture the parts," says Peter Raboin, W87-1 deputy program manager at the Laboratory. "It's too easy, however, to design 'excellent' parts that can't be manufactured. We are rewriting the playbook with our production partners by collaborating on the creation of designs optimized for manufacturing the W87-1 components. We're constantly in contact with our collaborators across the enterprise."

A good example is the development of additively manufactured polymer components for the stockpile, which began in the early 2000s with a handful of Laboratory Directed Research and Development (LDRD) projects to support high-risk, high-potential-reward additive-manufacturing (AM) techniques. As these short-term LDRD projects ended, some approaches showed promise for NNSA-funded programs at the Laboratory to further explore the technology.

Inks or feedstocks were developed and optimized to offer desirable properties at the molecular level for use in modern AM machines. Completely new capabilities were developed to efficiently determine how the ink can be deposited to produce unique components providing the necessary macroscopic properties. Computational scientists developed models to predict how variables would impact performance at the part and system levels. In addition, in situ spectroscopy was applied to scan each layer of an object as it was printed, allowing for real-time assessments of part integrity and performance. By the time the W80-4 LEP was underway, AM had matured enough for stockpile use and the concept for a Polymer Enclave materialized.



Senior explosives handler Anthony Olson crimps a shot wire to a firing cable to prepare for an explosives test inside the spherical tank at Lawrence Livermore's High Explosives Applications Facility. (Photo by Garry McLeod).

The Polymer Enclave is a new approach to taking a polymer-based design from concept to realization via a joint effort between Lawrence Livermore and KCNSC. Both sites have procured the same AM equipment and have essentially the same work environment. Close integration of the design, development, and production teams from Lawrence Livermore and KCNSC are central to the effort to advance the technology and accelerate iterative loops that optimize both component performance and manufacturability. The Polymer Enclave came online in early 2022 to support the W87-1 Modification Program and provide necessary development hardware for some of the nuclear components. (See *S&TR*, November/December 2021, pp. 12–15.) "The enclave concept is a remarkable example of a collaborative commitment to innovation through partnership," says Raboin.

Lawrence Livermore and Pantex Plant—the Department of Energy (DOE) and NNSA's primary facility for the final assembly, dismantlement,

and maintenance of nuclear weapons—northeast of Amarillo, Texas, are also exploring novel technologies to develop reliable high-explosive parts, some of which could reach maturity for inclusion in the W87-1 Modification Program. Similar to polymers, these high-explosive technologies have been researched and developed over the past decade, and a new Energetic Materials Development Enclave has been established. To support this collaborative effort, new facilities have been constructed at Lawrence Livermore's Site 300. (See *S&TR*, August 2021, pp. 16–19.)

The Laboratory is also working closely with DOD's Holston Army Ammunition Plant, in Kingsport, Tennessee, which supplies the NNSA with explosive materials, to perfect the insensitive high explosives that will serve as the main charge for the W87-1. "It's an old recipe, but the equipment has changed," says Raboin. "We learned with the W80-4 that explosive properties were specific to the equipment. Mixing tank sizes and types during the Cold War were different than the tanks available today. The difference in tank geometries changes stirring patterns, which in turn, alters the crystalline morphology and the properties of the explosives." Researchers have been modeling newer synthesis processes and conducting experiments at Lawrence Livermore's High Explosives Applications Facility (HEAF) to hone explosive behavior models, which inform product requirements and specifications for the production agencies. "I support the product realization team in their mechanical properties work, specifically with establishing an experimental capability for essential testing," says Rowan Baird, an early career mechanical engineer and high-explosives mechanical properties lead at HEAF. Working with stakeholders across the enterprise, communication is both essential and challenging. "I have to ensure the message I'm communicating is received by all the parties and take all areas of concern into consideration. I'm listening and thinking from a variety of perspectives," says Baird.

The Y-12 National Security Complex in Oak Ridge, Tennessee, focuses on processing and storing uranium and is responsible for producing the components for a nuclear explosive package. The W87-1 team in Livermore is working closely with Y-12 to modernize technology and production methods for manufacturing components more efficiently. One example is the installation of an electron-beam cold-hearth melter (EBCHM)—a machine that can melt various metals—in Tennessee so that Y-12 personnel can work directly with the new technology. The EBCHM has the potential to improve materials usage, reduce waste, and shorten the time for producing metal ingots. "By working collaboratively, the joint Livermore and Y-12 material team is able to test and rapidly mature the EBCHM technology, with the goal of making it a standard production method for some key stockpile components across the National Security Enterprise," says Tom Goodrich, W87-1 design lead responsible for overseeing product development.

Y-12 and Lawrence Livermore are also partnering on a key innovation that the W87-1 is introducing into the stockpile. Some of the materials used in Cold War weapon systems are hazardous and no longer producible in the modern safety environment. In the case of one particularly toxic material, Lawrence Livermore researchers invented an alternative that provides nearly the same material properties without the health hazards for workers. Researchers at the Laboratory have also developed a manufacturing process using a massive hot press to turn this new material into the needed weapon component. Y-12 has fielded a similar hot press, and a joint Livermore–Y-12 team is working to optimize the production process.

The W87-1 will also contain newly produced plutonium pits, which initiate the nuclear reactions when compressed by high explosives. LANL has been reconstituting pit manufacturing with SRS—a DOE industrial complex responsible for disposition of nuclear materials, waste management, environmental cleanup, and environmental stewardship—near Aiken, South Carolina. Lawrence Livermore designers are working closely with partners from LANL and SRS to establish pit specifications and evaluate the impact potential defects might have on the system. "These pits are a big deal," says Hsu. "If they don't work, the system won't go nuclear. The enterprise must get this right."

Experimental capabilities contribute to addressing W87-1 pit assessment and certification challenges. The JASPER two-stage gas gun at the Nevada National Security Site (NNSS) has played a central role in Laboratory designers' evaluation of plutonium under extreme conditions. In addition to these focused experiments at JASPER, Lawrence Livermore designers are conducting a series of hydrodynamic experiments that integrate relevant materials in warhead configurations. (See *S&TR*, November/December 2021, pp. 16–19.) These integrated tests at the Laboratory's Site 300 and LANL's Dual-Axis Radiographic Hydrodynamic Test Facility guide pit design to meet military requirements.

Modern Tools for Certification

Certification of a redesigned and fully rebuilt weapon is a formal process by which NNSA laboratory directors assert that the system meets requirements. In addition, modernization programs go through a process by which the DOD accepts the Final Weapon Development Report, which is based on the expert judgment of weapons designers, chemists, and engineers and supported by a comprehensive set of calculations and experiments. Historically, this

process included nuclear explosive tests. Today, Lawrence Livermore designers leverage decades of advanced simulations and nonnuclear-testing capabilities to resolve nuclear weapons performance queries. This meticulous understanding of weapons physics, engineering, materials science, and manufacturing processes gives the Laboratory's W87-1 team the confidence to design and deliver a safe, secure, effective, and fully modernized nuclear warhead that meets requirements.

Modeling and simulation in support of the W87-1 Modification Program is underway using the Sierra high-performance computer, currently ranked the sixth fastest in the world. The Laboratory is working with industry partners to develop NNSA's first-ever exascale supercomputer—El Capitan, which is scheduled for delivery in 2023 and projected to offer more than 15 times the peak compute capability on average over Sierra. El Capitan will facilitate regular use of high-resolution 3D simulations of W87-1 warhead performance.

Ensuring Longevity

Lawrence Livermore researchers must ensure new materials installed in the W87-1 will last. While it is impossible to produce a part that will not age over time, Laboratory engineers, materials scientists, and chemists work together to evaluate and predict how materials will age and interact as they age. "We need to know how long a material will last when it's exposed to environmental stressors," says Sarah Chinn, W87-1 materials science and chemistry lead. "If you put a rubber band in the sun for a week and stretch it out, it will break. That's an extreme example, but we want to understand long-term behavior of the materials going into the W87-1."

To predict material longevity, researchers use a variety of techniques to accelerate aging, including increasing the levels of thermal and radiation exposure,

Lawrence Livermore materials scientists prepare to consolidate raw materials into test components using a hot press.

as well as performing mechanical and chemical testing. Material compatibility across components must also be considered. For example, if a polymer in one component releases gases or produces moisture, the researchers need to ensure adjacent metal components will not corrode.

Prototypes are heated in ovens at Site 300 and compared with predictive models as well as actual legacy stockpile parts. Similar to the development of AM techniques, the foundation for this work—the ReSorT model (Reaction Sorption and Transport)—began as an LDRD project 10 years ago by materials scientist Libby Glascoe. After showing promise at a fundamental-science level, Lawrence Livermore's Aging and Lifetimes Program continued to mature the model through data gathered while evaluating legacy warheads in support of annual assessments of the stockpile. ReSorT benefited the W80-4 program and now informs component design decisions for the W87-1. "Livermore has a reputation for making high-quality weapons that last. One reason is those ovens. The others are our models and simulations," says Raboin.

Stockpile-to-Target Sequence

The W87-1 must operate as expected despite exposure to hostile environments including antiballistic missile attacks. Many experiments are underway across the enterprise to evaluate the stockpile-to-target sequence challenges in detail. They range from focused experiments on the new materials for the W87-1 to integrated tests to evaluate the reliability of the entire system.

At the National Ignition Facility (NIF)—the world's most energetic laser—researchers are bombarding the newly designed materials for the W87-1 with x rays and neutron fluxes. During the Cold War era, researchers bored tunnels beneath the mesas of the Nevada Test Site—now NNSS—and conducted nuclear explosive tests to evaluate a material's ability to survive hostile nuclear environments. Today, NIF recreates some of the extreme conditions that the designers previously could only create with nuclear detonations. The record-breaking neutron yields achieved at NIF in 2022 opened the door to

El Capitan, an exascale supercomputer, will facilitate regular use of high-resolution 3D simulations of the W87-1 warhead in operation. The Laboratory has completed infrastructure improvements to support the larger system while developers prepare codes to run on the exascale architecture.

creating additional experimental conditions not produced since the days of nuclear testing. "Now that NIF is producing higher yields, we are getting closer to replicating the actual hostile environments the W87-1 must operate in," says Hsu.

The Air Force, in partnership with Lawrence Livermore and Sandia researchers, will conduct flight tests to provide insight into the warhead's ability to withstand the extreme forces associated with intercontinental ballistic missile (ICBM) liftoff and reentry. Launched from the Vandenberg Space Force Base in southern California, Air Force ICBMs carry mock warheads of Lawrence Livermore's design with diagnostics that relay essential data about system performance. As the ICBM traverses the ocean, a flotilla of rafts packed with the Laboratory's diagnostics scans the night sky off the coast of Kwajalein Atoll in the South Pacific. Within minutes of launch, these rafts—known as the LLNL Independent Diagnostic Scoring System—lock in on the incoming mock warhead. Data from these flight tests will inform assessments and make it possible for the Laboratory to certify the warhead.

A Key Milestone

With the Laboratory's submission of its input to the Weapon Design and Cost Report (WDCR), the W87-1 Modification Program passed a key milestone in November 2022. With the conceptual design for the warhead complete, this cost report details the scope of work required and provides a cost estimate. The next phase of the program is development engineering, where the Laboratory will continue to work with production partners to manufacture prototypes at the plants and start to qualify their manufacturing processes as well as executing experiments with increasing fidelity to verify that the design will meet requirements. Every component in a nuclear weapon has a product realization team (PRT), which is a collaboration between Livermore and one or more production agencies. As components come off the production line, the PRT and the broader W87-1 team at Livermore will evaluate whether they meet requirements through testing and assessments. PRTs also work to improve manufacturability and minimize production risks.

Active risk management is crucial in executing such a complex program. Hiccups in fielding new manufacturing processes or unexpected experimental results will stress the project's timeline and budget. Risk also arises from the program's challenges in staffing appropriately. The program is hiring additional people, and along with the hiring push comes the need to train and develop this next generation of stockpile stewards. Another source of risk is the parallel development approach—in lieu of developing components one at a time—which is necessitated by the program's tight timeline.

To actively manage these risks, the W87-1 team is employing a set of strategies, including close collaboration between design and production agencies and project management techniques such as the implementation of an earned value management system (EVMS)—a method of breaking a program down into manageable work elements and defining key steps within those work elements that provide indicators of how the program is progressing. In implementing EVMS for the W87-1, Lawrence Livermore is applying lessons learned from the W80-4 LEP. "Many of us worked on the W80-4 program, and we learned a tremendous amount," says Rachael Weinbrecht, project controls manager for the W80-4 LEP and the W87-1 Modification Program.

During the COVID-related lockdowns, the W87-1 team adapted to working in a different way as the program entered its second year of work. This presented additional challenges because as a program enters its second year, staffing and the pace of work both typically increase as deliverable deadlines approach. Despite having to adapt to less in-person time and other related adjustments, the W87-1 Modification Program met all of its objectives and accelerated timelines in several areas. With the acceptance of the WDCR in November 2022, the W87-1 enters phase 6.3—the development engineering phase—where the Laboratory works closely with the production plants to ensure that the manufacturing process delivers parts that meet requirements. "This is an immensely challenging program to execute, both technically and from a project management perspective," says Williams. "The complex has never been busier. It's an exciting time to be here. We're breaking new ground with our collaborators across the enterprise. Technologies that started as just an idea, like additive manufacturing or longevity modeling, we've seen them evolve and advance, lay the groundwork, and provide the tools we need to design and build the W87-1. We've also seen our partnerships grow and change, and we're cultivating and benefiting from a more agile, collaborative enterprise."

As teams design, develop, and deliver the materials for the W87-1 Modification Program, the contemporary challenges generate questions about future capabilities. "We need to think about the future and explore the AM innovations, NIF upgrades, high-energy-density physics advances, and exascale computing possibilities," Budil says. "We are tasked with advancing weapons and weapons systems and developing the next generation of an expert workforce to fulfill our mission as a national security laboratory."

—Amy Weldon and Nolan O'Brien

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