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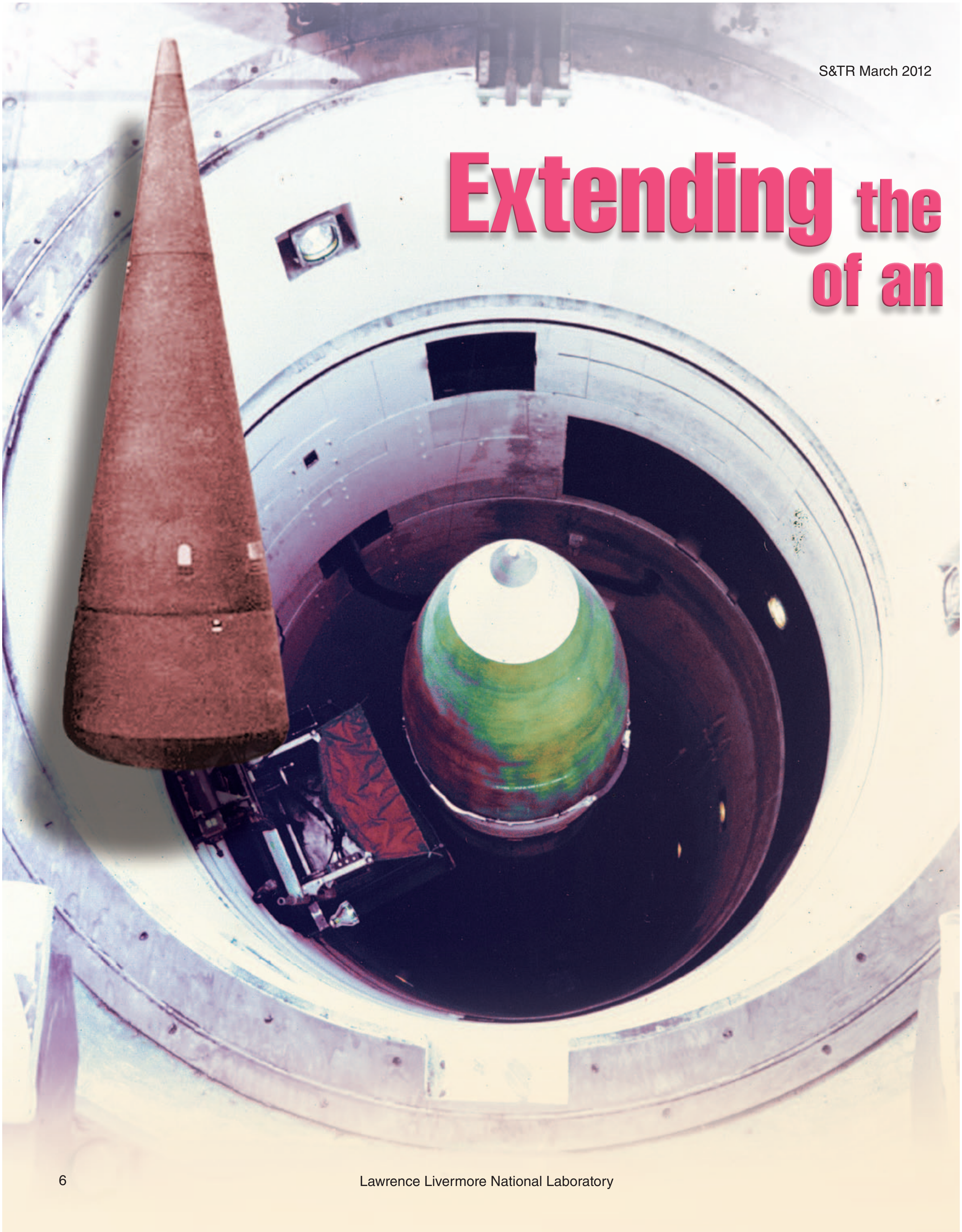


Life
Aging Weapon

Stockpile stewards modernize the W78 warhead for the nation's land-based intercontinental ballistic missiles.

FOLLOWING the end of the Cold War, the U.S. discontinued design and development of new nuclear warheads and halted underground nuclear experiments. In place of underground testing, the National Nuclear Security Administration (NNSA) pursues stockpile stewardship, a comprehensive set of scientific and engineering activities focused on ensuring that existing U.S. warheads remain reliable, secure, and safe.

The life-extension program (LEP) for the W78 warhead (above left) will evaluate options for refurbishing the nuclear weapon to address issues identified with aging components. The U.S. Air Force deploys the W78 warhead in its Minuteman III intercontinental ballistic missiles (ICBMs), which are dispersed in hardened silos (left) to protect against attack. (Courtesy of Department of Defense.)

By law, the directors of the NNSA weapons laboratories—Lawrence Livermore, Los Alamos, and Sandia—provide the secretaries of Energy and Defense with an annual assessment of the stockpile. Confidence in these assessments depends on the laboratories' abilities to evaluate the inevitable changes that occur inside nuclear weapons as they age and to effectively deal with any safety or performance issues that may arise from those changes. Stockpile stewardship activities enhance understanding of nuclear weapons and ensure their safety and performance through a combination of theoretical advances, nonnuclear experiments, supercomputer simulations, and stockpile surveillance. When necessary, life-extension programs (LEPs) are approved to prolong the service life of an aging warhead and enhance its safety and security.

LEPs address issues discovered through routine surveillance and annual stockpile assessments. Nuclear weapon components are made from various materials including high explosives, steel, plutonium, uranium, and plastics. Over decades, plastics can break down, metals corrode, and coatings deteriorate. A material's properties may change unpredictably in response to high radiation fields, fluctuating temperatures, and other environmental conditions to which stockpile components are subjected.

In July 2010, NNSA designated Lawrence Livermore the lead nuclear design laboratory to conduct an LEP on the Los Alamos–designed W78 warhead, with Sandia, California, responsible for the warhead's nonnuclear components. The announcement was made in a letter from Don Cook, deputy administrator for NNSA's Defense Programs.

The W78 is used on U.S. Air Force Minuteman III intercontinental ballistic missiles (ICBMs). The Mark 12A reentry vehicle encloses the warhead to protect it from heat as it speeds through the atmosphere. A team of about 30 Livermore physicists, engineers, and chemists are working on an options study in what is currently planned to be a 10-year effort to extend the W78's service life for another 30 years.

In Congressional testimony in 2011, Laboratory Director George Miller (now retired) underscored the importance of the W78 LEP, saying, "The role of any Life Extension Program is to fix issues that impact—or will soon impact—overall system effectiveness and take actions that will extend the stockpile life. Failure to address these issues can have immediate and drastic consequences for the viability of the deterrent our national security strategy relies on. In particular, it is imperative that we begin the study of options for refurbishing the W78 warhead to address evolving issues identified in the annual assessment of this weapon system."

"When the W78 was added to the stockpile in 1979, no one anticipated it would not have been replaced 33 years later," says physicist Hank O'Brien, who leads the W78 LEP for Livermore's Weapons and Complex Integration Principal Directorate. "We are seeing signs of aging among W78 components,

although these changes have yet to impact system reliability. It is important to start the LEP process to prevent this aging issue from becoming a real problem."

The W78 will be the fourth nuclear weapon system to undergo refurbishment. In 2004, Lawrence Livermore successfully completed NNSA's first LEP, refurbishing the W87. That effort enhanced the structural integrity of the warhead and extended its life by 30 years. For the W87, Livermore and Sandia scientists and engineers developed and certified the engineering design and worked closely with NNSA production facilities to ensure a cost-effective design and ease of manufacture. The W87 effort has served as a model for subsequent LEPs, including two being conducted by Los Alamos: the W76 warhead used in Trident II submarine-launched ballistic missiles (SLBMs) and the B61 family of nuclear bombs. (See the table on p. 9.)

LEPs progress through a series of phases labeled 6.X. Phase 6.1 is a concept study, during which scientists and engineers explore options, reviewing each one's performance characteristics, manufacturing issues, and technical challenges; expected improvements in performance margins, safety, and security; and long-term maintenance and surveillance requirements. Livermore stockpile stewards expect the W78's 6.1 phase to conclude this year. It will then be followed by three phases: option selection and detailed design and cost studies (6.2), development engineering (6.3), and production engineering (6.4). First production of the modified warheads (phase 6.5) is scheduled to begin about 2023, followed by full-scale production (phase 6.6).

As part of phase 6.1, Livermore and Sandia researchers are working with NNSA production agencies (Los Alamos, Y-12 National Security Complex, Kansas City Plant, Pantex Plant, Savannah River Site, and Sandia, New Mexico) as they assess the manufacturability of options for components and systems. In particular, they want to identify manufacturing processes that reduce waste and do not use hazardous materials.

The Minuteman III ICBM, shown in a flight test, contains the W78 warhead. (Courtesy of Department of Defense.)

A Project Officers Group, with representatives from the Department of Defense, NNSA, Livermore, Sandia, and Los Alamos, meets regularly to assess progress. At the conclusion of phase 6.1, Livermore managers will present the recommended LEP options to this group. "We are thoroughly analyzing all options to present decision makers with low-risk, cost-efficient alternatives," says O'Brien. "Our findings and recommendations are based solely on our best technical assessments of cost, risk, and ability to meet stockpile goals."

According to O'Brien, U.S. government policy requires LEP design teams to consider options for refurbishing the existing design, reusing components from other stockpiled designs, and implementing nuclear-test-based designs that are not in the current stockpile. The Department of Defense also requires LEP studies to identify and assess options that improve safety and security features and that make the warhead adaptable for deployment on SLBMs as well as ICBMs. No new military capabilities or missions are required. Among the suite of options identified, the stockpile component reuse designs show the most promise to address the LEP requirements cost-effectively and with high confidence in performance.

Looking to Increase Confidence

A modern nuclear explosive package includes nuclear and nonnuclear components that comprise a primary explosive device and a secondary, both enclosed within a case to confine radiation from the primary explosion. Among the options being considered as part of phase 6.1, designers for the primary and secondary are examining ways to increase confidence that the weapon will reliably achieve its predicted energy release, or nuclear yield.

A primary is typically a shell of fissile material—called the pit—that is imploded by a surrounding layer of chemical high explosive (HE). Options that entail changes to the weapon's primary to increase confidence in performance make it possible to accommodate insensitive high explosives (IHEs) and other safety and security components to meet U.S. Air Force requirements. However, says O'Brien, "We can't simply swap out IHE for the conventional HE being used in the W78. The primary design must be modified."

O'Brien explains that the conventional HE in older weapon systems can be sensitive to extreme shocks, which can complicate safeguarding and transport. Livermore designers incorporated a widely used IHE, triaminotrinitrobenzene (TATB), in the design of the W87 ICBM warhead, which includes modern safety features. TATB, however, has not been produced in 20 years. Livermore chemists are evaluating current manufacturing techniques that would be more environmentally friendly, should it be decided to use TATB in the refurbished W78 warhead. Advanced safety and security options for the warhead depend on the use of IHE, as well.

Physicist Juliana Hsu leads the effort to understand how the modified W78 could effectively accommodate IHE and other modified components. She notes that LEPs provide the opportunity to add safety and security features without degrading overall effectiveness or introducing new military capabilities. "We will probably have the W78 for the foreseeable future," she says. As a result, "We will be proposing safety and use-control features that were not implemented in the original warhead design. It makes sense to have the warhead safer and with more effective safeguards." Hsu adds that physicists and engineers are also considering options to modify the warhead so it can be adapted to multiple delivery platforms, which would provide a cost-effective hedge against future problems in the stockpile.

Many safety and security options ready for deployment on the W78 are based on results from past nuclear tests. Some features would provide enhanced protection from fire, while others would guard against unauthorized use and attack. One safety option being evaluated is a method to better ensure that the firing system commences only when an elaborate sequence of events takes place.

To that end, Livermore engineers are working on an advanced mechanical safe arming detonator (MSAD). This intricate nuclear safety component prevents accidental or unintended detonation of a warhead. MSADs protect nuclear weapons by preventing an outside source from using the weapon detonators to successfully ignite the IHE main charge. The miniature notches on an MSAD pattern wheel encode a signal set that must be received for the weapon to be operable. This unique signal set ensures that naturally occurring signals or an improper input cannot cause the weapon to function.

Current Weapon Systems in the U.S. Nuclear Stockpile

Weapon	Type*	Delivery system	Primary use	Service	Date added	LEP status
W78	ICBM	Minuteman III	Surface to surface	Air Force	1979	Phase 6.1
W87	ICBM	Minuteman III	Surface to surface	Air Force	1986	Completed
W76	SLBM	Trident II (D5)	Underwater to surface	Navy	1978	Phase 6.6
W88	SLBM	Trident II (D5)	Underwater to surface	Navy	1989	Future LEP
B61-3/4/10	Bomb	F-15, F-16	Air to surface	Air Force	1979/1990	Phase 6.3
B61-7/11	Bomb	B-52H, B-2A	Air to surface	Air Force	1985/1996	Phase 6.3
B83	Bomb	B-52H, B-2A	Air to surface	Air Force	1983	Not needed
W80-1	Missile	B-52H	Air to surface	Air Force	1982	Delayed

*ICBM = intercontinental ballistic missile; SLBM = submarine-launched ballistic missile.

	Refurbish	Reuse	Replace
Performance margins	Limited improvements	Large improvements	Largest improvements
Primary high explosive (HE)	Retains conventional HE	Enables insensitive HE	Enables insensitive HE
Added surety for nuclear explosive package	No	Yes	Yes
Multiple delivery platforms	No	Yes	Yes
Production rate	Limited by new production	Not limited by new production	Limited by new production

Green = meets requirement, **yellow** = partially meets requirement, **red** = does not meet requirement.

U.S. government policy requires the W78 LEP to consider three options: refurbishing the existing design, reusing components from other stockpiled designs, and using nuclear-test-based designs that are not in the current stockpile. Of the three options, only reuse meets all LEP requirements.

MSADs are an example of a so-called strong link—rugged mechanical safety devices that interrupt the firing chain until certain sensing systems indicate a normal launch sequence. These devices help safeguard the HE that detonates to begin the nuclear detonation.

A Better Look at the Fundamentals

"Stockpile stewardship is becoming scientifically and technically more challenging as weapons continue to age beyond their original design lifetimes," observes O'Brien. However, the physics-based understanding of nuclear detonations has improved significantly over the past decade thanks to theoretical advances, experiments, and simulations, together with the existing nuclear-test database. (See the box on p. 11.) This improved capability allows weapon scientists and engineers to assess with confidence a wide range of options in the W78 LEP.

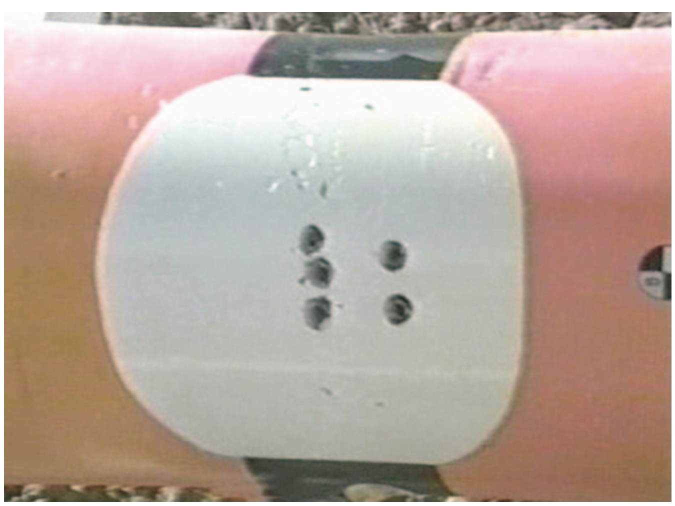
Because underground nuclear experiments ceased in 1992, simulations have become a major tool for assessing the stockpile and guiding LEP efforts. "Compared to the W87 LEP completed in 2001, we have a much greater technical basis for making decisions," says O'Brien. Full three-dimensional, high-fidelity simulations allow physicists to observe important nuclear-related phenomena nanosecond by nanosecond, with a level of spatial resolution and a degree of physics realism previously unobtainable.

"We're bringing substantially more computational power to bear on this LEP compared with the resources we had for the W87 LEP," says O'Brien. "Our codes have much more detail, allowing us to analyze options with even greater precision."

Advanced simulations require experimental validation, which, in the absence of nuclear testing, is provided by sophisticated nonnuclear experiments. For example, Laboratory physicists Aaron Puzder and Dana Goto designed experimental studies to investigate advanced safety technologies. Those experiments, which were fielded in 2010 and 2011 at the Dual-Axis Radiographic Hydrodynamic Test Facility at Los Alamos, provided valuable data for the W78 LEP.

In 2011, Livermore engineer Chad Noble received an NNSA award for a hydrodynamic experiment at Livermore's Contained Firing Facility, which provided an improved understanding of use-control technology for consideration in the W78 LEP. Physicist Steve MacLaren also won an NNSA award for work as lead designer in high-energy-density experiments on the National Ignition Facility at Livermore and the Z-pinch machine at Sandia, New Mexico. Those experiments produced data that validated key stockpile stewardship simulations.

A mechanical safe arming detonator (MSAD) prevents accidental or unintended detonation of a nuclear warhead. Stockpile stewards at Livermore are working on an advanced MSAD for the W78.



Small-arms fire discharged into the triaminotrinitrobenzene surrounding a nuclear weapon component does not detonate this insensitive high explosive.

The National Boost Initiative (NBI) is also helping scientists better understand the thermonuclear burn process. "NBI is an effort to examine the primary's performance, or the boost process, in greater detail," says Hsu. "The W78 LEP will leverage the increased scientific knowledge from this initiative to quantify and potentially reduce our uncertainties during warhead certification." Hsu notes that Ray Tolar, a physicist working on the W78 LEP, is also supporting a major NBI milestone. As a result, he will be able to maximize the synergy between the two projects.

Livermore physicist Omar Hurricane, who specializes in secondary design, won the Department of Energy's prestigious Ernest Orlando Lawrence Award for solving a mystery that had confounded weapon scientists for more than half a century. For decades, Hurricane says, scientists had to account for missing energy produced during nuclear tests. "There was consistent mysterious behavior of nuclear detonations from what we measured during underground tests. It was OK during the Cold War because we could do a test and make sure things were working properly. With the cessation of underground testing, we knew we had to resolve the discrepancy."

Over a decade, Hurricane led a team ranging from 20 to 40 physicists who worked on two vastly different areas of physics. "It was an intense, detailed effort," he says. The team identified the key physical processes involved and built computational tools to make predictions about the physics. They then conducted experiments to validate their theories. "We eventually resolved the problem and applied the solution to our codes," says Hurricane. That breakthrough has increased confidence in calculations that simulate performance for the modified W78 and other warheads.

Weapons scientists continue to benefit from a methodology known as quantification of margins and uncertainties (QMU). This methodology draws together the latest data from simulations, experiments, and theory to establish confidence factors for the key potential failure modes in weapon systems. QMU helps weapon scientists rank the design options identified for the W78 LEP. "QMU is a way to quantify our performance margins, to help us know we're in the regime where we're strongly confident," says O'Brien. "We want margins that are sufficiently robust."

Omar Hurricane received the Ernest Orlando Lawrence Award for helping to resolve a long-term mystery in weapons physics—accounting for the missing energy produced during nuclear tests.

Engineering's Major Role

The LEP effort requires input from engineers as much as from physicists. Engineers must ensure both the mechanical robustness of the overall system and the complete integration of every component and system, explains Peter Raboin, project engineer for the W78 LEP. Raboin notes that the warhead's nuclear explosive

Understanding Plutonium

Among all the elements, plutonium is the most mysterious because it exhibits six different phases (orientations of its atoms) at ambient pressure, with a seventh phase under pressure. What's more, phases readily transform from one to the other and are accompanied by large volume changes. In addition, plutonium's radioactive decay causes self-irradiation damage that can change the metal's properties over time, a matter of concern to stockpile stewards evaluating whether a weapon system should undergo a life-extension program (LEP).

Livermore scientists have labored for decades to unravel plutonium's secrets, using a combination of experiments, theoretical advances, and simulations. Determining the long-term behavior of plutonium is important for stockpile stewardship and for the eventual dismantlement and disposition of warheads. The U.S. and Russia have withdrawn thousands of nuclear weapons from their arsenals, and the excess plutonium recovered from these warheads must be dealt with safely.

"We've only studied the basic fundamental properties of plutonium metallurgy and properties," says materials scientist Brandon Chung. "Many questions remain. It's very much an ongoing science."

As part of the W78 LEP, special engineering test facilities will help researchers evaluate advanced safety and surety features that involve plutonium and uranium. Other facilities could help them explore the chemistry of new manufacturing methods for the warhead's plutonium pits. The National Nuclear Security Administration is changing the manufacturing process for plutonium pits because the production facilities of the Rocky Flats Plant no longer exist. "We need more efficient, cost-effective pit manufacturing," says Chung. "We will have no underground tests to prove that new manufacturing processes do not degrade pit performance, so a firmer understanding of plutonium is required."

Engineering efforts for the W78 LEP will simulate environmental stresses that components could experience from the time a warhead is produced until it arrives at a target. These stresses include being placed and driven on a truck, vibrations experienced at launch and during the flight sequence to a target, and high temperatures during reentry through the atmosphere. The planned tests include spinning components at high speed and subjecting objects to extreme heat and high gravitational forces.

package resides in a deployment vehicle located in the nose cone of an ICBM. The package and its support structures must be "fit to fly."

"The Department of Defense expects the W78 to arrive on target intact and functioning," says Raboin. "We pay very close attention to making sure components will survive the flight from launch to target. Parts could potentially be damaged or break during reentry into the atmosphere, when the Mark 12A experiences decelerations as high as 100 times the force of gravity."

To approximate the vibrations during flight, Laboratory engineers use centrifuges and so-called jerk and shaker tables. By combining such physical experiments with simulations, they mimic what happens to the warhead from the moment it leaves a production facility to the point at which it hits a target.

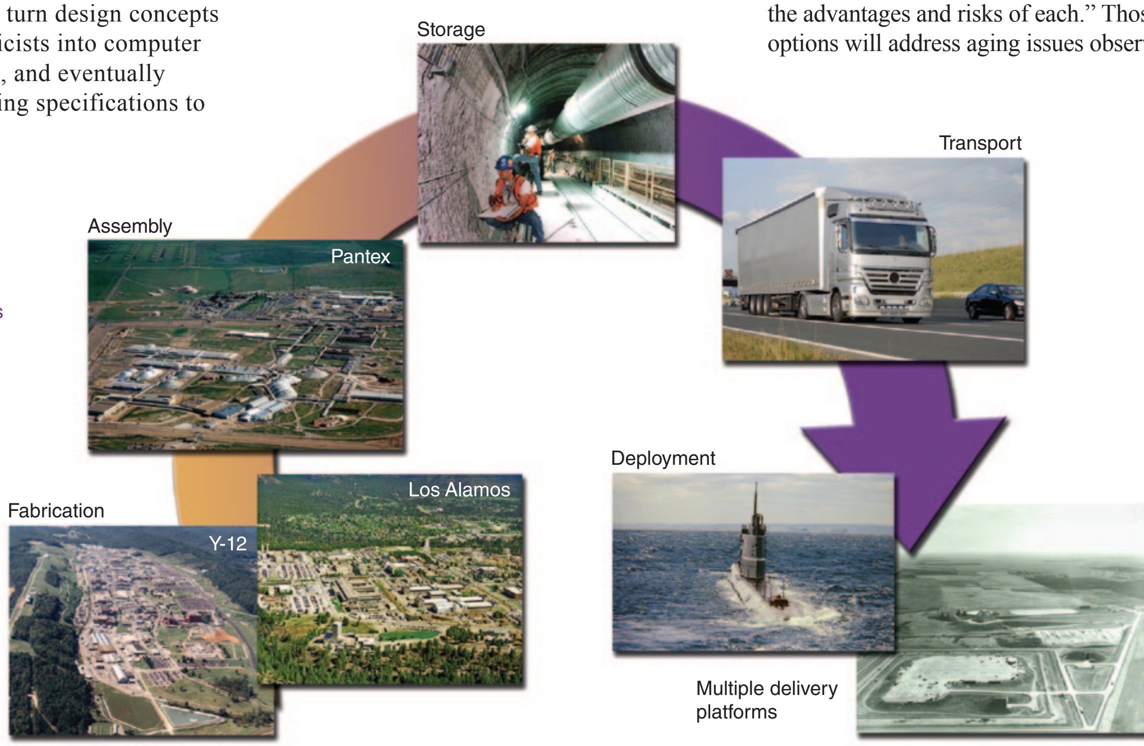
Engineers also turn design concepts prepared by physicists into computer drawings, models, and eventually detailed engineering specifications to be implemented by NNSA production facilities. In this activity, the Livermore team works closely with Sandia, which is responsible for the nonnuclear hardware that supports operation of the nuclear explosive package. Livermore and Sandia engineers then integrate the nuclear and nonnuclear hardware into fully functional warheads.

Chemists also contribute to this effort by searching for potential problems that stem from chemical incompatibilities in the widely different materials used in a warhead. Such problems could develop over time because components are in chemical contact with each other and are situated close to a field of high radiation. Engineers are also mindful of possible changes in the size of gaps separating components should a material shrink or expand. "Changes within the warhead may occur at a very slow rate," says Raboin. "But over 30 years, they can add up to a considerable amount."

O'Brien adds that LEPs in general help NNSA maintain the expertise required for stockpile stewardship into the future. (See the box on p. 13.) The special skills required for nuclear weapons work are developed over time through experience and mentoring. The W78 LEP provides the Laboratory with an opportunity to develop the next generation of scientists, engineers, and technicians to help sustain the nation's nuclear deterrent.

Best Analysis of Options

"The W78 LEP is a significant development program," says O'Brien. "It's the biggest effort of this decade for the Livermore weapons program. We're getting ready to present to the U.S. government our best analysis of options, including the advantages and risks of each." Those options will address aging issues observed



As part of the W78 LEP, Livermore engineers will evaluate the benefits of adding safety and security features to the warhead over its complete lifecycle, from fabrication to deployment.

Training the Next Generation of Stockpile Stewards

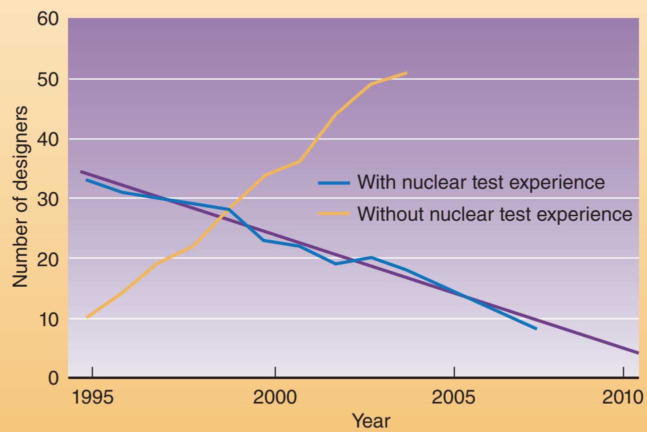
The W78 life-extension program (LEP) presents an excellent opportunity to develop and train stockpile stewards. The program will help the Laboratory maintain a knowledge pipeline by allowing the next generation of LEP scientists and engineers to work with mentors who have LEP experience.

W78 LEP manager Hank O'Brien notes that neither Livermore nor Los Alamos can execute all the LEPs needed to sustain the nation's nuclear deterrent. Of equal importance, stockpile stewardship in the absence of nuclear testing vitally depends on the two laboratories providing expert technical review of each other's work. To sustain expert judgment, both laboratories must be involved in all elements of stockpile stewardship, and each laboratory must attract, develop, and retain talented scientists, engineers, and technicians needed to maintain the nation's nuclear arsenal. The specialized skills and expertise required for nuclear weapons work take a long time to develop through hands-on experience and mentoring. In 2011, Laboratory Director George Miller (now retired) told Congress, "Confidence in the stockpile ultimately depends on confidence in the stockpile stewards at the [National Nuclear Security Administration] labs and production facilities."

"The W78 LEP will proceed as the last of the nuclear test-experienced designers will reach the end of their careers, while the first generation of stockpile stewards is in their professional prime, and will develop the next generation," said Miller. "This program is a vital element in maintaining the competency and capability of the Laboratory's weapons specialists through a project involving design, engineering, and manufacturing."

For the past three years, the Enterprise Modeling Group led by physicist Cliff Shang has been tracking the skill sets of current stockpile stewards at Livermore and projecting needs for the future. Shang notes that the W78 LEP effort is valuable because it "exercises" many key capabilities in the U.S. nuclear security enterprise: production plants, design laboratories, and most of all, the people.

"The nation has made an enormous investment in developing a cadre of weapons scientists and engineers," says Shang. "In the past, one way to mastery was achieved by leading and testing nuclear devices. Very few of these people remain in our current workforce. In today's era of science-based stockpile stewardship, mastery is achieved by integrating large-scale simulations with the design work required to field nonnuclear experiments. The scientists and engineers we hired for the W80 and W87 LEPs are the technical leaders for the W78 effort. The challenge for us now is to grow a new generation of scientists and engineers so they will have the skills, knowledge, and abilities needed to maintain the nation's strategic deterrent."



Livermore physicists with nuclear test experience are reaching the end of their careers, and the first generation of stockpile stewards is in its professional prime. The W78 life-extension program is thus critical to the Laboratory's efforts to maintain the skills, knowledge, and abilities required for effective stewardship of the nation's nuclear deterrent.

in surveillance of W78 units and will feature warhead designs that increase confidence in performance and meet requirements for enhanced safety and security.

Over the next decade, Livermore stockpile stewards will produce detailed engineering documents, supervise advanced experiments, and simulate every proposed modification and new part in three dimensions. And they will coordinate closely with NNSA production centers as the modifications slowly take shape.

The result will be a new lease on life for a warhead that was not designed to remain in service for 40 years. Thanks to the LEP, the W78 will have another three decades of service life, potentially with advanced safety and security features in place and changes that will give stockpile stewards greater confidence in its performance.

—*Arnie Heller*

Key Words: B61, intercontinental ballistic missile (ICBM), life-extension program (LEP), mechanical safe arming detonator (MSAD), quantification of margins and uncertainties (QMU), stockpile stewardship, triaminotrinitrobenzene (TATB), W78, W87.

For further information contact Hank O'Brien (925) 423-5017 (obrien6@llnl.gov).