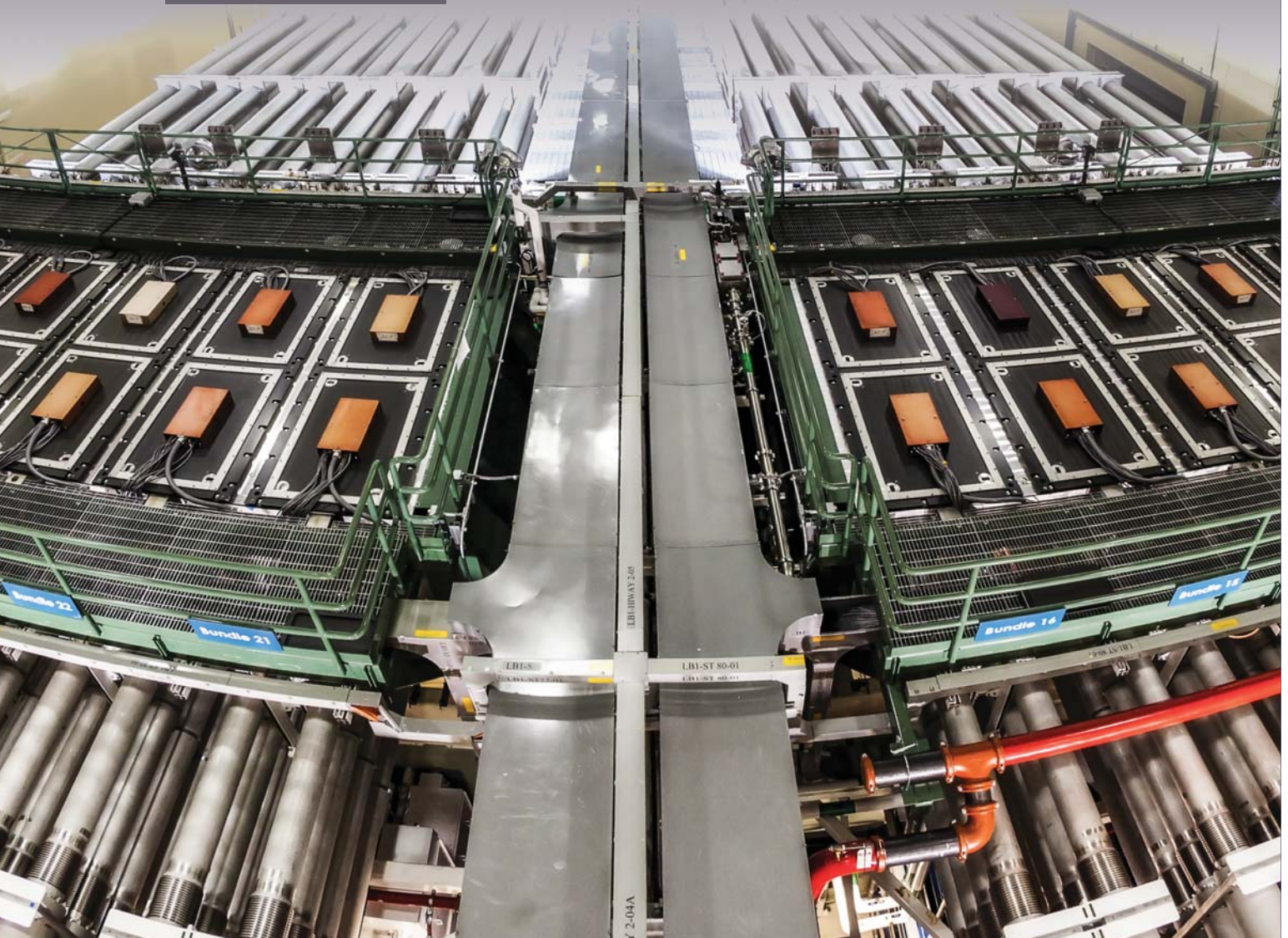


The Big Science of STOCKPILE STEWARDSHIP

Victor H. Reis,
Robert J. Hanrahan,
and W. Kirk Levedahl

In the quarter century since the US last exploded a nuclear weapon, an extensive research enterprise has maintained the resources and know-how needed to preserve confidence in the country's stockpile.



Victor Reis is on the staff of the Office of the Secretary, US Department of Energy. He was assistant secretary of energy for defense programs from 1993 to 1999. **Robert Hanrahan** and **Kirk Levedahl** are on the staff of the National Nuclear Security Administration of the Department of Energy.



At the height of the Cold War, the US possessed more than 30 000 nuclear warheads and exploded, on average, about one of them per week at a desert complex known as the Nevada Test Site. In 1992, after the Cold War ended, President George H. W. Bush halted production of all nuclear weapons and signed an authorization bill containing the Hatfield-Exon-Mitchell Amendment, which instituted a nine-month moratorium on nuclear explosive tests. His successor, Bill Clinton, extended the moratorium, and the US hasn't exploded a nuclear weapon since.

Two decades later the US nuclear deterrent is none the weaker. How has the American defense apparatus retained confidence in its ability to explode nuclear weapons—and how has it demonstrated that ability to the world—without actually exploding nuclear weapons?

A question of confidence

When President Clinton took office in January 1993, he directed a National Security Council review of the nuclear weapons testing program to focus on two specific questions: How many nuclear explosive tests should the nation conduct, and should the administration support a comprehensive test-ban treaty? Underlying those questions was the broader issue of the role of nuclear weapons and their institutions in the post-Cold War world.

On 3 July 1993, after a vigorous interagency debate, he stated in a radio address,

I have therefore decided to extend the current moratorium on United States nuclear testing at least through September of next year. . . . I therefore expect the Department [of Energy] to maintain a capability to resume testing. To assure that our nuclear deterrent remains unquestioned under a test ban, we will explore other means of maintaining our confidence in the safety, the reliability, and the performance of our own weapons.¹

His statement was codified into a Presidential Decision Directive, a form of executive order, and became law with the signing of the National Defense Authorization Act of 1994 (section 3138). That act included a specific direction to “ensure the preservation of the core intellectual and technical competencies of the United States in nuclear weapons.”²

The steps taken by Presidents Bush and Clinton drove ex-

traordinary changes in nuclear weapons strategy and its underlying institutions. During the Cold War, the US produced approximately 70 000 nuclear warheads of more than 70 different types and conducted more than 1000 nuclear explosive tests. That nuclear buildup was accomplished within an industrial complex that stretched from Hanford, Washington, to Pinellas County, Florida. It employed more than 100 000 skilled workers in nine states. At the heart of the enterprise were two fiercely competitive nuclear weapons design laboratories—Los Alamos National Laboratory (LANL) and Lawrence Livermore National Laboratory (LLNL)—and a third lab, Sandia National Laboratories (SNL), focused on weapons engineering.

Around the time President Bush left office in 1993, the US retained some 11 000 nuclear weapons,³ including two types of intercontinental ballistic missiles (ICBMs), five types of gravity bombs, two types of cruise missiles—one for the US Air Force and one for the US Navy—and two types of submarine-launched ballistic missiles. To comply with President Clinton's directive, the nuclear weapons enterprise would have to shift away from the Cold War model of aggressive competition between laboratories, continuous design and production of new nuclear weapons, and extensive underground nuclear explosive testing. By what other means could the US maintain “confidence in the safety, the reliability, and the performance” of its weapons while preserving “the core intellectual and technical competencies” in nuclear weapons?

The end of “build and test”

A new strategy was first envisioned by a small leadership team from the three weapons labs and the Department of Energy's Office of Defense Programs. The original team members were John Immele and John Browne from LANL, George Miller and Dick Fortner from LLNL, and Roger Hagengruber and Gerry

STOCKPILE STEWARDSHIP

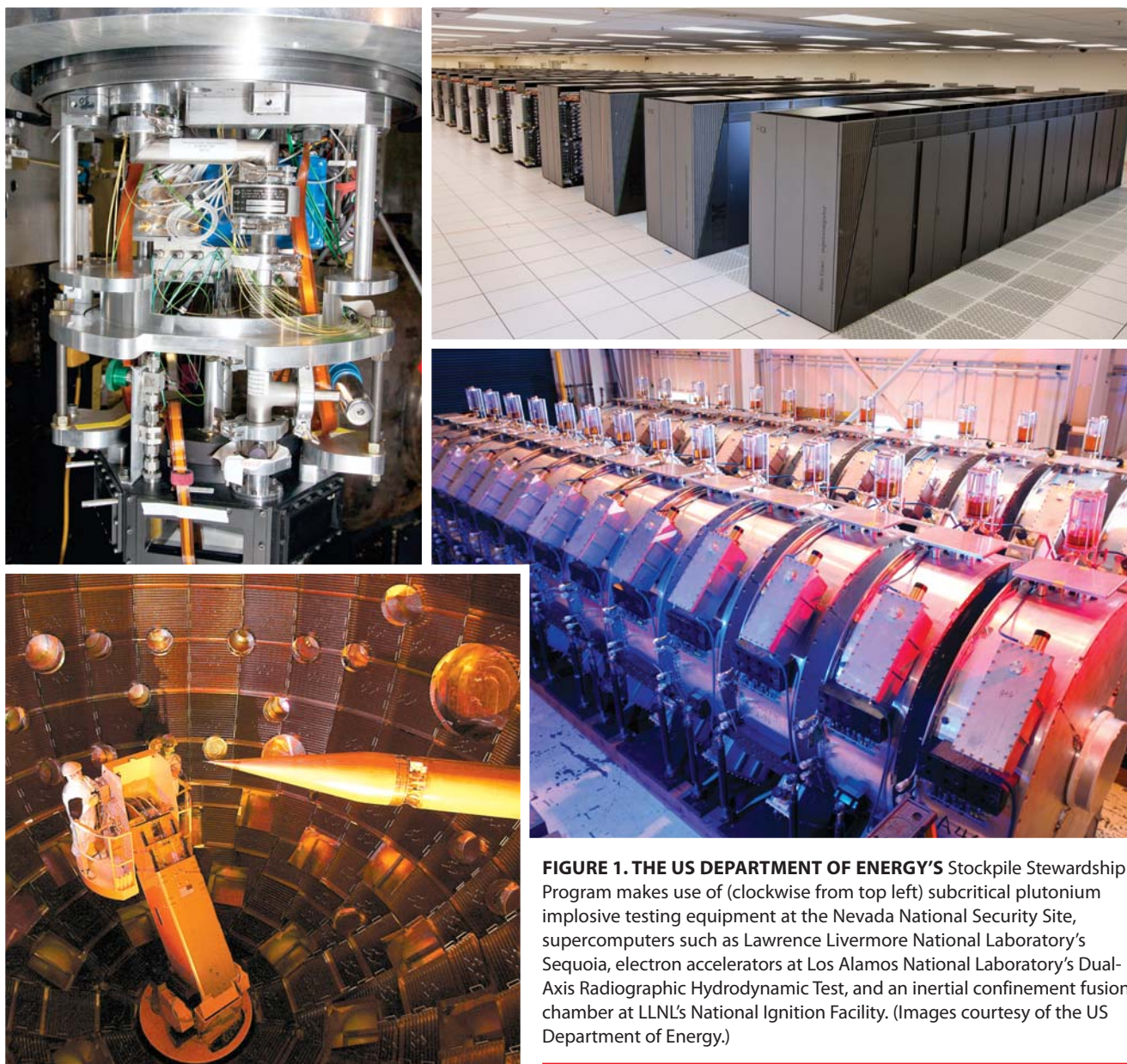


FIGURE 1. THE US DEPARTMENT OF ENERGY'S Stockpile Stewardship Program makes use of (clockwise from top left) subcritical plutonium implosive testing equipment at the Nevada National Security Site, supercomputers such as Lawrence Livermore National Laboratory's Sequoia, electron accelerators at Los Alamos National Laboratory's Dual-Axis Radiographic Hydrodynamic Test, and an inertial confinement fusion chamber at LLNL's National Ignition Facility. (Images courtesy of the US Department of Energy.)

Yonas from SNL. As the assistant secretary of energy for defense programs at the time, one of us (Reis) chaired the effort.

The team assumed that the nuclear stockpile would be reduced to between 1500 and 5000 weapons over the next 20 years, with similar weapon types. (That assumption proved prescient.³) The goal would be to attain sufficiently detailed scientific understanding of the nuclear explosive process to discover, comprehend, and correct any anomalies that might occur during the lifetimes of the stockpile weapons; advise the president on whether a return to nuclear explosive testing might be required; and carry out such tests, if needed.

To that end, the team recommended a new major project at each lab—the National Ignition Facility (NIF) at LLNL, the Dual-Axis Radiographic Hydrodynamic Test (DARHT) facility at LANL, and what became the Microsystems and Engineering Sciences Applications Complex at SNL. Each was a large-scale extension of an ongoing laboratory project and would require

greatly enhanced diagnostic capabilities. Each lab would have a dedicated high-performance computer.

The design, fabrication, and operation of the proposed new experimental and computational tools would serve a dual purpose: to equip the laboratories' scientists and technicians to solve anticipated issues with the current stockpile and to demonstrate their continued nuclear competence, adding to the nation's long-term deterrent posture. Crucially, the three DOE labs would share a common vision, shifting from an explosive-test-based confidence model to one of science-based validated simulation. For the US to maintain testing expertise, plutonium experiments at the Nevada Test Site would continue. But they would be subcritical, to avoid igniting a nuclear explosion. Figure 1 shows an apparatus used to conduct the subcritical experiments, along with other images of stockpile stewardship facilities at LLNL and LANL.

The team estimated that the cost for the new weapons strat-

egy would be roughly \$4 billion to \$5 billion per year for 10 years—about the same as had been required to fund the nuclear testing program. There would be no so-called peace dividend.

The team's concept was developed by the US nuclear weapons communities over the following months. It was then reviewed and endorsed by the administration's myriad national security agencies, Congress, and technical advisory groups, and it was adopted as official US policy.⁴

Thus a strategy of "build and test" was replaced with one that relied on a detailed understanding of nuclear warheads, enhanced technical surveillance of the stockpile, and new experiments and computer simulations. In essence, the viability of the weapons in the US nuclear stockpile was to be entrusted to the scientific competence and integrity of DOE's weapons labs. Thus the program's name: Science-Based Stockpile Stewardship (SBSS).

Much ado about zero yield

After a series of intense interagency and international negotiations—and the resumption of testing by the French government—President Clinton announced on 11 August 1995 that the US would support a "zero yield" comprehensive test-ban treaty, which would forbid nuclear explosions outright. His spokesman added,

I am assured by the secretary of energy and the directors of our nuclear labs that we can meet the challenge of maintaining our nuclear deterrent under a [comprehensive test ban] through a science-based stockpile stewardship program without nuclear testing.⁵

One year later the Comprehensive Nuclear-Test-Ban Treaty (CTBT) was adopted by the United Nations General Assembly and signed by President Clinton. In the ratification package that he sent to the US Senate, the president included an assurance that the US's acceptance of the CTBT was conditional on

the conduct of a Science Based Stockpile Stewardship program to ensure a high level of confidence in the safety and reliability of nuclear weapons in the active stockpile, including the conduct of a broad range of effective and continuing experimental programs.⁶

He also assured the Senate that under the treaty the US would maintain modern nuclear laboratory facilities, maintain the basic capability to resume nuclear testing, continue to improve its treaty-monitoring capabilities, and continue developing its nuclear-intelligence-gathering apparatus. As a final safeguard, he stated that

if the President of the United States is informed by the Secretary of Defense and the Secretary of Energy (DOE) . . . that a high level of confidence in the safety or reliability of a nuclear weapon type which the two Secretaries consider to be critical to our nuclear deterrent could no longer be certified, the President, in consultation with Congress, would be prepared to withdraw from the CTBT under the standard "supreme national interests" clause in order to conduct whatever testing might be required.⁶

Despite those reassurances, when the Senate finally took up ratification of the CTBT in October 1999, there was considerable skepticism as to the viability of stockpile stewardship. Brent Scowcroft, Henry Kissinger, and John Deutch evinced a typical concern in their open letter to the Senate Foreign Relations Committee:

But the fact is that the scientific case simply has not been made that, over the long term, the United States can ensure the nuclear stockpile without nuclear testing. . . . But even with adequate funding—which is far from assured—the Stockpile Stewardship Program is not sufficiently mature to evaluate the extent to which it can be a suitable alternative to testing.⁷

The Senate did not consent to ratify the treaty and has not to this day.

At the time of the CTBT ratification debate, the skepticism of the Senate and some of its advisers was arguably justified. But in the decades that followed, the scientists at the national labs tasked with carrying out stockpile stewardship would allay the sceptics' reservations.

A Big Science application

During the Cold War, underground nuclear testing at the Nevada Test Site was the centerpiece of the development and deployment of the US nuclear stockpile. The tests were "final exams" not only for the nuclear warheads themselves but for the laboratory scientists and engineers, who were continually experimenting with new ideas, apparatus, and diagnostics. The program was the quintessential Big Science endeavor, applied to an existential national security mission.

Replacing that program, and doing so under a demanding time schedule, represented a continuing set of challenges for the weapons labs. To address the challenges, the architects of the new nuclear strategy developed three major research programs: nuclear primary hydrodynamics, high-energy-density physics, and plutonium metallurgy. Each subject area would require its own analysis and computer models, which would ultimately be integrated into a series of high-fidelity simulations to assess performance and safety.

Nuclear primary hydrodynamics

A thermonuclear weapon functions through a sequence of events, beginning with the primary-stage implosion, which ignites a fissile material—most often Pu—and thereby releases a massive amount of x-ray radiation. That radiation is trapped inside a radiation case and provides the energy to trigger the thermonuclear secondary.

Understanding how the fissile Pu pit is compressed during the primary-stage implosion is fundamental to nuclear weapons design. By simulating the pit's compression using nonfissile Pu surrogates, researchers at LANL's DARHT facility are able to generate a variety of two-dimensional, full-scale images that then serve to inform weapons primary design. At the Nevada Test Site, now known as the Nevada National Security Site (NNSS), primary implosions are performed with fissile Pu, but material quantities are reduced sufficiently to ensure that the assembly remains subcritical at all times, in compliance with the CTBT.

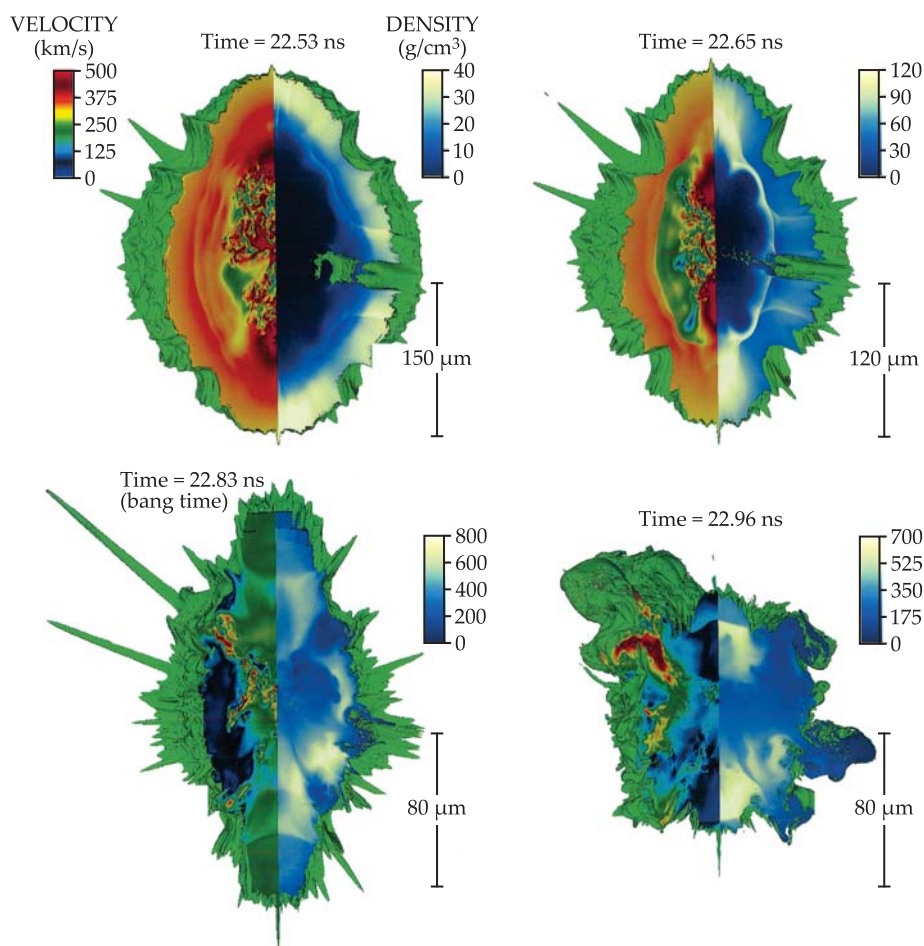


FIGURE 2. INERTIAL CONFINEMENT FUSION has proven elusive in part because tiny asymmetries and imperfections in the fuel-filled target capsule can produce vastly nonuniform implosion fronts. In this series of snapshots taken near a simulated implosion's "bang time"—the anticipated moment of ignition—spike-like perturbations arise from localized defects in the thin plastic capsule (green). In each panel, the cutaway surface shows fluid speed at left and fluid density at right. Over the course of the implosion, a hot spot develops at the upper left of the target. (Adapted from ref. 11.)

Advanced diagnostic tools both at the DARHT and at the NNSS allow implosions to be analyzed with far greater precision than was possible during the era of explosive testing. The precise diagnostics provide stringent tests of fabrication, designs, materials models, computer codes, the abilities of the designers to predict and understand results, and the ability of the researchers to execute the complex experiments. The Pu experiments at the NNSS also exercise many of the skills required to return to full-scale nuclear explosive testing, if such testing were ever required.

High-energy-density physics

From almost the beginning of nuclear weapons research, the Atomic Energy Commission and its successor agency, DOE, supported research on inertial confinement fusion (ICF), the ongoing effort to ignite a fusion reaction by compressing a target fuel with energy from lasers or other pulsed-power drivers.

Work on ICF has attracted interest not only because of its intimate connection to nuclear design and performance but also because of its potential as a long-term source of energy.⁸

Well before 1992 DOE appreciated that ICF could provide an alternative to underground tests for exploring radiation hydrodynamics—the study of the flow of matter under circumstances where strong coupling with electromagnetic radiation (in this case, x-ray radiation) significantly affects the observed phenomena. Experiments with ICF could also help maintain essential scientific, technical, and design skills. As part of the stockpile stewardship strategy, NIF, the Z machine at Sandia, and the Omega facility at the University of Rochester in New York now conduct studies that integrate radiation hydrodynamics with focused physics experiments.

The collective challenge of building, maintaining, and operating complex integrated facilities; improving the power of pulsed optical and electrical systems; designing and fabricating novel experimental targets; and upgrading the state of

the art in diagnostic instrumentation was similar in scale, complexity, and technical difficulty to the challenge of underground testing. The ICF experiments have elucidated fundamental properties of high-energy-density materials, atomic opacities, equations of state, kinetic effects in dense plasmas, and nonequilibrium processes—all with much greater precision than ever before. Many of the findings have become important components of radiation-hydrodynamics models, but they are also relevant to astrophysics, planetary physics, high-pressure science, and other fields of study.⁹

Of the SBSS facilities, NIF stands out in terms of its size, technological complexity, and breadth of scientific interest. At the time NIF was planned, the best radiation-hydrodynamics codes suggested that ignition of an ICF capsule was feasible at scales attainable in the laboratory.¹⁰ Despite considerable effort—and much public hoopla related to fusion energy—ignition has not yet been achieved.

Recent work enabled by vastly improved instrument resolution and full 3D computational capabilities helps explain why. Studies such as the one in figure 2 demonstrate that, *inter alia*, laser drive asymmetries, engineering features, and imperfections in the target capsule distort implosions to a far greater degree than was initially appreciated.¹¹ As shown in figure 3, even a plastic support membrane just 110 nm thick can substantially perturb an implosion.¹²

Run by DOE's National Nuclear Security Administration (NNSA), the ICF facilities provide the opportunity for scien-

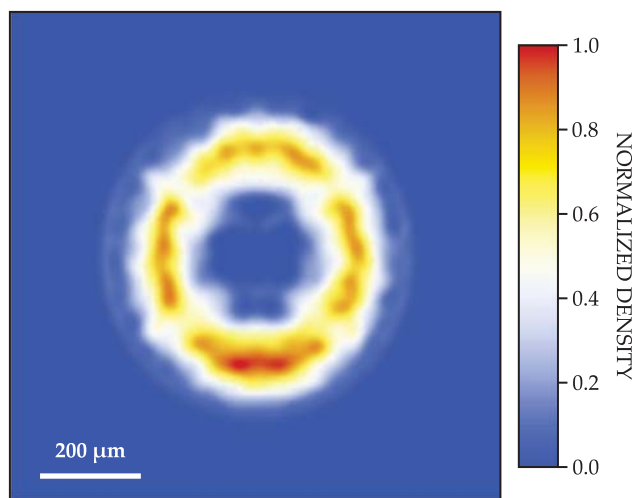


FIGURE 3. A CAPSULE OF NUCLEAR FUEL undergoing a laser-powered implosion shows density defects at four positions along its outer ring, as seen in this x-ray image. The defects occur where the capsule support membrane contacts the target surface. (Adapted from ref. 12.)

tists to gain experience applying new physical models and increasingly powerful computers to ignition and high-energy-density experiments—problems that closely parallel physical phenomena relevant to the performance and safety of the nuclear stockpile. Because much of the work performed for the ICF program is publishable, scientists responsible for stockpile stewardship have the opportunity to interact with the academic community, which in turn helps maintain public confidence in the stockpile scientists' abilities.

Plutonium aging

When stockpile stewardship began, American scientists understood little about how the material properties of Pu evolve with age. (Barely 50 years had passed since the first Pu metal was produced.) The scientists needed to either learn enough about aging to be able to certify the performance of existing Pu pits or build replacement pits from scratch. The latter task would have been formidable, given the closing of the US's pit-manufacturing facility at Rocky Flats, Colorado. So LANL and LLNL focused on three aspects of Pu aging: radioactive decay, helium ingrowth, and the microstructural changes those two processes induce under conditions ranging from near ambient to those of a nuclear detonation.

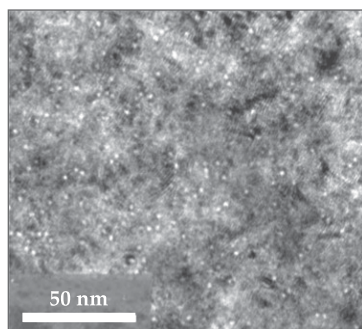


FIGURE 4. AGING WEAPONS-GRADE PLUTONIUM develops helium bubbles, visible as white spots in this transmission electron micrograph. Theorists initially hypothesized that those bubbles would coalesce into large voids that could compromise the material's viability as a nuclear fuel. Such void swelling, however, has yet to be observed in Pu. (Image courtesy of Lawrence Livermore National Laboratory.)

Materials scientists and nuclear scientists attacked the problem with a robust suite of tools: computational modeling to predict radiation effects at the atomic and lattice levels; continuum modeling to predict behavior at the grain scale; metallurgical studies on naturally aged materials from the stockpile; and studies on artificially aged alloys created by adding fast-decaying ^{238}Pu to the more slowly decaying, weapons-grade Pu alloy.¹³

Initially, many experts thought aging would be dominated by the onset of so-called void swelling, in which He bubbles agglomerate into voids in the Pu, causing a relatively rapid decrease in material density and strength under ambient conditions. The photomicrograph in figure 4 shows the distribution of He bubbles in aged Pu. The bubbles increase in number as the Pu ages, but to date, void swelling has not been observed. Rather, growing bubbles appear to become pressure stabilized: At an equilibrium size determined by the strength of the Pu matrix, the pressure of He inside the bubble equals the yield strength of the Pu alloy, and there is no strain field around the bubbles.

Other properties of Pu were found to vary relatively smoothly with age. In other words, under experimentally accessible conditions, Pu appears to age gracefully. Based on the aging work, scientists at LANL and LLNL were able to report initial estimates of pit lifetimes in October 2006. For the majority of weapons types, most Pu pits had estimated lifetimes of 85 years or more.¹⁴

Subsequent work on Pu has ranged from developing techniques to study its behavior under subcritical implosion conditions at the NNSS to measuring its crystal structure under high pressures at NIF. But the key caveat, in 2006 and still to this day, is that we do not have complete data for aged Pu under the high-explosive-drive conditions of a pit. Obtaining those data will require diagnostics that can measure the hydrodynamic behavior of Pu through all the conditions obtained in a subcritical implosion. Aging Pu will continue to be a stockpile stewardship research area for many years to come.

High-performance computing

Perhaps no aspect of the SBSS program demanded more resources and technical know-how than the high-fidelity simulation of the nuclear explosive process. Faced with weapons materials aging in a radioactive environment and the impending retirement of the few remaining nuclear weapons experts experienced in underground testing, the program's planners estimated in 1993 they had only 10 years to ramp up computation speeds by a factor of 10 000 over the highest performing

computers at the time, equivalent to a factor of 1 million over computers routinely used for nuclear calculations. The feat would require an annual speedup about twice that of the already optimistic expectation from Moore's law, which predicts a doubling in computing speed every 18 months.

To meet the goal, the DOE laboratories had to engage the computer industry in massively parallel processing, a technology that was just becoming available, to develop not just new hardware but new software and visualization techniques. It was a risky proposition,⁴ but one built on a historic partnership. From that effort sprang

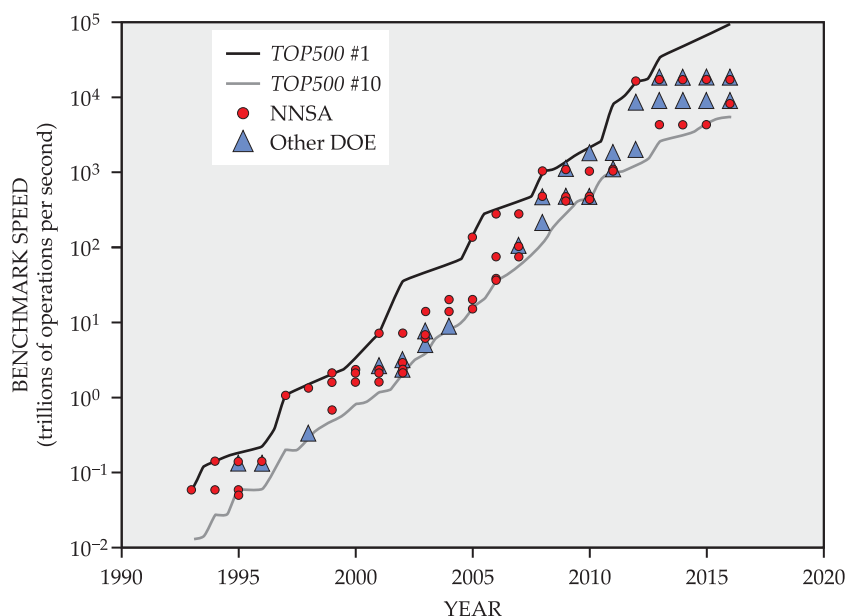


FIGURE 5. SUPERCOMPUTERS commissioned by the US Department of Energy's National Nuclear Security Administration (NNSA) for the purpose of stockpile stewardship have consistently ranked among the fastest in the world, as have other DOE computers. The black and gray lines, respectively, indicate the theoretical peak speeds of the world's fastest and 10th-fastest computers during a given year, according to *TOP500*. (Data from www.top500.org.)

a new dedicated program: the Accelerated Strategic Computing Initiative, now called the Advanced Simulation and Computing Program.¹⁵ In addition, DOE adopted a procurement strategy wherein each laboratory took turns buying a new machine that was larger—and capable of solving harder problems—than the last.

Despite the inevitable obstacles, the program met its milestones and now exceeds its 10-year goal for computing speed (100 teraflops) by a factor of 200. Meanwhile, massively parallel processing has become the global technology standard for high-performance computing and an integral part of stockpile stewardship and other DOE laboratory programs. Figure 5 shows how the computation speeds of DOE computers have stacked up with the world's leading computers over time, as reported annually by *TOP500*. The LLNL supercomputer Sequoia, which contains over 1.5 million processor cores, currently operates at 17 petaflops.

Extending the stockpile lifetime

The most direct application of the SBSS program to maintaining confidence in the US nuclear stockpile is the Life Extension Program (LEP), in which warheads are refurbished and modernized in order to prolong their useful lives.¹⁶ Because of the deep understanding of the nuclear explosive process gained through the SBSS—particularly through studies of Pu aging—the lifetimes of the warheads in the current stockpile will be extended for another 20–30 years. (See *PHYSICS TODAY*, November 2013, page 27.)

The US Air Force's W87 ICBM warhead has completed its LEP. The life extension of the US Navy's W76–1 warhead, a submarine-launched ballistic missile, is more than 50% complete. The LEP for the B61-12, a gravity bomb that will replace four existing versions of the B61, is completing development. And the LEPs for the navy's W88 ICBM warhead and the air force's W80 cruise missile warheads are in the early development stages.

In parallel with the LEP, scientists and engineers have had

to upgrade the nuclear weapons' electronics. Electronic systems for nuclear weapons must be highly integrated, reliable, and secure and must be designed to operate in unique, high-radiation environments. Working with Intel Corp, SNL developed the Permafrost Application Specific Integrated Circuit, and its Microsystems and Engineering Sciences Applications facility has produced some 3000 units for the navy.

In 2005, Congress directed the NNSA to investigate whether the SBSS's tools could be used to develop a new, high-confidence nuclear warhead and a responsive nuclear weapons production infrastructure. The NNSA sponsored a vigorous conceptual design competition between LANL and LLNL that generated two concepts for a reliable replacement warhead.¹⁷ (Both labs partnered with SNL.) Congress did not authorize any further development of either warhead, but much of the associated analysis has proven directly applicable to ongoing LEPs.

Passing marks

Science-Based Stockpile Stewardship sits at the confluence of US nuclear weapons, science, and technology policy. The effort didn't always run smoothly; it has at times had to withstand turbulent political climates, organizational reshuffling, cost overruns, and delays. Yet by prioritizing the scientific understanding of the nuclear explosive process, DOE, its nuclear weapons laboratories, and its partners at the Department of Defense have successfully answered President Clinton's challenge.

In the two decades since the Science-Based Stockpile Stewardship program became official US nuclear weapons policy, every annual stockpile assessment has culminated in a letter from the secretaries of defense and energy certifying the safety and performance of the stockpile. All the major tools recommended by the SBSS planning team have been developed and are operating at near full capacity.

In reviewing the results of the Stockpile Stewardship Program, the Congressional Advisory Panel on the Governance of the Nuclear Security Enterprise stated in March 2014,

To date, Science-Based Stockpile Stewardship has succeeded in sustaining confidence in the U.S. nuclear deterrent. Unmatched technical innovation on the part of NNSA's scientists and engineers has produced a dramatically increased understanding of the country's aging nuclear weapon stockpile.¹⁸

Looking forward, the nuclear landscape remains uncertain and dangerous. Although the Cold War has ended, the govern-

ments of Russia and China are modernizing their nuclear weapons. Nuclear proliferation and nuclear terrorism loom large. Our national response, as exemplified by the recent Joint Comprehensive Plan of Action to curtail Iran's nuclear program, is heavily dependent on DOE's laboratory system. (See PHYSICS TODAY, December 2015, page 26.)

In his 30 March op-ed in the *Washington Post*, President Obama wrote, "Even as the United States maintains a safe, secure and effective nuclear arsenal to deter any adversary and ensure the security of our allies, I've reduced the number and role of nuclear weapons in our national security strategy." Underpinning presidential confidence in the nuclear arsenal is the confidence in the integrity and competence of our national labs. That is what is meant by "science based."

The views and opinions expressed by the authors in this article do not necessarily state or reflect those of the US government or any of its agencies.

REFERENCES

1. The American Presidency Project, "The President's Radio Address, July 3, 1993," www.presidency.ucsb.edu/ws/?pid=46803.
2. GovTrack.us, "Text of the National Defense Authorization Act for Fiscal Year 1994," www.govtrack.us/congress/bills/103/hr2401/text.
3. See "Stockpile Numbers, End of Fiscal Years 1962–2015," http://open.defense.gov/Portals/23/Documents/frddwg/2015_Tables_UNCLASS.pdf.
4. See, for example, S. Drell et al., *Science Based Stockpile Stewardship* (rep. prepared for the US Department of Defense), MITRE Corp (November 1994).
5. See "Comprehensive Nuclear Test Ban" (11 August 1995), video, at the 7:09 minute, www.c-span.org/video/?66686-1/comprehensive-nuclear-test-ban.
6. Federation of American Scientists, "Comprehensive Test Ban Treaty Safeguards," <http://fas.org/nuke/control/ctbt/text/ctbsafeguards.htm>.
7. 145 Cong. Rec. S24603 (8 October 1999) (letter by B. Scowcroft, H. A. Kissinger, J. Deutch).
8. For a detailed discussion of the history of inertial confinement fusion, see J. H. Nuckolls, *Contributions to the Genesis and Progress of ICF*, rep. no. UCRL-BOOK-219136, Lawrence Livermore National Laboratory (2006).
9. B. A. Remington, R. E. Rudd, J. S. Wark, *Phys. Plasmas* **22**, 090501 (2015); J. E. Bailey et al., *Nature* **517**, 56 (2015).
10. J. Lindl, *Phys. Plasmas* **2**, 3933 (1995); J. Lindl et al., *Phys. Plasmas* **21**, 020501 (2014).
11. D. S. Clark et al., *Phys. Plasmas* **22**, 022703 (2015).
12. R. Tommasini et al., *Phys. Plasmas* **22**, 056315 (2015).
13. J. C. Martz, A. J. Schwartz, *J. Miner. Met. Mater. Soc.* **55**(9), 19 (2003).
14. R. J. Hemley et al., *Pit Lifetime* (rep. prepared for the US Department of Energy, National Nuclear Security Administration), MITRE Corp (January 2007).
15. A detailed history of the Accelerated Strategic Computing Initiative is available at <https://asc.llnl.gov/content/assets/docs/DeliveringInsightASCI.pdf>.
16. A full discussion of the Life Extension Program is available at <https://nnsa.energy.gov/ourmission/managingthstockpile/ssmp>.
17. J. Medalia, *The Reliable Replacement Warhead Program: Background and Current Developments* (rep. prepared for the US Congress), Congressional Research Service (December 2007).
18. N. Augustine, R. Mies, *Interim Report of the Congressional Advisory Panel on the Governance of the Nuclear Security Enterprise*, testimony before the US Senate Committee on Armed Services, 26 March 2014, www.armed-services.senate.gov/imo/media/doc/Augustine-Mies_04-09-14.pdf.



Surface

Composition Analysis

FOR ION MICROSCOPY



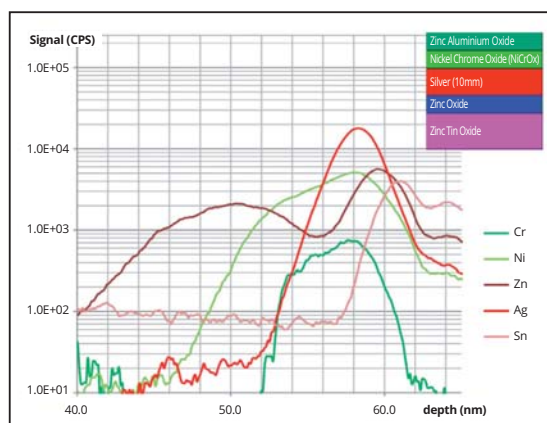
Hidden's EQS and MAXIM SIMS analysers provide:

- ▶ chemical surface composition analysis for ion probe microscopy
- ▶ depth profiling and surface imaging at the nano scale
- ▶ interface to existing systems

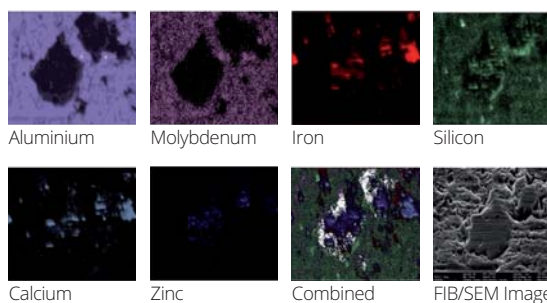
Hidden EQS (top left) on a Zeiss Auriga 60 FIB-SEM instrument



FIB-SIMS depth profile of low emissivity float glass



Multi Element Map showing the wear characteristics of an Alusil Engine liner



Courtesy of Dr John Walker, National Centre For Advanced Tribology, University of Southampton, UK.

Instrument is ZEISS NVision/Hidden EQS