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Stockpile Stewardship Considerations: Safety and Reliability Under a CTBT

The United States conducted its last underground nuclear-explosive test in September of 1992. In October of that year President Bush signed into law an amendment to the FY1993 Energy and Water Development Appropriations Act, which placed strict limits on the number and purposes of U.S. nuclear tests and established an initial 9-month moratorium on nuclear testing.[1] President Clinton subsequently extended the moratorium, first through September 1994 and then through the completion of the CTBT negotiations in September 1996. As indicated in the Introduction, the U.S. signature on the CTBT will continue to preclude U.S. testing unless and until the President announces formally that the country does not intend to ratify the treaty, and the position of the new Bush administration thus far has been that no need to resume testing is evident.

These decisions have been motivated by non-proliferation interests. They have been facilitated by the absence of military requirements for new nuclear designs that would require nuclear testing. As a result, the U.S. nuclear-weapon program has undergone a fundamental change from its earlier focus on new designs to its current focus on maintaining an enduring stockpile. The active component of this stockpile comprises eight different nuclear-explosive device designs (i.e., a nuclear subsystem comprising a sealed-pit primary, a secondary, and associated parts inside the weapon case) some of which occur in multiple weaponized versions.

The Department of Energy (DOE) has responded to these developments by restructuring the weapon program into a formal Stockpile Stewardship Program (SSP). This program is intended to ensure the continued safety, reliability, and operational readiness of the enduring stockpile, without nuclear testing, for as long as national policy dictates a need for such weapons.[2] The SSP places increased emphasis on strengthening the scientific understanding of nuclear device performance as well as the aging behavior of weapon materials and components. These efforts are supported by sizable capital-intensive facility investments, including development of high-performance computational simulation and modeling capabilities under the "Advanced Simulation and Computing (ASC)" program.[3] The SSP also addresses the need for enhanced surveillance of stockpile health and for essential manufacturing capabilities.

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[1] *Energy and Water Development Appropriations Act, 1993,* Public Law 377, 102nd Congress, 2nd session (October 2, 1993), section 507.

[2] U.S. Department of Energy, National Security Administration, *Stockpile Stewardship Plan: Executive Overview* (DOE/NNSA/DP-0141, June 12, 2000).

[3] ASC is the new name for Accelerated Strategic Computing Iniative; see http://www.nnsa.doe.gov/asc/.

A typical modern U.S. nuclear weapon consists of approximately 6,000 individual components. Of these, only the so-called nuclear subsystem, which includes the weapon's "primary" and "secondary," would be subject to the restrictions of a CTBT. The remaining components of a nuclear weapon and its delivery system could be tested at will under a CTBT.

It is assumed explicitly that the enduring stockpile will not depend on the introduction of new nuclear subsystem designs that would require nuclear testing for performance validation. However, the SSP is required to maintain the capability for executing new designs should a compelling need ever arise for such. In the shorter term it is conceivable that nuclear subsystems of established nuclear-test pedigree might be incorporated into new weapons to maintain compatibility with evolving strategic and tactical military delivery systems. This should not introduce uncertainties in weapon performance provided that none of the modifications intrude on the nuclear subsystem beyond established design practices.

The expectation that the United States will ratify the CTBT at some point in the future has fueled concerns in some quarters that confidence in the stockpile will inevitably erode over time in the absence of nuclear testing, notwithstanding the SSP. The fact that the stockpile has declined both in total numbers as well as in numbers of weapon types has added to this concern. In the remainder of this chapter we address these issues in four steps: a historical perspective on nuclear testing; a discussion of the factors affecting nuclear-weapon safety and reliability in the context of a CTBT; an analysis of five elements of an effective stockpile stewardship program; and a treatment of some issues in priority-setting in stockpile stewardship. We do not offer here a comprehensive or detailed assessment of the initiatives and facilities of the SSP—this would have been beyond our mandate—but confine ourselves mainly to the effects, on stewardship requirements and effectiveness, of a cessation of nuclear-explosive tests.

Nuclear Testing: Historical Perspective

Since 1945 the United States has amassed an extensive data, knowledge, and experience base derived from over 1,000 individual test explosions. The first 20 years were marked by rapid progress as measured by increasing yields, increasing yield-to-weight ratios, and advances in other militarily significant features. During the 1960s and 1970s tailored output concepts were explored, such as reduced residual-radiation, enhanced neutron, and hot X-ray devices. None of these advanced concepts, however, attracted lasting support from the military services, and none is part of today's enduring stockpile. During the 1970s and early 1980s the advances in nuclear-explosive technology reached a plateau as the nuclear designs of interest to the services approached performance limits set by the laws of physics. It is during this same period that the current stockpile designs evolved.

From a knowledge standpoint, nuclear-test data obtained during the past 25 years are of greatest relevance since many of these bear directly on the designs in the enduring stockpile and were obtained from well-diagnosed tests. Most nuclear tests were focused on the development of new designs—ranging from exploratory concepts to designs aimed at specific requirements promulgated by the military—although only a small fraction of the warhead designs subjected to nuclear testing were identical to the warhead designs that actually entered the stockpile. Other tests centered on weapon-physics issues not related to a specific weapon-development program. Some pursued novel ideas, such as the X-ray laser. Many primaries utilized in nuclear tests conducted for a variety of these purposes, however, were taken from the stockpile production line, which enabled these tests to contribute something to stockpile confidence. Certainly, the totality of the nuclear testing experience contributed to design and manufacturing expertise and to an overall sense of assurance that the U.S. design and production complex was delivering reliable weapons. But the number of tests was too small to provide a statistical basis for confidence, and it did not allow coverage, for each design, of the range of stockpile-to-target sequence (STS) conditions called for in the military specifications.[4]

A test of one stockpile system per year became institutionalized in the last decade of U.S. nuclear testing. These so-called stockpile confidence tests involved new-production units, with two exceptions (involving weapon types that were low on the priority lists and were retired soon after the tests). Since these tests primarily established confidence in the stockpile system as it was initially produced, validating the integrated performance of the nuclear subsystem at stockpile entry, they should be described more correctly as “production verification” tests. Any deviations from the expected results were attributed to final design and/or fabrication variations from units tested during development, certainly not to aging effects. Even in the absence of constraints on nuclear testing, no need was ever identified for a program that would periodically subject stockpile weapons to nuclear tests.

Thus, nuclear testing never provided—and was never intended to provide—a statistical basis for confidence in the performance of stockpiled weapons. Rather, it has always been deemed adequate to rely on inspection of the nuclear components as part of a systematic stockpile surveillance program, after the nuclear components had initially been tested. This reliance on surveillance is necessary because nuclear tests have always been too few to provide a statistically significant measure to assess weapons reliability quantitatively. Thus, nuclear testing in itself is intrinsically ill-suited to monitor the health of the stockpile. The question of whether nuclear testing might ever be needed to correct problems discovered in weapons after certification and deployment generated some controversy during the 1980s.[5] However, it was shown that almost all of the problems cited in support of this proposition were either of a kind not requiring nuclear testing to correct or represented cases where testing had been inadequate during development.[6] In relating these experiences to the current situation it is also important to note that the observed failures all occurred within three years after entry into the stockpile. The weapons in today’s active stockpile have long passed the age where anomalies in initial production units are a significant problem. Furthermore, they are all based on tested designs that have taken advantage of lessons learned from older vintages. Having analyzed the historical record, we judge that aging problems that may occur in the future will be detected in DOE’s surveillance program and that they can be corrected by replacement of the affected components, given adequate production facilities.

It should be recognized that the production run for a stockpiled system includes a range of variations—deviations from the ideal. The refurbishment and/or remanufacture of nuclear-subsystem components will involve similar variations. The effects of such variations in both cases can be expected to be small, although they are not reliably calculable. This is because the systems in the U.S. enduring stockpile are robust, meaning not very sensitive to small variations from design specifications or conditions. Straightforward practical measures, moreover, which

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[4] See, e.g., J. S. Foster (Chairman), et al., *FY1999 Report of the Panel to Assess the Reliability, Safety, and Security of the United States Nuclear Stockpile* (Washington DC, November 8, 1999), p 2.

[5] J. W. Rosengren, *Some Little-Publicized Difficulties With a Nuclear Freeze* (Report Prepared by R&D Associates for the Office of International Security Affairs, U.S. Department of Energy, October 1983), and *Stockpile Reliability and Nuclear Test Bans: A Reply to a Critic’s Comments* (RDA-TR-138522-001, R&D Associates, November 1986).

[6] R. E. Kidder, *Evaluation of the 1983 Rosengren Report from the Standpoint of a Comprehensive Test Ban (CTBT)*, UCID-20804, Lawrence Livermore National Laboratory, June 1986, and *Stockpile Reliability and Nuclear Test Bans* (UCID-20990, Lawrence Livermore Laboratory, February 1987).

have been validated by previous nuclear tests, can enhance primary performance margins, compensating for the cumulative effect of many small variations due to aging or remanufacture. These measures are discussed in the section on "Performance Margins of the Primary."

Critics of a CTBT have pointed to examples of the risk of introducing new designs into the stockpile without testing. We do not believe that this should be done; we accept that a constraint on U.S. freedom of action imposed by a CTBT would be to preclude the certification of new designs for addition to the stockpile with confidence in performance equal to that associated with the weapons now there. But previously tested nuclear subsystems or components of these could be used in modified or entirely new delivery systems, provided that any influences of the altered system on the nuclear subsystem were deemed to be within acceptable limits in the light of prior nuclear-test experience. The key constraint on deployment of additional nuclear weapons of previously tested designs under a CTBT, should the country wish to do this, would not be the absence of the ability to conduct new nuclear tests but the lack of capacity for manufacturing new primary pits. (The exception to this constraint is one previously tested design that is based on reuse of primary pits from a retired system.)

Critics also assert the difficulty of maintaining weapon-laboratory competence in the absence of nuclear testing. We believe that the absence of new programs of nuclear-weapon development for deployment is a bigger part of the challenge of recruitment and retention than is the absence of testing *per se*. Whether nuclear weapons are seen as an important national asset is also important, as are working conditions at the weapons laboratories. How this challenge can be addressed is discussed in the section on "Human Talent Pool."

The fact that older nuclear designs are no longer being replaced by newer ones means that the average age of the nuclear subsystems in the stockpile will increase over time beyond previous experience. (The average age will eventually reach a maximum that depends on the rate at which weapons are remanufactured or retired.) This means that the enhanced surveillance activities that are part of the current SSP will become increasingly important. But that would be so whether nuclear testing continued or not. Nuclear testing would not add substantially to the SSP in its task of maintaining confidence in the assessment of the existing stockpile.

Finally, we note that it has never been possible for practical reasons to explore the full operating range specified by the "military characteristics" during the development phase of nuclear designs that entered the stockpile. Computational modeling, using codes and computers that were often primitive by modern standards, was relied on to interpolate and extrapolate the test data over the specified range. In this manner estimates were generated for primary yield variations with boost-gas age, secondary yield variations, and other critical performance measures covering the extremes of the stockpile-to-target-sequence requirements. Modern simulation capabilities have significantly improved the ability to predict the performance of nuclear weapons.

Factors Influencing Safety and Reliability

To understand more fully why confidence in the stockpile historically has remained very high even though nuclear confidence testing has not played a significant role in substantiating this confidence, it is necessary to understand the factors that enter into the assessment of weapon safety and reliability. Nuclear weapons with their thousands of individual components are complex both in function and design. Failure of a critical component can lead to total system failure. This has led to assertions that, in the absence of nuclear testing, the safety and reliability of the weapon cannot be guaranteed. This belief is erroneous on several counts. Most importantly, the vast majority of weapon components are not integral to the nuclear subsystem and can therefore be tested under a CTBT. Furthermore, redundancies in system design guard against the most probable failure modes and, as regards safety, designs of current weapon safing, arming, fuzing, and firing systems are based on fail-safe architectures as described in the following section.

Safety

Safety criteria for nuclear weapons fall into two categories: nuclear-detonation safety and plutonium-dispersal safety. While accidental dispersal of plutonium poses a far less catastrophic threat than does a nuclear detonation, the cleanup costs for a wide-area plutonium dispersal would still be substantial. Over the years, solutions have been incorporated in weapon designs that have reduced the risk of an accidental nuclear detonation to a very low level. Progress has also been achieved regarding plutonium dispersal. It remains true, nonetheless, that operational and logistical measures that minimize weapon exposure to serious accidents still form the most important line of defense, one that is both cost-effective and meets applicable standards if rigorously implemented.

Operational and logistical safety standards have been established for two distinct environments. **Normal environments** are defined in the stockpile-to-target sequence and military-characteristics specifications as those in which the weapon is required to survive without degradation in reliability. **Abnormal environments** are those in which the weapon is not expected to retain its reliability, as would be the case for accidents in which a weapon is subjected to severe damage.

- For **normal-environment** stockpile-to-target sequence scenarios both nuclear-detonation safety as well as plutonium-dispersal safety are determined entirely by the characteristics of the electrical subsystem with its various electrical and mechanical safing, arming, fuzing, and firing components. To prevent inadvertent firing of the primary detonators the weapon electrical subsystem incorporates a degree of fault tolerance in its design that is believed to satisfy the requirement of no greater than a one in one billion (10^{-9}) probability over a warhead's lifetime.
- For **abnormal-environment** stockpile-to-target sequence scenarios one-point nuclear-detonation safety is the only safety criterion that hinges on the nuclear performance of the nuclear subsystem. (This criterion specifies that the probability of a nuclear yield greater than 4 pounds TNT equivalent must not exceed 10^{-6} in the event that a detonation is initiated at any point in the high explosive surrounding the primary.) Confidence that the one-point criterion is satisfied derives from the nuclear-test-based pedigree of primaries in the existing stockpile, all of which have been certified by calculation and testing to be one-point safe. It follows that even under abnormal conditions nuclear-detonation safety is dominated by the electrical subsystem architecture. Analysis of accidents involving nuclear weapons that occurred during the 1950s and 1960s raised serious concerns that the electrical subsystems of that era could conceivably cause a nuclear detonation under the influence of fire, impact, or other accident-related assaults. While these concerns could not be quantified, it became clear that the safety margins under a wide range of credible abnormal conditions fell far short of the 10^{-6} per incident requirement established in 1958. This led initially to operational changes that reduced the probability of accidents. It was followed in the early 1970s by the development of an "Enhanced Nuclear Detona

> tion Safety" (ENDS) electrical-subsystem architecture with predictable fail-safe characteristics.[7] Although the fundamental weak-link/strong-link concept for isolating sources of electrical energy from the primary detonators has remained unchanged, the design and location of the safety-critical links in this architecture have evolved over time. In some cases links have been integrated into the detonator design, thus placing them as close to the high explosive as is functionally possible. While not directly testable for all conceivable accident scenarios, confidence in the robustness of the architecture and its various implementations is firmly rooted in experiment and analysis. Currently a large majority of U.S. weapons feature ENDS subsystems. There are no plans to retrofit weapons lacking ENDS because it is anticipated that these will in time be retired from the stockpile.

While the probability of inadvertent nuclear detonations has been reduced by modern electrical-subsystem designs to acceptably low levels there still remains the threat of plutonium dispersal in accidents. The consequences of such dispersal become greatly amplified if the high explosive detonates, causing the plutonium to become aerosolized. Beginning in 1974, the incorporation in nuclear primary designs of "insensitive" high explosives (IHE) that fail to detonate at rigid-target impact velocities as high as 2,000 feet/second has provided an effective solution to that problem. Not every existing weapon utilizes IHE, primarily because of performance considerations arising from the lower energy density of IHE. Decisions to use conventional high explosive instead of IHE were supported by judgments that the formal weapon-system requirements could not be met with an IHE design, and that the existing safety margins would be adequate for the intended application. Even with IHE, however, pit melting in high-temperature fires and subsequent dispersal of plutonium oxidation products remain as a serious, though lesser, concern. Several stockpile weapons, as well as a nuclear-test-validated alternate weapon system, feature so-called "fire-resistant" pit designs that provide containment of molten plutonium in fuel-fire environments. Nonetheless, it is clear that the most effective way to prevent plutonium dispersal is to minimize the likelihood of energetic accidents that would cause plutonium to be spread beyond the accident site. The exposure to such accidents is greatest during weapon transport, and the potential consequences are much greater for air shipments than for road or rail shipments in protective transporters.

We therefore conclude that the safety of the enduring stockpile as designed is not dependent on nuclear testing. With the exception of one-point safety, which is an intrinsic design feature of all U.S. primaries, nuclear detonation safety is entirely a function of electrical subsystem design. The introduction of IHE and "fire-resistant" pits in some weapon types has resulted in significant reduction of the risk of plutonium dispersal. Adding one or both of these features to a conventional primary requires a new primary design and is therefore not possible in the absence of testing unless a previously validated system having these features can be incorporated into a modified delivery system.

Improvements in ENDS implementations as well as in other command-and-control functions such as use-control will undoubtedly evolve over time. This includes the important matter

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[7] The safety-critical electrical and electro-mechanical components in the ENDS architecture are located within a structurally robust exclusion volume. The power source required to initiate detonation of the primary high explosive is isolated from the weapon detonators by a "strong-link" switch that is only closed when the weapon is intentionally armed during its delivery trajectory. This switch is also designed to remain open prior to arming, under any conceivable accident scenario, for a length of time long compared to the time required for a "weak link" to cause collapse of the power source. A high-voltage capacitor that stores the charge needed to fire the detonators is a simple example of such a weak link. It can be designed to fail predictably under high-temperature and/or energetic-impact conditions as might be experienced, for example, in an aircraft crash. By placing two weak-link/strong-link sets in series one can achieve confidence that the 10^{-6} failure criterion is satisfied. In practice, the two sets employ very different designs in order to eliminate the possibility of common-mode failures.

of preventing unauthorized use. These improvements can be incorporated without nuclear testing as long as they only affect components outside the nuclear subsystem. From time to time ideas for improvements have been advanced that involve placement of components inside the nuclear subsystem. It is conceivable that these could be accommodated without nuclear testing provided the required mass/volume perturbations are judged to be so small as to pose no threat to the performance of the nuclear subsystem. On the other hand, more intrusive concepts, especially those aimed at increasing plutonium-dispersal safety by means of primary configurations that would keep the fissile material separated from the high explosive until the weapon is armed, could not be implemented without nuclear testing and would therefore be unavailable under a CTBT. Considering the high cost involved, serious reliability concerns, and the uncertain benefit to be derived, however, it seems questionable whether incorporation of any of these ideas into the enduring stockpile could be justified even if nuclear testing were permitted.[8]

Reliability

The reliability of the stockpile is derived from reliability models for each weapon type. These models decompose each weapon type into its functional parts, which are assigned reliabilities derived from the available data. A fault-tree methodology is used to estimate the overall system reliability.

Nuclear subsystems in the enduring stockpile historically have been certified to achieve the specified yield range with 100 percent certainty over the entire range of specified stockpile-to-target sequences, provided that the firing, neutron-generator, and boost-gas subsystems function within their specified tolerances corrected for the range of STS conditions. Although the physics governing the detonation of the nuclear subsystem is exceedingly complex, the engineering complexity in terms of parts count and structural features is for the most part not very great. This has permitted an approach to guaranteeing reliable operation in which the manufacture of the nuclear components and their assembly is carefully controlled within tight tolerances, yielding production versions that replicate devices whose pedigree was established through nuclear tests during the development phase. Periodic inspection of nuclear subsystem parts from weapons withdrawn randomly from the stockpile, together with remedial action when required, ensures that conformance to specification is maintained over time. Analysis of nuclear-test diagnostics data for the systems in the U.S. enduring stockpile has shown that none operate near catastrophic failure thresholds. In addition, there are available measures to increase confidence in nuclear subsystem reliability. These measures are discussed in the section on "Performance Margins of the Primary."

It follows that the formally assessed system reliability of existing systems is determined entirely by the "non-nuclear" subsystems. This includes the safing/arming/fuzing/firing subsystem, the neutron-generator subsystem, the boost-gas handling subsystem, and a large variety of other electrical, mechanical, and structural parts. The parts count runs to several thousand and many of the active components are complex both in design and function. The "non-nuclear" parts do not require nuclear testing for full functional evaluation and a CTBT would therefore

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[8] The statement transmitted to the Armed Services and Appropriations Committees of the House and Senate by President George H. W. Bush on 19 January 1993 upon signing the law initiating a 9-month moratorium on U.S. tests declared that "we do not believe it would currently be cost-effective to incorporate [additional safety improvements] in the existing stockpile." Undersecretary of Defense John Deutch testified to the House Armed Services Committee on 3 May 1993, early in the Clinton administration, to the same effect (Testimony by J. Deutsch, U.S. House of Representatives. 1993. Armed Services Committee. Panel on Military Application of Nuclear Energy. 103rd Congress, 1st session. May 3).

not impact weapon-reliability assessments. (Ensuring conformance to radiation-hardening specifications under a CTBT is discussed below.) The determination of failure probabilities for the functional blocks in the weapon reliability model is based on data obtained from random-sample tests. These are conducted on parts withdrawn at various stages during production, on parts obtained from newly assembled warheads (New Material Evaluation), and on parts obtained from warheads withdrawn at varying intervals from the stockpile (Stockpile Evaluation).

In order to meet the stated goal of affirming, at 2-year intervals, a 90 percent level of confidence that if 10 percent or more of the warheads of any given type contained a flaw this would be detected, 21 warheads of each type with a population under 500 and 22 warheads of each type with a population of 500 or more are withdrawn randomly from the stockpile every 2 years for examination. These weapons are disassembled and the parts inspected, including the nuclear components (one per weapons type is destructively disassembled each year). The non-nuclear parts from approximately 70 percent of these weapons are subjected to extensive functional tests. The remaining 30 percent of the disassembled weapons are subsequently converted into "Joint Test Assembly" (JTA) units and flight-tested. A JTA is a weapon in which the nuclear subsystem has been removed and replaced, typically by a diagnostic telemetry system with closely matching mass properties. The recent introduction of "high-fidelity" test vehicles in which the special nuclear materials have been replaced by matching surrogates allows even more realistic tests of integrated system function. Depending on the particular configuration, JTA flight tests of a bomb or missile enable various weapon functions from arming to detonation of the primary explosive to be evaluated for realistic stockpile-to-target sequence delivery scenarios. These and other (e.g., ground-based) system-level tests have proven to be especially important over the years.

Weapon military characteristics generally include requirements for hardening against nuclear radiation (neutron, X-ray, gamma ray) to reduce vulnerabilities to defensive nuclear bursts (e.g., from a nuclear-armed anti-ballistic missile) and to prevent fratricide in the case of dense targeting. Reliability assessments for weapons in such "hostile" environments have in the past benefited from underground nuclear-effects tests. These tests involved exposure of material samples, components, subsystems, and occasionally full-up reentry systems (minus fissile components) to the radiation of a low-yield nuclear device. A large database on weapons effects has resulted from experiments carried out by the Department of Defense and DOE. Although this database remains of great value to this day, laboratory simulators (pulsed nuclear reactors, electron-beam sources, Bremsstrahlung X-ray sources, lasers, light-initiated explosives, etc.) combined with computational modeling had begun to replace underground nuclear-effects tests for radiation hardening purposes even before the moratorium. The reasons were not only related to the lower cost and greater accessibility of laboratory simulators. For some weapon effects the laboratory simulations were shown to have superior fidelity due to the fact that the radiation from underground explosions had characteristics quite unlike the postulated threat. As a result of these efforts the current stockpile is believed to meet the vulnerability requirements established at the height of the Cold War. Laboratory simulation and analysis as new technologies are introduced into future non-nuclear component designs can provide verification of these radiation hardness levels under a CTBT.

The previous discussion allows two important conclusions to be drawn regarding existing weapon reliability: (1) Weapon reliability is dominated by the non-nuclear system elements, which are testable under a CTBT; and (2) Confidence in the continued reliability of the nuclear subsystem can be maintained by ensuring that in any future rebuilds, especially of the primary, the original specifications are adhered to closely. Because of the potential difficulty, but crucial need, for adhering to original specifications, it is important to recognize that additional measures are available to increase confidence in system reliability (see the section on "Performance Margins of the Primary").

Elements of an Effective Stewardship Program

The Secretaries of Energy and Defense are required to submit to the President an annual weapon-stockpile certification report.[9] As in the past, the report for 2000 certified that all safety and reliability requirements are being met without need for nuclear-yield testing.[10] The analysis presented above makes it possible to define five imperatives for the nuclear-weapon complex that will enable it to provide this assurance into the indefinite future under a permanent test ban.

Human Talent Pool

It is self-evident that a highly motivated, competent work force throughout the complex, supported by a modern infrastructure and adequate budgets, is of overarching importance.[11] The three weapon laboratories and the production complex have found it increasingly difficult to retain their top technical talent and to recruit replacements. Reasons for this vulnerability include attractive career opportunities in the private sector, uncertainties about the future of the nuclear-weapon program, and burdensome restrictions such as those imposed following recent security incidents. Clear signals about future program direction and scope, long-term program commitments to technically challenging assignments, and greater attention to quality of work-life issues should assist in reversing this troubling trend.

The challenge of technical staff retention, recruitment, and training is especially pressing in the core weapon areas at the two nuclear design laboratories (Los Alamos and Lawrence Livermore). The lack of requirements for new nuclear-weapon designs and the end of nuclear-explosive tests have eliminated some of the traditional technical opportunities in the nuclear-weapon field. At the same time it is clear that the importance of the nuclear-weapon experience base will not diminish; rather it is likely to grow. As pointed out earlier, even when nuclear testing was permitted, confidence in the reliability of the nuclear subassembly ultimately rested on the informed judgments of a competent technical staff. It would have been impossible, for example, to establish manufacturing tolerances on the basis of nuclear testing alone. In the future the same informed judgment would be needed to decide at what point nuclear components in the aging stockpile need to be replaced. Despite best efforts it is likely to prove impossible in the future to adhere exactly to the original material and process specifications in the remanufacture of nuclear components. Any changes in the specifications will have to be of a nature that does not perturb in a significant way the nuclear-test pedigree of the design; that is, they will need to remain well within the range of parameters where subsystem behavior is understood based on

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[9] In preparing the certification report, the Secretary of Energy receives assessments from the Directors of the three weapon laboratories and the Secretary of Defense receives assessments from the Strategic Command and the military services.

[10] The reports for 2001 and 2002 have not been completed as of July 2002.

[11] An extensive discussion of recent circumstances relating to this issue is available in the report of the Chiles Commission (H. G. Chiles, et al., *Report of the Commission on Maintaining U.S. Nuclear Weapons Expertise*, Washington DC, 1 March 1999). The specific work force impacts of recent security measures are discussed in the report of the Commission on Science and Security chaired by former Deputy Secretary of Defense John Hamre (Center for Strategic and International Studies, *Science and Security in the 21st Century: A Report to the Secretary of Energy on the Department of Energy Laboratories*, Washington, DC: CSIS, April 2002).

nuclear-test data. Defining the boundaries of permissible change, then, will again require informed judgments.

There is no reason to fear that talent will be unavailable in the near term (several years) to support any decisions that might have to be made concerning aging effects on nuclear components. As the current experience base erodes due to retirements or resignations, however, a gradual transition will by necessity take place to reliance on experts with no prior "hands-on" nuclear-test experience. We believe that this need not pose a fundamental problem, for several reasons. The extensive U.S. nuclear-test database will continue to be accessible and be capable of providing much additional understanding through further analysis. We also note that the existing knowledge base has been validated not only against nuclear-test data, but against laboratory-scale hydrodynamic experiments, computational simulation and modeling, as well as a broad spectrum of supporting scientific and technological investigations. During recent years dramatic advances have occurred in diagnostic and analytical tools and techniques. Today's weapon codes and computers provide capabilities in speed and fidelity far beyond the state of the art as it existed at the time current weapons first entered the stockpile. New hydrodiagnostic capabilities, deep-penetration radiography (core punch), and high-resolution multi-beam velocimetry are part of the current state of the art. In combination with higher-fidelity simulations of production hardware these capabilities can be used to update our experimental understanding. The "science-based" component of DOE's SSP will provide more realistic material-property models and further improvements in weapon codes. These should lead to a deeper, more detailed understanding of the nuclear-test database and thus provide the underpinnings for a rational decision process concerning nuclear-performance issues as they may surface in the future. They would also help in maintaining a capability to produce new designs if ever needed.

An important component of the Stockpile Stewardship Program is the development of a broad spectrum of advanced diagnostic tools in support of the surveillance function. These tools are intended to yield a more complete understanding of weapon performance and potential failure modes for nuclear as well as non-nuclear components and subsystems. This effort represents a continuation of the traditional knowledge-based approach to problem solving in the nuclear-weapon program, albeit at a significantly accelerated rate of progress. The SSP can already point to significant successes in that regard, as seen, for example, in the implementation of numerous new, relatively small-scale, measurement and analysis techniques ranging from new bench-top inspection instruments to larger-scale laboratory facilities (including, e.g., accelerated aging tests, novel applications of diamond-anvil cells and ultrasonic resonance, synchrotron-based spectroscopy and diffraction, and subcritical and hydrodynamic tests). All of these provide additional assurance that defects due to design flaws, manufacturing problems, or aging effects will be detected in time to enable evaluation and corrective action if such is deemed necessary.

While the smaller-scale diagnostic developments will remain key to a robust surveillance function, and therefore require continued emphasis, to date most of the debate over the need for new diagnostic tools has focused on larger-scale, capital-intensive experimental and computational facilities currently under development or being planned for the future. Current programs include the Dual Axis Radiographic Hydro Test (DARHT) facility, the National Ignition Facility (NIF), and the Advanced Simulation and Computing (ASC) program. In the immediate future, because of the enormous scientific and engineering challenges associated with the development and eventual utilization of these tools, they can play an important role in helping the nuclear-weapon laboratories attract and retain essential new technical talent. In the longer term they can also be expected to strengthen the scientific underpinnings of nuclear-weapon technology, and thus offer the potential for enlarging the range of acceptable solutions to any stockpile problems that might be encountered in the future. The initial capabilities achieved in the DARHT and ASC programs have already proven to be of value.

Despite these obvious benefits, the importance of this class of tools to the immediate core functions of maintaining an enduring stockpile should not be overstated. In particular, it would be very unfortunate if confidence in the safety and reliability of the stockpile under a CTBT in the next decade or so were made to appear conditional on the major-tool initiatives having met their specified performance goals. Most importantly, their costs should not be allowed to crowd out expenditures on the core stewardship functions, including the capacity for weapon remanufacture, upon which continued confidence in the enduring stockpile most directly depends.

Although a properly focused SSP is capable, in our judgment, of maintaining the required confidence in the enduring stockpile under a CTBT, we do not believe that it will lead to a capability to certify new nuclear subsystem designs for entry into the stockpile without nuclear testing—unless by accepting a substantial reduction in the confidence in weapon performance associated with certification up until now, or a return to earlier, simpler single-stage design concepts, such as gun-type weapons. Our belief that the introduction of new weapons into the stockpile will be restricted to nuclear designs possessing a credible test pedigree is not predicated on any conjectures as to the likelihood of DARHT, NIF, ASC, or other major facilities achieving their design goals. Thus, we do not share the concern that has been expressed by some that these facilities will undermine the CTBT's important role in buttressing the non-proliferation regime.

Stockpile Surveillance

The first line of defense against defects in the stockpile that would adversely affect safety and reliability is an aggressive surveillance program. Stockpile surveillance has always been a critical part of the weapon program and it is imperative that all of its traditional activities, including JTA flight tests, continue to be fully supported. This need has been recognized and, accordingly, the SSP includes an Enhanced Surveillance activity that involves increased focus on the nuclear components, an increased number of diagnostic procedures applied to the weapons that are randomly withdrawn from the stockpile, and increased technical depth of the inspections.

In the past, changing military requirements usually caused weapons to be retired before aging became a pressing issue. Aside from occasional anomalies in initial production units, significant aging effects were only rarely encountered. In contrast, one may anticipate that weapons in the enduring stockpile will have to be maintained for the indefinite future. It is prudent to expect that age-related defects affecting stockpile reliability may occur increasingly as the average age of weapons in the stockpile increases in the years ahead, and that such defects may combine in a nonlinear or otherwise poorly specified manner, but nuclear testing is not needed to discover these problems and is not likely to be needed to address them. The rigor applied to understanding the nature and cause of such defects will become an increasingly important aspect of lifetime extension activities. The ability to predict age-related problems before they occur in the stockpile will assist in planning and executing necessary remedial actions. Based on past experience it is clear that the majority of aging problems will be found in the non-nuclear components. Nuclear testing will not be needed to address these problems.

The study of aging phenomena will also provide fertile ground for scientifically challenging research, as recent experience has already demonstrated, thereby contributing to staff retention. Much of the relevant science deals with topics that lie outside the classified domain. This opens up opportunities for collaborations with the broader scientific and engineering communities. Vigorous pursuit of these opportunities, including funding of university research that is done in collaboration with laboratory scientists and engineers, will add greatly to the vitality of the enterprise.

Nuclear-Subsystem Remanufacturing Capability

Remanufacture to original specifications is the preferred remedy for the age-related defects that materialize in the stockpile. This makes it essential that a capability to remanufacture and assemble the nuclear subsystems for nuclear weapons be maintained in the U.S. production complex (LANL, Y-12, Pantex, etc.).[12] The production capacity must be consistent with best estimates of component lifetimes based on current knowledge, realistic projections of future stockpile trends, and allowances for occasional unexpected problems. Current estimates, based on projections of the size of the enduring stockpile, indicate that the technical challenges of ongoing repair and remanufacture can be met at existing production-complex sites, provided that their facilities are brought up to and maintained at modern standards of operation. Establishment of a limited-quantity production capability for certified pits at Los Alamos is a particular necessity, as no other facility for this exists in the United States. Major facility expansion is only likely to be needed in the event of unforeseen problems requiring rapid manufacture of large numbers of stockpile weapons or rapid manufacture of large numbers of new ones. For example, the capability for manufacture or remanufacture of large numbers of pits does not currently exist, nor is it planned for the future. Acquiring such a capability would be an arduous, expensive, and lengthy process. Fortunately, the sealed pit is probably the most stable component of U.S. nuclear subsystems. Lifetime estimates for these pits are currently in excess of 50 years. Accelerated-aging tests now underway should lead to more certain estimates within a few years.

In any refurbishments of the nuclear subsystem, changes in materials and processes from the original specifications should be minimized and in all events, as already noted, must remain within the parameter range explored in prior testing. To minimize the need for substitutions it may become necessary to establish in-house sources for materials (e.g., adhesives) that are no longer obtainable from commercial sources. Materials that have been classified in recent years as hazardous to health or the environment may require development of special handling facilities and procedures in order to permit their continued use. Nevertheless, it would be unrealistic to assume that all future replacements will exactly match the originals. There may arise compelling cost arguments for changes in specifications. In some cases it may be desirable to substitute materials with better aging characteristics. Whatever the justifications may be, the potential performance impact of any change proposals must be carefully weighed and experimentally verified wherever possible.

Performance Margins of the Primary

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[12] The importance and the challenges of maintaining the needed capabilities in the production complex have been stressed in both the FY2000 and the FY1999 reports to the Congress by the Panel to Assess the Reliability, Safety, and Security of the United States Nulear Stockpile (J. S. Foster [Chairman], et al., Washington DC, November 8, 1999 and February 1, 2001).

A primary yield that falls below the minimum level needed to drive the secondary to full output is the most likely source of serious nuclear-performance degradation. In many cases this minimum yield is known only from calculations of uncertain validity. The single production verification test was never able to explore all worst-case stockpile-to-target sequence conditions. This was also true of the development tests, which additionally seldom involved designs precisely identical to the production versions. Because primary yield margins in these weapons can be increased by changes that would not require nuclear testing, it is possible to use enhanced margins to provide insurance against minor aging effects and changes in material or process specifications arising in the refurbishment of the weapons. Margin enhancements, as recommended strongly in several JASON studies, would therefore constitute a significant additional confidence measure.[13]

Primary yield margins can be increased by appropriate changes specific to each stockpile system. These include changes in initial boost-gas composition, shorter boost-gas exchange intervals, or improved boost-gas storage and delivery systems. These modifications have been validated by nuclear test data for the appropriate systems, and they would not place burdens on the maintenance or deployment of the systems by the military. They would not require further nuclear testing, would help compensate for potential future uncertainties arising from remanufacturing, and are highly desirable where appropriate independent of a CTBT. We urge that these be done.

Non-nuclear Component Development and Manufacture

Since the non-nuclear components and subsystems external to the nuclear subsystem can be fully tested under a CTBT, it is possible to incorporate new technologies in these weapon parts as long as these can be shown not to have any adverse effect on proper functioning of the nuclear subsystem. In fact, it would be very costly to replace some non-nuclear components with exact copies as changeouts become necessary. If technologies involved in the non-nuclear components become prohibitively difficult to support with the passage of time because they are no longer utilized in the private sector, needed replacements can be based on current materials, technologies, and manufacturing processes.

This does require, however, the provision of adequate resources to provide not only the needed manufacturing capability and capacity but also for the associated engineering R&D and systems integration capabilities, on an ongoing basis. In many cases the component designs are complex, necessitating a lengthy development process and tight manufacturing controls. Safing devices, neutron generators, boost-gas subsystems, firing sets, radar fuzes, retarding parachutes, among many other active subsystems, must tolerate many years of storage and afterwards are expected to function flawlessly the first (and only) time that they are activated. A thorough understanding of possible failure modes during the entire stockpile-to-target sequence is essential. Because of the demanding specifications, a “science-based” approach to development and surveillance has long been a necessity.

Since a CTBT does not inhibit non-nuclear component development (with the possible exception of features related to radiation hardening) it introduces no new impediments to the recruitment of new scientific and engineering talent for such purposes. The principal requirement for program sustainability, especially at Sandia where most of this activity is centered, is a stable

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[13] See, for example, JASON Report JSR-99-305, *Primary Performance Margins (U)* (McLean,VA: Mitre Corporation, December 1, 1999).

budget at a level adequate to maintain the diversity of facilities and scientific/engineering talent that are needed to perform the non-nuclear stewardship function in a competent manner. In addition, it will be essential to practice "change discipline"—the avoidance of changes that are not strictly necessary—because modifications, even outside the nuclear subsystem, can influence the entire weapon system.

Maintaining Nuclear Design Capabilities

Nuclear-weapon design activities are not prohibited under the CTBT, and preserving the capability to develop new designs—in case such are ever needed—is a stated goal of U.S. policy.[14] The use of ever more capable computational tools and more realistic material models to understand the relevant database from past nuclear tests, together with the use of advanced hydrodiagnostic techniques to study stockpile-related issues, is an important part of preserving this design capability, as is the engagement of new people in design activities while more senior designers are still available to share their insights. The associated design and evaluation expertise will aid in interpreting and perhaps anticipating foreign activities in nuclear-weapon development. We do not believe that nuclear testing is essential to maintaining these design and evaluation capabilities, even though such testing *would* be essential to certifying the performance of new designs at the level of confidence associated with currently stockpiled weapons.

Change-Control Discipline

It is conceivable that confidence in the performance of the nuclear subsystem might erode over time because of concerns over the cumulative effects of multiple small changes in materials and/or processes that may be introduced in the course of periodic refurbishment operations. The need for such changes is expected to arise very infrequently because of the inherently robust nature of nuclear components. The rate at which changes that individually are too small to have a significant performance impact could collectively cause unacceptable performance degradations is consequently very slow, perhaps measured in decades. Nevertheless, it is prudent to avoid the possibility of such problems, or at the very least push their onset beyond any time horizon of interest, by instituting a rigorous, highly disciplined, change-control process. Such a process must begin with a thorough documentation of the original design and manufacturing specifications.

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[14] In 1994—before the 1996 signing of the CTBT—the Department of Defense conducted a Nuclear Posture Review (NPR). The relevant portion of the classified September 1994 Presidential Decision Directive, "Nuclear Posture Review Implementation," PDD/NSC 30 (S), is summarized in an unclassified paragraph on page 14 of the report of the Stockpile Assessment Team of the U.S. Strategic Command (Birely et. al., *Strategic Advisory Group Stewardship Conference Report (S)*, U.S. Strategic Command, April 2001) as follows: "The NPR contains infrastructure requirements for the Department of Energy to ensure high confidence in the enduring stockpile, namely: maintain nuclear weapons capability without underground testing or the production of fissile material; develop a stockpile surveillance engineering base; demonstrate the capability to refabricate and certify weapon types in the enduring stockpile; maintain the capability to design, fabricate and certify new warheads; maintain a science and technology base; ensure tritium availability; and accomplish these tasks with no new-design nuclear warhead production." This reiteration of the NPR requirements in a 2001 STRATCOM report indicates that they have not been superseded since the signing of the CTBT. We note, however, that the requirement to "maintain the capability to design, fabricate and certify new warheads" does not imply an intention to *exercise* that capability while a CTBT is in force. As indicated above, we believe it would not be possible to certify new-type nuclear subsystem designs for entry into the stockpile without nuclear testing—unless by accepting a substantial reduction in the confidence in weapon performance associated with certification up until now, or a return to earlier, simpler, single-stage design concepts, such as gun-type weapons. Thus, if not only design but also certification for entry into the stockpile of sophisticated new nuclear-weapon types were deemed necessary in the future in the national interest, and a CTBT were in force, we judge that the United States would need to withdraw from the treaty in order to conduct the nuclear tests needed for certification.

Any subsequent deviations from these specifications during stockpile maintenance and subsequent remanufacture of nuclear components must be minimized even if they are judged to be acceptable from a performance standpoint. Any deviations that are judged necessary must be thoroughly analyzed and documented before adoption. The resulting audit trail should make it possible to include consideration of possible cumulative effects in judging the acceptability of any change proposal. In order to avoid the introduction of interference effects between nuclear and non-nuclear components, prudence dictates that a similar discipline be practiced in regard to any design changes or changes in location of non-nuclear components in proximity to the nuclear subsystem.

Priorities in Stockpile Stewardship

DOE's Stockpile Stewardship Program addresses all of the critical areas identified above, including plans for an aggressive "Stockpile Lifetime Extension Program" (SLEP). There remains the question of program balance. Since there will never be enough resources to pursue all relevant areas with maximum intensity, priorities become an important issue. We emphasize that the quality and quantity of people needed in the SSP constitutes the most important resource. This resource can become the limiting factor even if budgets are not a constraint.

Two somewhat related balancing issues, in particular, need careful consideration:

1) <u>Short-range versus long-range emphasis</u>: Each year since the moratorium the stockpile has been formally certified safe and reliable. Plans to maintain the stockpile in that condition for the foreseeable future can be carried out by the weapon complex as it now exists, augmented by appropriate near-term investments both in the laboratories as well as in the production plants. Simultaneously, efforts are under way to address problems that are anticipated to arise in the more distant future. Much of this work is aimed at achieving a much deeper and detailed scientific understanding of weapon phenomenology, especially as it relates to the physics of nuclear subsystem performance. It is imperative that a balance be maintained between the longer-range activities and the more immediate program needs. When judged in terms of their stewardship role, the goals and associated timetables for the longer-range efforts have sufficient flexibility that it should be possible to sustain these without sacrificing the short-term deliverables.
2) <u>Nuclear versus non-nuclear subsystem emphasis</u>: Understandably, the ongoing debate on stockpile safety and reliability has focused on possible consequences of a CTBT. What has not emerged from this debate is a clear recognition that safety and reliability are determined largely by the non-nuclear subsystems, and that these are not subject to CTBT constraints. Yet, it is the inability to test the nuclear subsystem under a CTBT that has stimulated increased Congressional support for the weapon program at a time when the program as a whole was suffering budget shortfalls. This creates the possibility that future budgets will become skewed in a direction that would make it difficult for the non-nuclear component and subsystem work to be performed at the laboratories and the production plants.

Concluding Remarks

Stockpile stewardship by means other than nuclear testing is not a new requirement imposed by the CTBT. It has always been the mainstay of the U.S. approach to maintaining confidence in stockpile safety and reliability. Based on the available evidence, we conclude that the measures outlined in the preceding sections are both necessary and sufficient for maintaining confidence in the continued safety and reliability of the enduring stockpile. These measures are independent of nuclear testing and are therefore unaffected by a CTBT.

An essential requirement is to safeguard the vitality of the DOE nuclear-weapon activities at the three laboratories, the production plants, and collaborating institutions. In the event that quantity replacements of major components of the nuclear subsystem should become necessary, prudence would indicate the desirability of extensive formal peer reviews. Evaluation of the acceptability of age-related changes relative to original specifications and the cumulative effect of individually small modifications of the nuclear subsystem should also be subject to periodic independent review. Such reviews, involving the three weapon laboratories and external reviewers, as appropriate, would evaluate potential adverse effects on system performance and the possible need for nuclear testing.

We judge that the United States has the technical capabilities to maintain confidence in the safety and reliability of its existing nuclear-weapon stockpile under the CTBT, provided adequate resources are made available to the Department of Energy's (DOE) nuclear-weapon complex and are properly focused on this task. Specific measures to bolster stockpile confidence include intensifying stockpile surveillance, strengthening manufacturing/remanufacturing capabilities, and increasing the performance margins of nuclear-weapon primaries. With no new weapons replacing older weapons, one can anticipate that the average age of weapons in the enduring stockpile will increase over time far beyond past experience. For this reason we regard these measures to be essential with or without nuclear testing or a CTBT. Refining computational understanding of the existing nuclear-test database and stockpile-related hydrodynamic experiments can play a key role in protecting the capability to produce new designs against the possibility that new weapon types were deemed needed in the future and a return to testing mandated to develop and certify them.

Some have asserted, in the CTBT debate, that confidence in the enduring stockpile will inevitably degrade over time in the absence of nuclear testing. Certainly, the aging of the stockpile combined with the lengthening interval since nuclear weapons were last exploded will create a growing challenge, over time, to the mechanisms for maintaining confidence in the stockpile. But we see no reason that the capabilities of those mechanisms—surveillance techniques, diagnostics, analytical and computational tools, science-based understanding, remanufacturing capabilities—cannot grow at least as fast as the challenge they must meet. (Indeed, we believe that the growth of these capabilities—except for remanufacturing of some nuclear components—has more than kept pace with the growth of the need for them since the United States stopped testing in 1992, with the result that confidence in the reliability of the stockpile is better justified technically today than it was then.) It seems to us that the argument to the contrary—that is, the argument that improvements in the capabilities that underpin confidence in the absence of nuclear testing will inevitably lose the race with the growing needs from an aging stockpile—underestimates the current capabilities for stockpile stewardship, underestimates the effects of current and likely future rates of progress in improving these capabilities, and overestimates the role that nuclear testing ever played (or would ever be likely to play) in ensuring stockpile reliability.