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Does the U.S. Science-Based Stockpile Stewardship Program Pose a Proliferation Threat?

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INTRODUCTION

The principal nonproliferation benefit of the recently signed, but still largely unratified Comprehensive Test Ban Treaty (CTBT), is the restriction it imposes on the development by additional states of more efficient pure fission weapons, fusion-boosted fission weapons, and two-stage thermonuclear weapons. To mitigate the impact of the CTBT on the U.S. nuclear posture, the Department of Energy's (DOE's) Science-Based Stockpile Stewardship (SBSS) Program seeks to model the performance of nuclear weapons from "first principles," thereby diminishing and perhaps eliminating the historical dependence of the U.S. weapons program on nuclear test-based empiricism to verify nuclear explosive performance and calibrate nuclear design code predictions with actual test results. While the non-proliferation restraints of the CTBT currently appear robust, dissemination of SBSS nuclear weapons research will tend to erode the Treaty's security benefits.

Past state decisions to share weapons information (shown graphically in Figure 1) have served to influence the current international system. By and large, the rationale for these acts had been the strengthening of an ally. But alliances change: Moscow, for example, grew to regret its early nuclear weapons assistance to Beijing. Over time, the Nuclear Non-Proliferation Treaty (NPT) of 1968 has established a consensus that restricting the number of nuclear weapon states to the pre-established five, while seeking the elimination of nuclear weapons over the longer term, bolsters international security.

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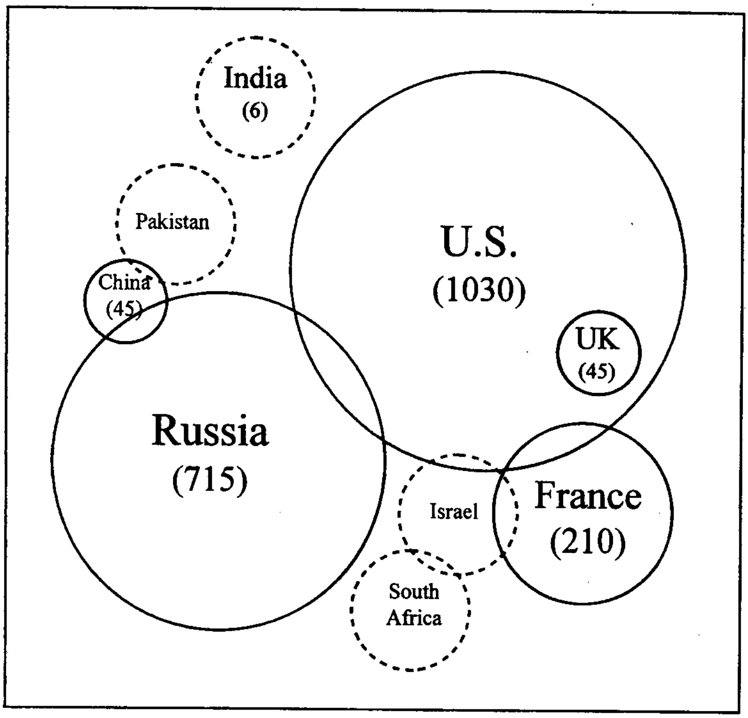

Figure 1: Venn diagram displaying the historical sharing of nuclear weapons knowledge among declared nuclear weapon states (solid circles), undeclared nuclear weapon states (dashed circles), and South Africa, a former undeclared nuclear weapon state. The number of explosive nuclear tests performed is given in parentheses. Area of overlap is not strictly proportional to the degree of knowledge sharing, as this is difficult to quantify. The Russia-U.S. overlap reflects the recent purchase by the U.S. Defense Special Weapons Agency (via a detailed negotiated contract) of a large amount of data concerning the former Soviet test program.[1] Transfer of information from nuclear weapon states to non-nuclear weapon states that would assist the latter "in any way" to acquire nuclear explosive devices is prohibited under Articles I and II of the Nuclear Non-Proliferation Treaty.

Articles I and II of the NPT broadly prohibit any transfer or receipt of information "that would in any way assist" a non-weapon state in acquiring nuclear weapons.

The publicly-acknowledged goal of the SBSS Program is to develop complex computer simulations as a replacement for nuclear explosive tests of integrated weapon system performance. This effort, likened in scope to the Manhattan Project or Apollo Mission, is based on the systematic pursuit of fundamental advances in each of the constituent disciplines of nuclear weapons science and engineering, including an increased reliance on unclassified

Table 1: Access to nuclear weapons science experiments under the NPT and CTBT.

Access to:	NPT nuclear-weapon state	Threshold state party to the CTBT	NPT non-weapon state
Past nuclear explosion test data.	YES	MARGINAL[a]	No, but subject to risk of espionage and state-to-state transfer.
Fast critical assemblies and pulsed reactors.	YES	YES	Yes, in the context of a nuclear power program or as basic research.
Laser or particle beam fusion and/or fission.	YES	YES	Yes, based on U.S. 1975 NPT Review Conference Statement.[b]
Electrical and high-explosive driven pulsed power experiments.	YES	YES	Status of these devices under NPT has never been clarified.
High-explosive driven experiments with fusion materials.	YES	YES	Yes, based on Polish and Canadian precedent, and 1996 German unilateral statement.[c]
High-explosive driven experiments with surrogates (e.g., U-238, Ta).	YES	YES	Yes, if experiment has valid non-nuclear weapon engineering or scientific purpose.

a. Concerning the possible threshold state parties to the CTBT, India has conducted one known full-scale nuclear explosive test; Pakistan has reportedly received test-proven weapon design data from China, Israeli weapon scientists reportedly participated in the early French test series in Algeria and a probable but not proven full-scale nuclear test in the South Atlantic in 1979 as well as very low yield events in caves in the Negev over an extended period.

b. The unopposed U.S. unilateral statement at the 1975 NPT Review Conference expressed the view that "nuclear reactions initiated in millimeter-sized pellets of fissionable and/or fusionable material by lasers or by energetic beams of particles, in which energy releases, while extremely rapid... are nondestructively contained within a suitable vessel...(do) not constitute a nuclear explosive device within the meaning of the NPT..." Test of the full statement can be found in, *The National Ignition Facility and the Issue of Nonproliferation*, Final Study Prepared by the U.S. Department of Energy, Office of Arms Control and Nonproliferation, (December 19, 1995), p. 35.

c. The "Polish precedent" refers to high-explosive-driven fusion research published in the 1970s by a group led by Sylwester Kaliski (1925–1978) at the Institute of Fundamental Technological Research, Warsaw. Although the journals which Kaliski and his collaborators published in (largely *Bulletin de l'Academie Polonaise des Sciences, Proceedings of Vibration Problems, Archiwum Mechaniki Stosovanej*, and *Journal of Technical Physics, Polish Academy of Sciences* (the last of which Kaliski founded and served as editor-in-chief)) are difficult to find in the West. Los Alamos published a report on this work in 1979 entitled, "Kaliski's explosive driven fusion experiments," by J. Marshall (LA-UR-79-1835). Kaliski was a member of the Central Committee of the Polish United Workers Party and of the Polish Parliament. In June 1969, Poland deposited its instruments of Ratification to the NPT and in September 1996 signed the CTBT.

The "Canadian precedent" refers to a 1982 article in *Physics of Fluids*, Vol. 25, (February 1982), pp. 269–270, by I.I. Glass and D. Sagie of the Institute for Aerospace Studies, University of Toronto, Canada, entitled, "Applications of explosive-driven implosions to fusion." Canada deposited its instruments of ratification to the NPT in January 1969 and signed the CTBT in September 1996.

Germany made the following declaration upon signature of the CTBT: "It is the understanding of the German Government that nothing in this Treaty shall ever be interpreted or applied in such a way as to prejudice or prevent research into and the development of controlled thermonuclear fusion and its economic use." "XXVI.4: Comprehensive Nuclear Test-Ban treaty," United Nations Status Document on the CTBT (Doc. A/50/1027), (August 1997), p. 930.

(or partly classified) fusion experiments using a wide range of driver technologies[2]—including high explosives, recently developed super-energetic explosives,[3] high explosive pulsed power, electric capacitor bank pulsed power, particle beams, and lasers. While macro-scale nuclear explosive processes are no longer accessible to the SBSS nuclear weapons modeling effort, the large data set represented by past tests is being archived and utilized in conjunction with micro-scale fission and fusion experiments accessible to both nuclear-weapon and non-weapon states as summarized in Table 1.

Aspects of the SBSS represent a broad-based proliferation threat that can facilitate the acquisition of nuclear weapons expertise by other nations. Of course, whether this expertise is ultimately converted into actual weapons depends in each instance on the evolution of particular political circumstances. But in an unstable world filled with simmering conflicts and gross inequities within and between nations, the prospect of proliferating even latent capabilities for the design and development of improved fission and thermonuclear weapons can scarcely be regarded with equanimity.

SCIENCE BASED STOCKPILE STEWARDSHIP "VIRTUAL TESTING"

Senior DOE and national weapons laboratory officials have stated repeatedly that a major objective of the SBSS program is to achieve a "computational weapons testing—virtual testing"—capability as part of "DOE's long range strategy to move nuclear design from a test-based to a simulation-based approach."[4] Then Secretary of Energy, Hazel O'Leary, hailed the signing of a DOE-funded contract with Intel Corporation in 1995 to develop the world's most powerful supercomputer at Sandia National Laboratory by noting, "Computers of this scale will unlock the ability to confidently simulate nuclear weapons tests in the laboratory. This effort demonstrates a step forward for our scientific-based stockpile stewardship program."[5] And Dr. John Hopson, the Program Manager for Weapons Computing and Computational Physics at Los Alamos National Laboratory, told a 1996 National Academy of Sciences panel that "stockpile stewardship assessment simulations are likely to be more difficult than those needed to design new weapons. They must be fully 3D (i.e., three-dimensional), high resolution, and based on fundamental physics without 'fudge' factors (i.e., empirically derived calibration factors) of any kind. Future codes must have the ability to model full systems in a integrated fashion."[6]

The SBSS program strategy was summarized in a February 1996 report by a JASON/MITRE Corporation scientific advisory group[7] entitled, "Preliminary Review of Stockpile Stewardship and Management," as follows:

> The Stockpile Stewardship and Management Program depends on an ever increasing science-based understanding of nuclear weapons design and engineering. This is a task without foreseeable limits... Research and progress toward new, more advanced techniques and facilities adding to our understanding of both primaries and secondaries is important to the future.[8]

However, a January 1998 JASON study focused on what it said were more immediate (5–10 year) SBSS priorities, which it enumerated as: the effect of binder aging on the formulation of high explosives; experiments on aged, weapons-grade Pu-239; sub-critical experiments examining possible differences between old and young plutonium; testing and improving components external to the nuclear package; and surveillance of secondaries. The report also included a mild critique of the current SBSS programmatic focus:

> It is necessary to implement these priorities in a timely fashion... To do so will require strong, effective leadership (within the three weapon labs and from DOE Washington) to make program choices and to assign appropriate resources among and within the three weapon labs. The individual program briefed to us by the three labs did not show a balance, focus, and a coordination consistent with these requirements... It is of particular importance,... to coordinate and balance the diverse activities of stewardship, (enhanced) surveillance, and refurbishment... We note that such a [management] structure clearly exists for the large new facilities that will be important components of the stewardship program over the longer term.[9]

The long-term SBSS strategy, with its focus on "virtual testing," is now being implemented with markedly increased collaboration between nuclear weapons specialists and the open scientific community, with the attendant risk of disseminating thermonuclear weapons knowledge. This is occurring for a variety of reasons and over a range of SBSS component programs. Subsequent sections of this paper discuss the proliferation impacts of the following SBSS activities:

- increased external peer review and open publication of weapons physics research;
- integration of nuclear weapons laboratory research into the unclassified scientific community, and vice versa, primarily through the aegis of the Academic Strategic Alliances Program (ASAP);

- aggressive programs in beam-driven Inertial Confinement Fusion (ICF) and electrical pulsed-power research; and
- continued investigation of alternative methods for initiating an explosive release of fusion energy, including direct high-explosive driven implosion, high explosive driven magnetic flux compression, and electrical pulsed power approaches to igniting fusion reactions in a hot dense plasma.

We note in passing (but do not discuss further in this paper) two other SBSS developments with possibly serious proliferation implications:

- the transfer of classified weapons codes from the remaining vector supercomputing platforms of the 1980s to less restricted, dispersed networks of supercomputers based on "Massively Parallel Processing" (MPP) which use commercially available microprocessors and operating systems; and
- the development of 3-D CAD/CAM "solid models" of nuclear weapons components and entire weapons to guide highly automated manufacturing processes, and the exchange of these files via allegedly secure networks.

SBSS "TECHNICAL DETERRENCE" AND "OUTSIDE" PEER REVIEW

The ways in which the inherent nuclear proliferation potential of the SBSS program could actually affect other countries' capabilities depends in part, just as it has in the past, on the evolution of government, agency and laboratory policies regarding dissemination of nuclear weapons research techniques and results. Recently, Dr. Stephen Younger, the Director for Nuclear Weapons Technology at Los Alamos National Laboratory (LANL), the nation's premier nuclear design laboratory, has elaborated new concepts of "visible technical deterrence"—to replace the overt manifestations of Cold War deterrence such as nuclear explosions and alert force postures—and unclassified "peer review" for fundamental weapons science research—to replace nuclear testing as the "great arbiter" of scientific judgment. These concepts have since been employed in testimony by other laboratory leaders,[10] and clearly suggest a heightened proliferation risk for information and expertise generated in SBSS facilities.

Regarding "technical deterrence," Dr. Younger wrote:

> During the Cold War... our nuclear forces were visible through flight tests and through nuclear tests detectable at seismographic stations around the world. No one doubted the performance of our nuclear weapons. How will we maintain the same level of visible confidence in our nuclear stockpile in the absence of underground testing?...

> As I see it, at the end of the Cold War, the nuclear weapons laboratories took on a new mission. Not only must we maintain the stockpile, but we must do so in a manner visible to the world, a manner that demonstrates our technical competence in scientific and engineering fields that are obviously related to nuclear weapons... our work on Pegasus [an existing LANL SBSS facility] can be communicated, and such experiments will clearly demonstrate our performance to a community traditionally supported by the nuclear weapons programs of almost every nuclear state. Foreign scientists see us at conferences, see that we are doing work at the leading edge, and note that we stop short of presenting all of our results, possibly due to classification. Technical respect is won in this way. Our presence in the international scientific community is not "publish or perish"—it is the visible demonstration of capability, what might be termed scientific deterrence. It is part of our job.[11]

Another potential spur to proliferation from within the SBSS Program is the belief that it is now more important to have the technical competence of nuclear weapons scientists evaluated by their "peers" in the outside world than it was during the era of nuclear testing. This impetus towards external peer review of Stewardship research was described recently by Dr. Younger as follows:

> In the past, the Nevada Test Site (NTS) served as the great arbiter of technical judgment. No matter how persuasive the arguments, NTS would decide the facts. Now, without the ability to perform integrated nuclear tests, we must employ other mechanisms for assuring that our arguments are not only plausible but indeed correct. Above-ground experiments will certainly assist us here, but we must look to other means to ensure that we are as good as we say we are.
>
> One essential way of doing so is through our interaction with the external scientific community. Since some of our scientific work is now unclassified, particularly at the basic physics level, we can use the peer review process as a measure of quality in our work. If a research team is able to get papers accepted in prestigious journals on a regular basis and is invited to present papers at conferences, then we can be reasonably sure that the team is considered to be worth hearing from by people who have little interest in politics or funding rivalries.[12]

The 1997 Annual Meeting of the Division of Plasma Physics (DPP) of the American Physical Society was held in Pittsburgh, Pennsylvania from November 17–21.[13] In addition to the many participants from academia, representatives from the nuclear weapons research centers—such as, Los Alamos National Laboratory, Lawrence Livermore National Laboratory (LLNL), Sandia National Laboratory (SNL), Commissariat à l'Énergie Atomique (CEA-

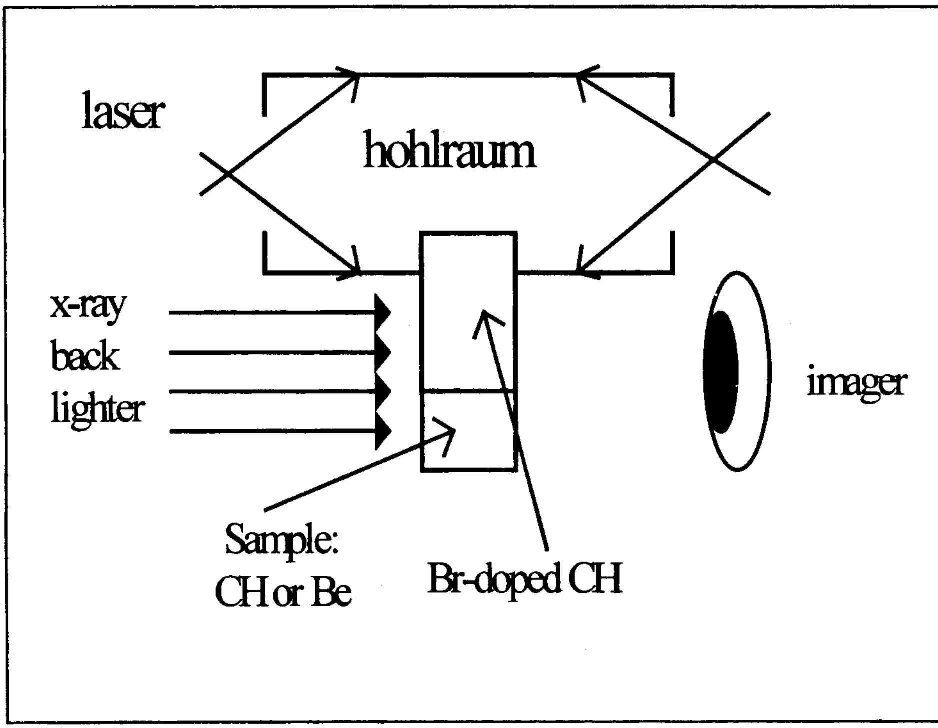

Figure 2: Sketch of experimental set-up described by Robert Cauble of Livermore at the 1997 DPP Annual Meeting.

France), Atomic Weapons Establishment, Aldermaston (AWE-U.K.), and the Nuclear Research Center-Negev (Israel)—spoke on current research in various aspects of plasma physics, including: hydrodynamics, equation-of-state, non-local thermodynamic equilibrium (non-LTE) physics, inertial confinement fusion, and z-pinches. Including collaborative work, representatives from nuclear weapons laboratories accounted for 60 percent of invited talks on inertial confinement fusion, 68 percent of talks in the three oral sessions on hydrodynamics, and 100 percent of talks in the oral sessions devoted to "hohlraums" and "EOS & ICF" (equation-of-state and inertial confinement fusion).

At this DPP Annual Meeting, Robert Cauble of Livermore gave a talk entitled "Equation of State Measurements of NIF Ignition Capsule Ablator Materials,"[14] work which was subsequently published in *Physical Review Letters.*[15] These experiments, sketched in Figure 2 and described further in endnote 14, were performed with the LLNL Nova laser. In Cauble's presentation, he compared equation of state measurements for polystyrene (CH) and beryllium (Be) with Los Alamos and Livermore equation of state (EOS) libraries and with data from nuclear weapons tests. Of the three EOS libraries available at the national labs—referred to in the talk as "QEOS," "Sesame," and "LLNL EOS"[16]—it was found that QEOS and Sesame were in reasonable agreement with the Nova measurements in the 10–40 Mbar high pressure region, while "LLNL EOS" was not. With respect to the nuclear test data: "The absolute laser-driven Be results confirm earlier nuclear-weapon-driven impedance match data for Be and imply that [the] entire set of nuclear-drive data, including Hugoniot data for several materials and pressures up to 65 Mbar, are accurate."[17] A graphical comparison between the nuclear test data and the Nova measurements is given in *Physical Review Letters.*

Cauble's talk, and subsequent *Letter*, exemplify several main aspects of the SBSS: new experimental techniques are being used to improve the quality and the understanding of data from past explosive nuclear tests; SBSS experiments are being used to calibrate the next generation of weapons codes and the physical models on which they are based; and some of this research, which is serving to lessen DOE's reliance on nuclear testing for its mission, is being made available to the general scientific community. Given both the inherent capabilities of the SBSS and twin impulses toward "visible technical deterrence" and external "peer review" that now appear to be implanted in the SBSS program, it is reasonable to posit that this program will increase the knowledge of nuclear explosive phenomena transferred to other nations and subnational groups via publications in the open literature, presentations and discussions at scientific and technical meetings, and by encouraging investments in similar nuclear weapons-related experimental facilities in other countries.

These proliferation possibilities are multiplied by the fact that the SSBS program now includes international arrangements for "cooperative stewardship" with the U.K. and France, and cooperative experimental programs in electrical and high-explosive driven pulsed power with Russia's nuclear weapons laboratories. The operating concept for the National Ignition Facility embraces plans for both classified and unclassified cooperation with a host of nations.

According to Dr. John Immele (director of LANL's Weapons Technology Program from 1991–96 and now senior technical adviser to the principal architect of the SSM Program, DOE Assistant Secretary Vic Reis), Los Alamos held a conference in April 1996 that explored "cooperative stewardship among the major nuclear powers—not only stewardship of nuclear weapons but also stewardship of the technologies that underpin deterrence and indeed, stewardship of the regime itself."[18] This remark raises the disturbing prospect that the SBSS Program is being guided as much by narrow and largely hidden institutional imperatives to maintain the strategic relevance of Cold War laboratory infrastructures as it is by bona-fide technical requirements for maintaining the safety and reliability of a declining arsenal of weapons. In such circumstances, freighted with institutional imperatives for self-preservation, agency decision-making on the SBSS Program is not likely to accord proper weight to non-proliferation concerns.

THE DOE ACADEMIC STRATEGIC ALLIANCES PROGRAM

The Accelerated Strategic Computing Initiative (ASCI) within the SBSS program undertakes supercomputer acquisitions, other computer and communications hardware acquisitions and nuclear weapons software development. ASCI is the principal programmatic implementation of the "virtual testing" strategy described above. According to the five year budget summary given in the Department of Energy FY 1999 Congressional Budget Request, between FY 1997 and FY 2003, DOE intends to spend four billion dollars on nuclear weapons computing. As a fraction of the "Total Stockpile Stewardship" budget authority, "ASCI and Stockpile Computing" increases from 18.5 percent in FY 1997 to 32.8 percent in FY 2003. University participation in ASCI occurs largely through DOE's Academic Strategic Alliances Program (ASAP).

Under the ASAP, DOE's Defense Programs has contracted with leading U.S. academic institutions to conduct research and development activities jointly with its nuclear weapon laboratories. According to DOE, the ASAP has five major goals:[19]

(i) Establish and validate the practices of large-scale modeling, simulation, and computation as a viable scientific methodology in key scientific and engineering applications that support DOE science-based stockpile stewardship goals and objectives.

(ii) Accelerate advances in critical basic sciences, mathematics, and computer science areas, in computational science and engineering, in high performance computing systems and in problem solving environments that support long-term ASCI needs.

(iii) Leverage other basic science, high performance computing systems, and problem-solving environments research in the academic community.

(iv) Establish technical coupling of [Academic] Strategic Alliances [Program] efforts with ongoing ASCI projects in DOE laboratories.

(v) Strengthen training and research in areas of interest to ASCI & SBSS and strengthen ties among LLNL, LANL, SNL and Universities.

In order to inform universities about the ASAP, and thereby encourage submission of research proposals that would be useful to its nuclear explosive simulation effort, DOE held an "ASCI Alliances Pre-proposal Conference" in Dallas, Texas on December 5–6, 1996. A total of 134 faculty, staff, and graduate students attended the conference from 47 universities.[20] The conference included presentations on the DOE weapons research areas of interest in Computational Physics, Materials, Energetic Materials, and Computational and Computer Science Infrastructure. Additionally, DOE Defense Programs (DOE DP) researchers prepared a set of background papers "to assist in understanding what is technically relevant for the ASCI program."[21]

From a total of 48 "pre-proposals" submitted by universities, DOE requested that 20 be developed as full proposals, from which seven finalists were chosen and site visits conducted.[22] The winning universities were chosen based on "Select[ing the] Best Overall Combination of Disciplines to Meet ASCI Goals."[23] Insight into what DOE meant by this can be had from a vugraph presented by DOE Deputy Assistant Secretary Weigand to the attendees at the Pre-proposal Conference, shown in Figure 3. Here, the explosion of a nuclear weapon is divided into eight sequential processes beginning with the detonation of the high explosive surrounding the fissile core of the thermonuclear primary and culminating in the weapon effects. Read vertically, the figure shows the role played by (2) simulation (computation & modeling) in the integration of (1) SSMP nuclear weapons experimental capabilities (i.e., facilities such as the National Ignition Facility which can approach some of the physical conditions occurring in a nuclear explosion) with (3) scientific research, including "academic & lab scale scientific studies & experiments."

Prior to the preliminary submission of Alliances Program research proposals, two frequently asked questions of DOE were: (1) "Must nuclear issues be included to get consideration?" and (2) "Will these be the determining factor?" The DOE response in part was:

> Direct nuclear issues are not the focus nor are they a required or determining factors for selection [of a winning Alliances Program proposal], as such a focus would likely result in an undesirable number of proposals that duplicate ongoing efforts at ASCI laboratories"... [I]t is important to specify and pursue an ASCI-relevant physical science simulation problem so that the computer science and infrastructure research is directed towards enabling and supporting ASCI-relevant problems... [A] fundamental principal of this [Academic Strategic Alliances] program is intellectual independence and creativity, while

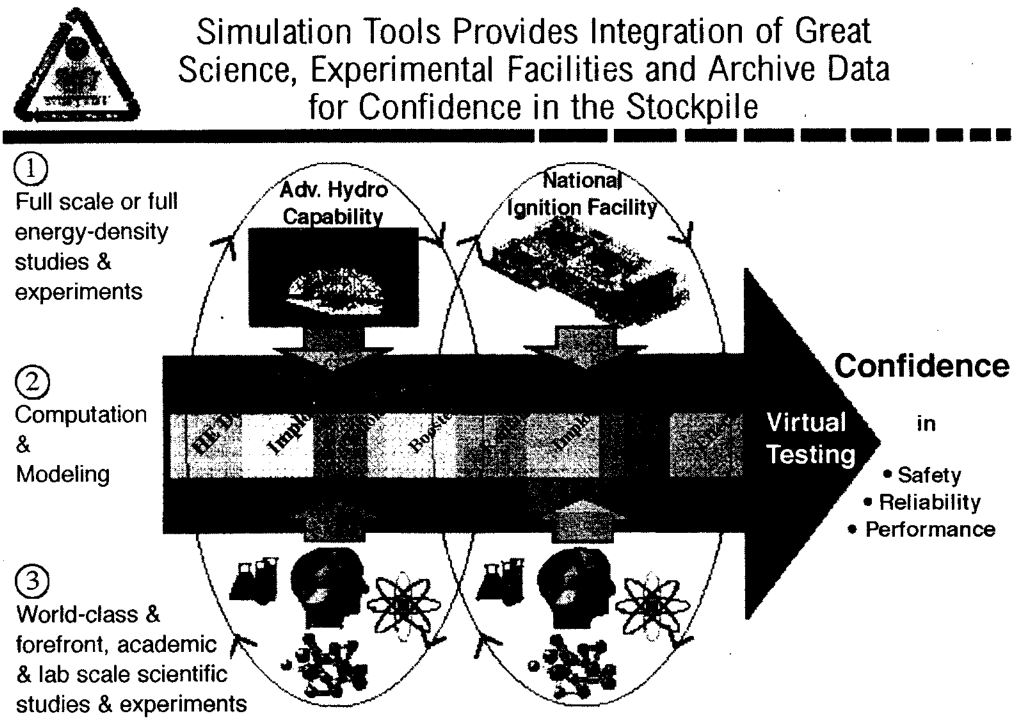

Figure 3: DOE vu-graph presented at the ASCI Alliances Program Pre-Posal Conference.

remaining relevant to the ASCI program. Proposed work should not, therefore, merely furnish extra labor to accomplish laboratory programmatic work.[24]

The Academic Strategic Alliances Program is now structured to have three "Levels," as listed in Table 2. Only Level 1 funds have been dispersed thus far, pursuant to negotiated contracts establishing the five university "Centers of Excellence" at the California Institute of Technology (Caltech), Stanford University, the University of Chicago, the University of Illinois, Urbana-Champaign (UIUC), and the University of Utah. These contracts are for an initial five years at a total of between $20 and $30 million per university with the possibility of an additional five-year extension. A request for proposals was

Table 2: The three-level structure of the DOE *Academic Strategic Alliances Program*.

Program level	Number of current contracts in program level	Funding range	Brief description
Level 1: Strategic Alliance "Centers of Excellence"	5	\$1.5–\$2.0 million first year; growing over a 2–3 year period to \$4–\$5 million annually.	"Long-term, critical mass, multidisciplinary university centers."
Level 2: "Strategic Investigations"	TBD	\$200–\$400 thousand per year (total budget of \$3–\$5 million)	"Aimed at individual university departments."
Level 3: "Individual Collaborations"	TBD	\$50–\$100 thousand per year.	"Primarily between one DOE nuclear weapons laboratory and one researcher.

issued by the DOE on November 7, 1997 for Level 2 research. Several research contracts were quietly awarded to universities prior to the public announcement of funding for the five ASAP Centers (i.e., prior to July 31, 1997).[25]

Historically, nuclear weapon computer codes themselves, and even descriptive data about them, were highly sensitive and classified, both to prevent them from falling into the hands of potential proliferants and to prevent the Soviet Union and other weapon states from improving their weaponry, possibly by ascertaining what weapon physics topics were the focus of U.S. research.[26] DOE described some of its nuclear weapons science and computing research requirements to the universities in order to solicit useful grant proposals. And as seen in Table 2, Level 1 of the Academic Strategic Alliances Program involves an historically unprecedented degree of access by university researchers to supercomputers at the national nuclear weapons laboratories. One example of the research to be performed under the Academic Strategic Alliances Program is the "Facility for Simulating the Dynamic Response of Materials," established at Caltech to create a virtual shock physics facility, the "virtual shock tube" (see Appendix).

While other Alliances Program Centers are emphasizing the simulation of gas turbine engines (Stanford), astrophysical events (Chicago), solid rocket boosters (UIUC), and accident scenarios involving fires and explosions

(Utah)—applications which present physics and computer simulation issues analogous to and in part directly relevant to SBSS "virtual testing"—no application of the research other than to nuclear weapons was developed in Caltech's grant proposal to the DOE. This begs the question of whether or not the Caltech virtual shock tube could in fact be used as a nuclear weapons code, as it is intended to ultimately contain the combined simulations of high explosives, shocked materials; the effects of material interfaces; and shock-induced compressible turbulence and mixing. A bomb code would additionally need to incorporate criticality, fission and possibly fusion nuclear processes, and the energy released in the explosion. These processes and related computer coding have been developed as part of the civil fission and fusion energy programs. In addition, the University of Chicago's ASAP Center is engaged in advanced modeling of fusion ignition and burn processes as part of an astrophysics research program.

Thus, if the Caltech research program continues for its five to ten year course and the virtual shock tube produced, much of the work behind generating a bomb code will have been accomplished, at the same time incorporating fore-front physics and computer science calibrated against data from state-of-the-art university and SBSS facilities. Given that the Caltech program has the simultaneous missions of producing unclassified research products while remaining relevant to nuclear weapons simulation and also educating foreign nationals, it is clearly of concern with regard to the proliferation of nuclear weapons technology.

INERTIAL CONFINEMENT FUSION

The DOE's Office of Arms Control and Nonproliferation (NN-40) examined the SBSS proliferation problem as it concerned the National Ignition Facility in a December 1995 report: "The National Ignition Facility and the Issue of Nonproliferation." Here DOE acknowledged, and indeed described, the contribution of ICF research to the proliferation of capabilities for thermonuclear weapon design. For example, in the case of a "Category Two" state that already possesses the capability to develop a simple single-stage fission weapon, the report notes:

> ...research in ICF could provide [the] state with a cadre of knowledgeable individuals who could enhance computer codes related to weapons design activities associated with equations of state, instability and mix at [material] interfaces, deuterium-tritium implosions, and DT burn. NIF and, to a lesser degree, other openly available ICF might help a Category Two state discover significant errors in its codes. [27]

As for advancing to the next step—a two-stage thermonuclear weapon capability—the report notes, "A modern sophisticated proliferator with access to ICF computer codes and today's computer workstations would have far more tools for designing a secondary than the U.S., U.K., or USSR had in the 1950s, or France and China in the 1960s." [28] Despite these and other similar assessments, the report simply decrees—in what appears to be a foreordained conclusion—that the "technical proliferation concerns" involving NIF "are manageable and therefore can be made acceptable."

Nevertheless, the report notes in its "Compendium of Public Comment and Departmental Responses" section:

> The Department recognizes that there will be a tension between openness measures at NIF and the need to keep certain information classified to prevent the spread of nuclear weapon design information to proliferant nations... DOE/Defense Programs is already developing a proliferation management plan to address some of these issues, and is taking public comment garnered from this process into account in developing the plan.[29]

Unfortunately, in today's world of computer networks, technical data banks, and complicated webs of international commercial and scientific relationships, any system of control predicated on controlling the spread of sensitive data and technology by targeting specific countries, while allowing further proliferation of such information to the vast majority, is destined for failure.

The full magnitude of the technical proliferation concern regarding the SBSS program's proposed approach to NIF can be more fully appreciated by outlining the DOE's classification guidance for NIF, and then examining what the U.S. nuclear weapons program intends to achieve within the parameters of unclassified research:

> All information, experimental and calculational, for laboratory capsules that absorb an amount of energy less than or equal to 10 megajoules and whose maximum dimension is less than or equal to 1 cm is unclassified (with some exceptions). [Note: this would appear to include all or most current NIF ignition capsule designs, as NIF's nominal drive energy is only 1.8 megajoules.]
>
> All information pertaining to laboratory ICF hohlraums [i.e., small cylindrical or other shaped cavities that convert laser light to x-rays] that reach a peak temperature of 400 eV or less, either by calculation or experiment, are unclassified (with some exceptions). [Note: NIF hohlraums for the current ignition capsules designs are currently limited by laser-plasma instabilities to about 300 eV.]
>
> Calculations, modeling, and experimental data on hydrodynamic instabilities and mix in unclassified ICF targets are unclassified (that would not reveal other classified information). The association with, applicability to, or actual use of mix data or mix models in nuclear weapons design remains classified.[30]

Dr. David Crandall, the Director of DOE's Office of Inertial Fusion Research, informed a National Academy of Sciences (NAS) Review Committee in September 1996, that "it is apparent that most experiments on NIF will be unclassified in and of themselves. This means that, in most cases, it will be possible to publish the results. However, while perhaps 80 percent of the work will be unclassified, 80 percent will likely also have some relevance to weapons. Information which is otherwise unclassified can become classified when it is associated with a particular weapons system. This distinction must be kept in mind." Indeed it must. The "Alice-in-Wonderland" quality of the SBSS Program's approach to "controlling" the proliferation of weapons-relevant ICF information is exemplified by this problem of "association" of nominally unclassified information with formally classified information. The Chairman of the NAS/ICF Review Panel asked two senior scientists from the University of Rochester's Laboratory for Laser Energetics (LLE)—the lab that houses DOE's 60-beam OMEGA Upgrade Laser—about the possibility of directly comparing the results from LLE's "unclassified" "direct-drive" ICF codes with those obtained from the "classified" design code (LASNEX) used by the weapons laboratories for modeling indirect drive ICF, by tasking both codes to simulate the same problem. "Drs. McCrory and Verdon both expressed the fear that if this were attempted it would lead to classification of the LLE codes."[31]

In light of this now large unclassified domain for NIF experimentation—encompassing essentially all laser-driven experiments designed to achieve ignition and some 80 percent of all planned ICF experiments—it is useful to review what the relevance of this nominally unclassified work is believed to be for the U.S. nuclear weapons program, and thus, by extension, for the proliferation of nuclear weapons design capabilities of other nations. Dr. Michael Anastasio, a senior weapons designer at LLNL, recently gave a presentation entitled, "Role of Ignition in Stockpile Stewardship," to the same NAS Panel charged with reviewing the DOE's ICF program. According to the DOE's minutes of the meeting:

> Dr. Anastasio described the way in which weapon designers integrate the available science base and apply that knowledge to present and future stockpile stewardship issues. He compared this process to achieving ignition on the NIF, which will be a "grand-challenge integrated test" similar in many ways to the nuclear design process [for weapon secondaries]. Both systems are imploded by x-rays which are transported through hot, high Z flowing matter. In both cases the codes used to model experiments must integrate radiation flow and opacities, plasma hydrodynamics including instability and mix, and thermonuclear ignition and burn.

> Dr. Anastasio noted that such integrated experiments develop and test the judgment of weapons designers. This is critical for the training of new weapons personnel, because even a 'perfect' computer code and physics data can turn to 'mush' in the hands of an inexperienced designer.
>
> Dr. Anastasio discussed cases in which numerical techniques developed to model ICF experiments have been adapted for weapons applications... In conclusion, Dr. Anastasio noted that the intellectual vitality and technical judgment of the nuclear design community of the future are important assets which the NIF will steward. [32]

Z-PINCH AND HE-DRIVEN PULSED POWER MACHINES

The role of such "grand-challenge integrated tests" in improving nuclear weapon design codes is not limited to laser-driven ICF. Something of a convergence is occurring in the SBSS Program between the capabilities of increasingly powerful electrical pulsed power facilities originally designed to simulate nuclear weapons effects and laser-driven ICF. In fact, Sandia's existing pulsed power program has already met or exceeded several of the key NIF parameters at the Z Machine—such as the x-ray pulse width, peak x-ray power, and total radiated x-ray energy—believed to be essential for achieving fusion target ignition, and it is now closing in on a fourth—extremely high temperatures. At the Z Machine, the passage of high currents (currently 10–20 MA) through a cylindrical array of fine wires produces an azimuthal magnetic field, causing the wire plasma to accelerate radially inwards. Stagnation and thermalization of the plasma on axis (on the axis usually labeled by the variable z, hence the term z-pinch) provides a source of soft x-rays. It has been found that the total x-ray energy output scales as the current squared, and is a strong function of inter-wire distance and wire thickness.[33]

Hohlraums are incorporated into this arrangement in three ways: currently referred to as "static," "dynamic," and "secondary." A static hohlraum surrounds the z-pinch, thereby increasing the x-ray power within the cavity as the z-pinch radiation is reflected, absorbed and re-emitted by the hohlraum. A dynamic hohlraum resides inside the z-pinch and undergoes compression upon being shocked and irradiated by the imploding pinch, while a secondary hohlraum can be attached to the primary hohlraum to conduct studies of radiation flow.

In September 1997, Sandia's Z Machine achieved an x-ray flux temperature of 146 eV (about 1.6 million degrees Celsisus) "in a container the size of a spool of thread."[34] Subsequently, a peak temperature of 190 eV (about 1.6 million degrees) and an x-ray power output of 290 trillion watts was achieved by using a more sophisticated z-pinch: nested wire arrays which reduce hydrodynamic instabilities in the implosion.[35] By comparison, laser-plasma instabilities limit NIF indirect drive ignition experiments to a temperature of around 320 eV, and the baseline NIF indirect drive target is designed to operate at around 250–300 eV. According to Sandia scientists, these recent results at the Z Machine suggest that the already planned next generation pulsed power machine—the X-1 Advanced Radiation Source (see below)—"should be able to produce 16 million joules of energy, more than 1,000 trillion watts of power, and temperatures of more than 3 million degrees."[36] Temperatures in the range of 2–3 million degrees Celsius are generally thought to be an essential condition for fusion.

In April 1998, permission to prepare a conceptual design for the X-1 was formally requested of DOE by Sandia President C. Paul Robinson.[37] It will likely be proposed for construction at the Nevada Test Site. Until some time in 1995, Sandia had been planning an even more powerful x-ray facility, called Jupiter, as part of a "Joint DOE/DoD Advanced Development Program" that responded to the fact that "with the loss of Underground Nuclear Testing, both DOE and DoD have a need to produce ultra-high energy density plasmas."[38]

HE-DRIVEN FUSION EXPERIMENTS

Publicly-accessible information on high-explosive driven D-T fusion experiments in the U.S. is sparse. A relatively recent Los Alamos experimental program was code-named "Gifthorse." Several articles on this program appeared in the classified journal *Defense Science* in 1990.[39] An analogous Livermore program of the late 1950s and early 1960s included nuclear design projects code-named "Dove" and "Starling," for which Edward Teller made extravagant claims of imminent success during the test ban debate in the early 1960s.[40] More recently, scientists at the former Soviet weapons laboratories claimed to have achieved ~10^{13} fusions from an experiment involving the direct compression of D-T gas by high explosives using the layered shock cumulation technique in the late 1980s.[41] Some of the same Russian scientists working on Magnetized Target Fusion (MTF—the subject of an accompanying paper by Jones and von Hippel) in the LANL/VNIIEF (All Russian Scientific Research Institute of Experimental Physics, formerly Arzamas-16) collaboration are listed as co-authors in the high-explosive fusion work.

U.S. nuclear weapons specialists were very surprised to learn at the 1989 Megagauss V conference of the extent of Soviet progress in the field of high explosive pulsed power (HEPP). Subsequently, Los Alamos Director Sig Hecker identified this as an "appropriate" area for collaboration with cash-starved Arzamas-16. More important than MTF applications are high-energy-density studies and hydrodynamic instability experiments. According to Los Alamos scientists:

> Russian technology is expected to play a major role in the Los Alamos AGEX-II [i.e., a category of SBSS above-ground experiments] research program. By collaborating with the Russians, we hope to save many millions of dollars in research money that would be needed to reproduce and understand their successes. Moreover, we are progressing much faster in our understanding of the principles involved in high energy density than we would have on our own.
>
> We have moved cautiously in establishing our relationship with VNIIEF. At each step, we have kept Laboratory and Department of Energy officials informed; in return, they have encouraged us to continue to expand our interactions. Other United States agencies, including the Department of Defense, the National Science Foundation, the United States Air Force, and the Defense Nuclear Agency, are monitoring our progress in anticipation of finding ways to incorporate Russian technology into their programs through similar collaborations.[42]

In November–December, 1997, the LANL/VNIIEF collaborations were extended to the point of performing joint Liner Stability experiments on the Pegasus II pulsed power facility, the forerunner to the more powerful Atlas machine now under construction at Los Alamos.

It should be appreciated that the MTF/HEPP research program is but one component of the overarching SBSS effort to construct a three-dimensional, full-physics, full-system computer simulation of the explosion of a nuclear weapon. While the possibility of novel HE-driven fusion weapons concepts emerging from "loopholes" in the CTBT and NPT merit scrutiny from the disarmament and non-proliferation community, the true import of such work for both nonproliferation and arms control cannot be appreciated in isolation from the rest of the SBSS. MTF and HEPP are components of DOE's multi-front assault on the presently coupled fusion energy and stewardship problems.

THE STATUS OF FUSION EXPERIMENTS UNDER THE CTBT AND NPT

High-explosive pulsed power experiments are highly controversial, so much so that a dispute exists within and between governments regarding the compliance of such experiments with U.S. obligations under the CTBT. The CTBT bans the conduct of a "nuclear weapon test explosion, or any other nuclear explosion." However, the treaty itself does not define what constitutes a "prohibited nuclear explosion," nor does the final treaty text contain any negotiated exceptions to this comprehensive prohibition. The plain language of the treaty covers all nuclear processes in which both the amount and rate of energy release can be fairly characterized as "explosive."

On August 11, 1995, President Clinton announced that the United States would support and seek to negotiate a "zero-yield" treaty. On October 27, 1995, the Secretary of Energy announced that SSBS program experiments planned for NTS would remain "subcritical." DOE explained that underground SSBS high-explosive driven experiments with nuclear materials at the Nevada Test Site (NTS) would not produce any nuclear yield from a prompt critical assembly of fissile materials, i.e., plutonium or highly enriched uranium in the required amounts would never be brought into an explosively chain-reacting ("prompt critical") configuration, and would therefore remain "subcritical."

However, neither President Clinton nor the DOE announced how the SBSS Program was planning to interpret the U.S. CTB obligation with respect to nuclear weapons-related experiments and other experiments utilizing fusion as opposed to fission reactions. High explosive driven fusion and pulsed power experiments utilizing deuterium-tritium targets and up to 70,000 lbs of high explosive are planned for the Big Explosive Experimental Facility (BEEF)/HEPP facility as part of DOE's preferred alternative for "expanded use" of NTS over the next decade. Such experiments are not covered by the 1975 U.S. statement at the First Nonproliferation Treaty Review Conference that advanced the view, unopposed and thus "accepted" at the time by other nations, that fully contained laser- and particle beam-driven fusion experiments, presumably requiring large-scale fixed experimental facilities, did not constitute nuclear weapons development within the meaning of the NPT.

In other words, other forms of Inertial Confinement Fusion—such as HE-driven implosions, electrical pulsed power driven x-ray sources for imploding D-T fusion targets in a hohlraum cavity and HE-driven magnetic flux compression of hot magnetized D-T plasmas are not covered by the existing NPT statement regarding beam-driven ICF. These experiments could well fall under the CTB prohibition against "any other nuclear explosion" if the fusion energy released per unit mass (i.e., the "energy density") exceeds that of chemical high explosive. While not specifically permitted under the 1975 NPT exemption, capacitor bank pulsed power x-ray sources resemble particle beam and laser ICF in that they require large fixed facilities to approach fusion conditions. On the other hand, high-explosive and magnetic flux compression fusion devices are on a much smaller scale, on the order of a 1 to 3 meters in length, roughly the size of nuclear bombs.

The energy density of the chemical high explosive (TNT) typically used to measure equivalent nuclear energy release is about 1,100 kilocalories per gram. This level of energy release is equivalent to 1.64×10^{15} DT fusions per gram of target material. It is clear that existing fusion experiments have already exceeded this level. The Omega Laser at the University of Rochester, has reportedly achieved a fusion yield of 1.3×10^{14} neutrons in less than a milligram of material using DT target capsules fabricated at Los Alamos. Indeed, the goal of all these experimental approaches—both sanctioned and unsanctioned—is to achieve fusion ignition, which would obviously exceed the HE energy density "standard" by many orders of magnitude.

Reflecting the National Laboratories' concern over possible interpretations of U.S. treaty commitments which could preclude experimental components of the SBSS, SNL Director C. Paul Robinson testified to Congress in March 1996:

> If the ICF language of the 1975 Nonproliferation Treaty [Review Conference] were to be carried over to a Comprehensive Test Ban Treaty, some of the high-energy accelerators the laboratories used today to simulate a variety of conditions, and some that will be needed in the future, would have to be abandoned. Such restrictions were not part of the laboratory directors' understanding when we told the President we could perform our mission without underground nuclear testing. Our clear expectation was that further limitations would not be placed on our ability to employ the various approaches to inertial confinement fusion in support of stockpile stewardship. In my view, it is essential that inertial confinement fusion be permitted under a CTBT without such restrictions. [43]

As noted, however, the CTB as signed by the United States in September 1996 does not specifically permit "all the various approaches to inertial confinement fusion in support of stockpile stewardship." The treaty is silent on this particular issue, but does contain a very broad prohibition on conducting "a nuclear weapons test explosion, or any other nuclear explosion." The negotiating history makes clear that the latter phrase is intended to close the possible loophole represented by nuclear explosions conducted for ostensibly "peaceful" rather than weapons purposes, and thus the treaty would ban HE-driven pulsed power fusion experiments whenever they attain the level of a nuclear "explosion."

While no internationally agreed definition of a nuclear explosion exists, U.S. policy, explicitly or tacitly endorsed by many nations, has determined that to remain in compliance with the CTB, a nuclear experiment involving the assembly of fissile materials using high explosives must remain "subcritical." That criterion restricts the release of nuclear energy from such high-explosive driven fissile material experiments to on the order of 0.1 microgram of TNT equivalent, or perhaps as much as a tenth of a gram if the experiment is illuminated by a powerful additional source of neutrons. [44]

Another concern with HEPP systems is whether a transfer or sharing of HEPP devices, such as has recently occurred between Russia and the United States and described below, would violate the Nonproliferation Treaty's blanket prohibition on the transfer of nuclear explosive devices between parties to the treaty (including weapon states) if such novel compression devices are capable of producing appreciable fusion or fission yields.

As noted above, the scope of the U.S. NPT obligation is very broad, encompassing a commitment not to engage in transfers involving "other nuclear explosive devices." While the NPT clearly bans such transfers, it does not define the operative phrase—"other nuclear explosive device." While the energy output of HEPP devices today is very low, this may not remain the case in the future, as one purpose of both the DOE and Russian HEPP programs is to increase the output of such devices such that they produce energy "gain"—i.e., more energy out than goes in.

THE "SCIENCE BASED STOCKPILE STEWARDSHIP" STRATEGY: IS IT NECESSARY?

The argument that the current DOE Stewardship effort has not accorded proper weight to non-proliferation concerns is borne out by examination of what may legitimately be called a founding document of the program, the August 1994 report by a JASON/MITRE Corporation advisory group chaired by Dr. Sidney Drell of Stanford University, entitled, "Science-Based Stockpile Stewardship," (hereafter referred to as the "Drell SBSS Report). While several JASON reports have appeared subsequently on various aspects of the SBSS program, none have assessed its technical proliferation impacts. With respect to this issue, the original Drell SBSS Report was preoccupied with the problem of political appearances surrounding the NPT Extension Conference in May 1995:

> ... SBSS program implementation must avoid the appearance that, while the U.S. is giving up nuclear testing, it is as compensation introducing so many improvements in instruments and calculational ability that the net effect will be an enhancement of our advanced weapons design capabilities.

The report called "for care in designing an appropriate SBSS program that meets two very different, and at times countervailing objectives... enhancing the weapons science and engineering programs that underpin our ability for advanced diagnostics, related computations, and ultimately scientific understanding of all aspects of their behavior" [versus] "securing the indefinite extension of the nuclear non-proliferation treaty at the 1995 Conference."[45]

A number of SBSS program activities clearly involve the generation of experimental weapons physics data and techniques useful in the design and engineering of nuclear weapons, including boosted and two-stage thermonuclear weapons currently beyond the capabilities of most nations with inherent capabilities for nuclear weapons development. As we have seen above, in the interests of "technical deterrence" and "peer review" some of this data will be unclassified. Based on the history of the U.S. nuclear weapons program to date, additional information of importance to nuclear weapons design will be deducible or derivable from the data that is considered unclassified, and additional data will be deliberately declassified, pursuant to a political strategy of "openness" that is intended to defuse negative international perceptions of the underlying nuclear deterrent mission and capabilities of the SBSS program.

The Drell SSBS Report warned that the stewardship program, "unless managed with restraint and openness, including international collaboration and cooperation where appropriate, might end up as an obstacle to the Non-Proliferation Treaty." It then advanced two arguments which the authors' felt might induce other countries to welcome (or at least tolerate) a comprehensive SBSS:

> The first is that stewardship is an essential responsibility of the declared nuclear weapons states, in that they must guarantee the safety of the weapons and provide security against possible theft or other misuse of them... The first argument leads to the conclusion that the declared nuclear weapon states can accept a ban on underground tests only if they maintain a technical base of both experiments and theoretical analysis to discover flaws in the weapons as they age, to analyze the consequences of these flaws, and to correct them.[46]

This argument may be objected to, however. Meeting weapon state "responsibilities" for maintaining the safety and security of nuclear weapons (as opposed to reliability) in no way justifies a new experimental program for discovering and correcting aging flaws in U.S. nuclear weapons, much less a comprehensive program to achieve the simulation of nuclear explosions from first principles. Security is a function of fences, guards, guns, alarms, electronically coded locks and other devices that are technically independent of the issues of nuclear explosive package reliability and safety.

Moreover, as Dr. Ray Kidder, an LLNL senior physicist, has reported to Congress, aging can affect nuclear explosive package reliability, but not its one-point nuclear detonation safety, if such has previously been demonstrated to be an inherent characteristic of the design in question.[47] Nuclear weapons in the U.S. stockpile have been certified as adequately safe, and the sensitivity to impact or fire of the high-explosives used in nuclear warheads does not increase with age. Safety problems with nuclear warheads are generally inherent in the design of the warhead itself, not the result of aging or other causes.[48]

The second argument offered in the Drell SBSS Report for why non-weapon states should embrace stewardship is also not persuasive:

> Second, presumably all underground nuclear tests will be stopped by an eventual CTBT. A CTBT has been designated as a goal in the negotiating history of the NPT and is believed to be necessary to gain support from the NNWS [Non-Nuclear Weapon States] for the U.S. position seeking indefinite extension of the NPT... The second argument then leads to the conclusion that, with a CTBT in place, new facilities must be built to strengthen the science base of our understanding of nuclear weapons in order to at least partially replace the knowledge once obtained from tests. [49]

These statements could well lead the unwary reader to conclude that nuclear weapons test explosions were widely and routinely used to detect and correct problems in nuclear stockpile weapons, when in reality, they were almost never used for this purpose.

Of the total of some 830 specific recorded "findings" of defects in stockpiled weapons since 1958, less than 1 percent were discovered in nuclear tests, and all these tests involved weapons that entered the stockpile before 1970 and are no longer in the U.S. nuclear stockpile today.[50] After 1970, zero defects in nuclear stockpile weapons were discovered in underground nuclear tests, and only 4 out of 141 (i.e., less than 3 percent) of "Product Change Proposals" to war reserve stockpile weapons involved underground nuclear explosive tests to develop or confirm the corrective action. As of the end of the Cold War in 1991, while some weapons types, such as the B-28 strategic bomb, had been in the national stockpile for 33 years, no U.S. weapon type had ever been retired because of nuclear explosive device "aging."[51]

Since underground nuclear test explosions have so rarely been relied upon to discover and correct flaws in weapons as they age, there is no immediate and compelling link between the SSM activities designed to "replace" nuclear explosive testing and the continuing "safety and reliability" of a nuclear stockpile. Hence, there is no compelling national security justification for running the proliferation risks inherent in the current U.S. SBSS program.

The principal link between nuclear explosive testing and the safety and reliability of the stockpile is an indirect one, involving the application to stockpile problems of expertise and judgment that was originally acquired, and in part sustained, through the process of designing, engineering, and manufacturing new nuclear explosive devices, and of having performance predictions for these devices either confirmed or disproven in underground nuclear explosive tests. Thus, the main issue confronting the U.S. stockpile stewardship program does not involve plugging some imagined gap caused by the loss of nuclear testing in the ability to maintain U.S. nuclear weapons in the near term (i.e., the next 10–15 years).

Rather, the main issue confronting the program is how best to conserve and utilize the accumulated nuclear weapons expertise of DOE's test-experienced personnel so as to minimize the likelihood of future stockpile problems occurring when these persons have retired and are no longer available to DOE. A number of alternative strategies for dealing with this problem have been proposed, but only one approach was ever seriously considered by DOE—training a new generation of weapon designers by giving them the challenge of reproducing past test nuclear test results using new nuclear weapon design codes based on a first principles understanding of nuclear explosive phenomena. Such simulations would, in theory, allow confident modification and even design of weapons in the future using computer based "virtual testing" and above ground experimental tools as replacements for underground nuclear testing.

An alternative approach, with definite political and technical advantages for nonproliferation, is to acknowledge that the expertise and judgment of nuclear-test experienced personnel need not, should not, and probably cannot be replicated in a new generation of designers without resort to nuclear explosive tests. On the contrary, every attempt should be made to limit future changes in weapons designs, in order to limit the class of weapon problems likely to arise in the future to those susceptible to resolution within the existing conserved and tightly held base of nuclear weapons design knowledge. This conservative, risk-minimizing, and proliferation sensitive approach points in the direction of using DOE's cadre of nuclear test-certified personnel —while they are still available to the nation—to thoroughly specify and certify nuclear explosive package configurations for the weapons to be retained in the enduring stockpile so that these components could be remanufactured by the DOE complex with continuing confidence in proper performance.

Rather than emphasizing certification of the enduring specifications required for confident remanufacture, however, DOE's preferred strategy emphasizes using the waning asset of test-qualified personnel in what amounts to a crash program to develop and validate new three dimensional simulation capabilities, capabilities that DOE hopes a new generation of U.S. designers—but no one else—will employ, ostensibly to optimize requirements for remanufacture by predicting when materials aging will degrade weapons performance, but more plausibly to implement future changes in the nuclear explosive packages of stockpile weapons.

The Drell SBSS report seemed to acknowledge the weakness of its arguments for the international acceptability of the U.S. SBSS effort when it later observed that the two arguments noted above "may not be enough to entirely dispel suspicions on the part of the non-nuclear weapons states." Incredibly, however, the report suggested, "What would go a long way to relieve these suspicions would be to declassify as much of the stewardship program as possible." The report then noted:

> Following recent declassification actions [in 1993] a large part of the ICF program and the precursor [NOVA laser] to instruments such as the National Ignition Facility [NIF] are already unclassified. The LANSCE [Los Alamos Neutron Science Center] is also already completely unclassified. Parts of the pulsed power program at Sandia remain classified but many parameters including hohlraum temperatures are unclassified.[52]

The Drell SBSS Report went on to urge:

> There should be a detailed study be undertaken, taking into account what is already available outside the weapons program, to further reduce the need for classification, both of experimental results and theoretical calculations. Any restraint on making weapon codes available should be justified on clear grounds of preventing proliferation... Only critical parts of the weapon codes that would be used to analyze some of the experimental data or which would be directly applicable for weapons design would remain classified... Altogether, the more open the stewardship program is, the more easily suspicions regarding U.S. intent to use the program as a cover for new weapons development can be overcome.[53]

By this standard, very little need be withheld, as it is usually impossible to demonstrate that any single act of restraint in disseminating nuclear weapons knowledge will serve to "prevent" a specific, identifiable act of nuclear weapons proliferation. This is especially true today, given that proliferation mainly involves the spread of latent technical capabilities to design and produce nuclear weapons rather than the kind of more easily detected weapons testing, production, and deployment activities likely to arouse concerted international opposition.

CONCLUSIONS

A strong possibility exists that the United States is poised to repeat the errors of the Atoms for Peace Program in the 1950s, in which a torrent of public relations regarding the "peaceful atom" enveloped a release of sensitive nuclear fuel cycle technology that was intended politically to counterbalance the U.S. decision to abandon the goals of disarmament and international control of atomic energy in favor of massive nuclear weapons buildup. In a little noticed, unpublished dissent from the conclusions of the Drell SSBS Report in which

[redacted]

he participated, Washington University physicist Jonathan Katz contrasted the SBSS approach to maintaining the U.S. deterrent with an approach he called "curatorship." Under this strategy, new experimental facilities such as NIF are not built, "design and development skills are allowed to atrophy, and only those skills required to remanufacture weapons according to their original specifications are preserved." Curatorship is preferable to SBSS, Professor Katz argued, because "the chief nuclear danger in the present world is that of proliferation, and stewardship will exacerbate this danger, while curatorship will mitigate it while preserving our existing nuclear forces."

> ... The construction and operation of the National Ignition Facility and related facilities would not be cheap. More important are the consequences for the present and future danger of proliferation. NIF will bring together the weapons and unclassified communities. People will rub elbows, share facilities, collaborate on unclassified experiments, and communicate their interests and concerns to each other. Information and understanding will diffuse from the classified to the unclassified world, without any technical violation of security. The desire to achieve renown and career success by publication in the open literature will diffuse from the unclassified to the classified world.
>
> Inertial (chiefly laser) fusion has similarly brought its classified and unclassified communities into intellectual and geographical contact over the last 25 years. The consequence has been the declassification of many nuclear weapon concepts and information. It is common knowledge that there is a great deal of physics in common between inertial fusion and nuclear weapons. The unclassified inertial fusion community has reinvented weapons technology, and the classified community has pressed successfully for declassification of formerly classified concepts, some applicable to inertial fusion and some not so applicable...
>
> This process would continue at NIF, which would provide a facility and funding for the unclassified world to rediscover nuclear weapons physics and (implicitly) to develop the understanding and computational tools required to design weapons. This reduction of the barriers to proliferation of both fission and thermonuclear weapons is not in the national interest.[54]

In addition to the broad proliferation consequences of the SBSS raised in this paper, as yet unanswered questions unavoidably present themselves concerning specific pulsed power and HE-driven approaches to fusion. If such experiments are not prohibited under the NPT or CTBT, with or without any interim limit on fusion neutron output, who gets to conduct such experiments? Absent further clarification, it appear that Germany, a non-weapon state under the NPT, and possibly others, are reserving the legal "right"—while per-

[redacted]

haps not any immediate intention—to do so (see Table 1, footnote c). Should the international community therefore acquiesce in the conduct of such experiments by *any* non-weapon state?

In their zeal to create a "technically challenging" program in nuclear weapons simulation research to replace the perpetual cycle of nuclear weapons development and testing that historically had supported a lavish and cloistered research environment at the nation's nuclear weapons laboratories, the current managers of the U.S. nuclear weapons complex have confronted policymakers with a Hobson's choice between false alternatives—either buy the entire $4.5 billion "virtual testing" paradigm and absorb the self-inflicted proliferation risks that it entails, or lose confidence in stockpile reliability and safety by the middle of the next decade. As we have argued in this paper and elsewhere, this is a false choice, predicated on a concatenation of fallacies.

First, the record of the stockpile surveillance program shows that the nuclear explosive packages in operational U.S. nuclear weapons can be maintained—as opposed to developed or improved—over time without reliance on nuclear explosive testing. Hence, stockpile "stewardship" that is consistent with the CTBT's avowed intent to constrain development and qualitative improvement of nuclear weapons need not, as a technical matter, seek to fashion a way around these constraints through an elaborate "virtual testing" program.

Second, it is not inherently necessary to predict (through complex simulations) the occurrence of aging effects and the point at which they cumulatively will begin to seriously degrade nuclear explosive performance —it is necessary only to detect deterioration that exceeds, in the case of the nuclear explosive package, the previously demonstrated parameters associated with acceptable performance, or in the case of other components, the demonstrable parameters of acceptable performance, as the performance effects of "aging" on these components is not constrained by the existing database and can be exhaustively explored. While such an approach might result is a less than "optimal" schedule for remanufacture of the nuclear explosive package, we have seen no analysis that suggests that the incremental cost would even begin to approach the significant incremental cost of DOE's accelerated nuclear explosion simulation effort. Moreover, as the future stockpile decreases in size—one would hope dramatically so—any cost savings from "optimizing" schedules for remanufacture disappear as well, as these savings pale in comparison to the large capital investment and annual fixed costs of the SBSS program. But even if there were significant cost advantages from taking this approach, these must weighed against the proliferation risks of the current program, and such a comparison finds DOE's current approach wanting.

Third, although the authors see no compelling reasons to do so, from a purely technical perspective, existing nuclear explosive packages can be integrated into new or modified warhead and bomb systems, and these systems in turn can be mated to new or modified delivery systems, without resort to the highly challenging but proliferation-prone "first principles" nuclear explosive simulation effort now being undertaken by DOE. In other words, under a CTBT many of the operational characteristics of nuclear weapon systems can be adapted—within the limits imposed by the certified performance envelopes of existing nuclear explosive packages—to changing military missions without incurring the considerable proliferation risks entailed by the DOE'S massive and increasingly unclassified "science-based" program of nuclear explosive simulations, weapon-physics, and fusion experiments. Improved casings, radars, altimeters, boost-gas delivery systems, neutron generators, detonators, batteries, integrated circuits, fuzing and arming systems, permissive action links—all can be developed and integrated into nuclear bomb and warhead systems without modifying the nuclear explosive package design.

Given these technical realities, there is a legitimate cause for wondering exactly what *is* driving the U.S. decision-making process toward unquestioning acceptance of the SBSS program's fiscal, technical, and proliferation risks. We have a tentative answer to this question, and it is largely institutional and political in nature. Because the Clinton Administration has done so little to change the ways in which the U.S. defense bureaucracies are directed to think about the future roles and missions of nuclear weapons in support of U.S. security policy, the vigorous and politically potent self-preservation reflex of the U.S. nuclear weapons research and development complex has filled the policy void, fashioning a program that assures, in essence, that all *status quo* nuclear weapon design capabilities will be preserved, and where possible, even enhanced. The result is a hugely ambitious surrogate weapons R&D program that integrates greatly expanded computational capabilities, fundamental data gathering on constituent bomb materials and explosive processes, and integrated demonstrations of nuclear design code predictive capabilities in a range of powerful new experimental facilities.

All of this is ultimately justified, we are told, not by the present state of Russian or other nuclear threats to American and allied security, which have arguably diminished to their lowest level in five decades, but by two other factors: (1) the need to retain a robust nuclear deterrent "hedge" against an uncertain future in which something like the Cold War complex of nuclear weapon design capabilities might once again be needed; and (2) the need to retain a convincing and "flexible" nuclear deterrent to biological and chemical weapons use by so-called "rogue nations."

However, it is difficult to envision any national security threat to which resumption of the arms race would constitute a rational response, and the U.S. assertion of the need for further development of nuclear weapons for use against chemical and biological threats merely invites other nations to reach for a nuclear deterrent.

One is lead inexorably to the conclusion that a more compact, technically restrained, and tightly focused U.S. stockpile stewardship program would provide an adequate hedge against both the improbable resurgence of the nuclear arms race and weapons of mass destruction proliferants while better serving both technical and political nuclear nonproliferation objectives.

APPENDIX

One example of the research to be performed under the DOE's Academic Strategic Alliances Program is the "Facility for Simulating the Dynamic Response of Materials," established at Caltech to create a virtual shock physics facility, the "virtual shock tube." A diagram of one configuration of Caltech's virtual shock tube is shown in Figure 4. In Caltech's planned virtual experiments, a computer simulation will be performed of: the detonation of a high explosive charge; the effects of the ensuing shock waves on test materials (such as fracturing and phase changes); and the shock-induced compressible turbulent flow and mixing at material interfaces. Five research initiatives have been planned at Caltech in order to create the virtual shock tube:

- Modeling and simulation of fundamental processes in detonation;
- Modeling the dynamic response of solids;
- First principles computation of materials properties;
- Computation of compressible turbulence and mixing; and
- Computational and computer science infrastructure.

All nuclear weapon designs include the detonation of chemical high-explosives to produce shock waves in materials—most significantly in plutonium and uranium, but in lighter bomb constituents as well. Both TATB-based (insensitive) and HMX-based (sensitive) plastic-bonded high-explosives are used in deployed or stockpiled U.S. nuclear weapons.[55] Experimental, theoretical, and computational research on high explosives is a core research component of the U.S. nuclear weapons program. Shock-wave induced symmetrical implosion and compression of fissile material is the principal method by which a fission chain reaction with significant energy yield is produced in a thermonuclear weapon's primary component.

The DOE currently operates several so-called "hydrotest" facilities for performing implosion experiments with subscale (i.e., subcritical) or non-fissile primary assemblies. In full-scale hydrotests, a non-fissile material such as depleted uranium or plutonium-242 is substituted for the primary's fissile core, so as not to produce a nuclear chain reaction, leaving shock-wave induced spherical, hemispherical, or cylindrical implosion -- and the properties and behavior of weapon materials in various states of compression -- as the primary phenomena to be examined. Under DOE's SSMP a next generation hydrotest facility is under construction at Los Alamos National Laboratory: the Dual Axis Radiographic Hydrodynamic Test Facility (DARHT). An

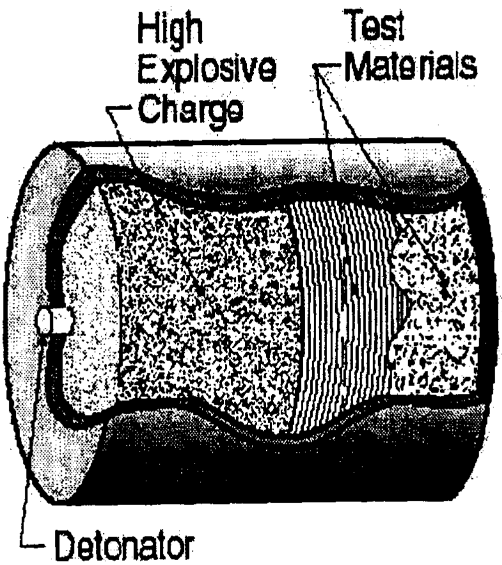

Figure 4: A diagram of Caltech's virtual shock tube, showing detonator, high explosive charge, and test materials.

upgrade to Livermore's hydrotest facility (the Flash X-Ray Facility, or FXR) is being carried out in order to provide both nuclear weapon design laboratories with state-of-the-art capabilities for penetrating, time sequenced radiographic images of densely imploded objects, such as the plutonium core of a weapon primary.

At the "Facility for Simulating the Dynamic Response of Materials," Caltech has organized an interdisciplinary team to improve upon existing capabilities to model the detonation of high explosives. A trend in this field is noted in its Alliances Program research proposal:

> With increasing [length] scale, models [of the detonation of high explosives] become less rigorous and more empirical until finally, at the macroscopic level, the models are only reliable if they have been carefully calibrated against experiments with specific materials.[56]

Caltech scientists proposed to conduct calculations of the molecular/electronic structure of high explosives, develop detailed models of the chemical reactions (for explicit explosive systems), and explore "the interaction of chemistry with mechanical deformation." The latter effort aims at a better understanding of how the chemical reactions are modified if the explosive materials are subject to high strains(at the shock front, for example, or at the interface between the crystal grains of high explosives and the plastic binder.

Caltech states that the computational capabilities of the ASCI program are expected to permit modeling the detonation of a macroscopic piece of the high explosive material using the molecular-level description of the process.[57] If successful, this would represent an advance over current capabilities, in which Caltech characterizes the molecular-level computer simulations and macroscopic computer simulations as largely distinct efforts.

In terms of the detonation of high explosives, the Caltech Center's agenda extends beyond basic science and computer simulation to the production of a computer research tool advertised for use in the U.S. nuclear weapons program:

> High explosives are a key component in nuclear weapons and realistic modeling of detonation in high explosives is a long-standing issue in performance, safety, and reliability studies carried out in the DP Laboratories. A major deliverable from this portion of our program [i.e., "Modeling and simulation of fundamental processes in detonation"] will be integrated into a problem-solving environment...Our computational environment will provide ASCI researchers a means to explore systematically chemical, mechanical, and numerical issues through high-fidelity detonation simulations.[58]

This computational environment is an evolution of the Caltech code AMRITA[59] from a two-dimensional capability to a three-dimensional one, while incorporating the molecular-level modeling research discussed above. AMRITA is one of several candidate codes which Caltech may choose to develop into the virtual shock tube. Experimental validation of the detonation simulations "will be carried out through comparison with gas phase detonation experiments carried out at Caltech and HE experiments carried out at DP Laboratory facilities."[60]

The portion of the Caltech *Alliances Program* work devoted to "Modeling the dynamic response of solids" has two research components related to simulating the response of solid targets to strong shocks: 1) deformation and failure mechanisms in materials (such as the fracturing); and 2) polymorphic phase changes (the change of a material from one solid phase to another solid phase, such as the rearrangement of atoms to form a new crystalline structure.) "Algorithms must be developed to describe these processes in multidimensional Eulerian and Lagrangian codes."[61] As in the Caltech Center's study of detonation, issues associated with modeling phenomena across many orders of magnitude in length scale is at the center of the research problem:

> A key requirement in simulating the response of solid targets to strong shocks is the resolution of multiple length scales straddling the gray zone between atomistics and continuum behavior. We have developed a quasi-continuum method that seizes upon the strengths of both atomistic and continuum theories and allows for the seamless and simultaneous consideration of multiple scales.[62]

With funds from the Academic Alliances Program, Caltech will extend this method to three dimensions (from two) and to dynamic (instead of merely static) problems. Caltech advises DOE that solid-to-solid phase transitions, a common phenomenon in shocked materials, currently lack a quantitative theoretical description which can be implemented in codes. Caltech proposed to model polymorphic transitions in silicon dioxide (SiO_2), titanium dioxide (TiO_2), sodium chloride (salt, NaCl), iron (Fe), iron oxide (FeO), beryllium (Be), boron (B), thorium (Th), uranium (U), and zirconium (Zr).[63] According to Caltech's proposal, "the installation of new DP [DOE Defense Program] Laboratory radiography facilities (such as DAHRT) provides additional opportunities for [experimental] validation [of the new modeling approach]."[64]

The section of Caltech's Alliances Program research devoted to "First principles computation of material properties" describes research that touches upon nearly all the other aspects of the Center's agenda. Again, the central problem of simulating phenomena over a large range of length scales leads the discussion:

> In this section, we propose a hierarchical approach to materials modeling in which parameters are derived from quantum mechanics (QM) through averaging over successively larger scales of time and length. The approach leads to a rigorous description of continuum parameters required in describing crack initiation, spallation, chemical decomposition, etc. These computational techniques will be directed toward calculating phase behavior of metals, reaction kinetics relevant for HE, and structural information for metallic alloys (<u>including actinides</u>) at high temperatures and pressures (emphasis added).[65]

Given that plutonium and uranium—actinides—are used in nuclear weapons, U.S. classification guidelines exist for the equations-of-state for these materials.[66] The pressure regime Caltech intends to explore under its Alliances Program contract—up to 1 TPa (Tera-Pascal or 10^{12} Pascals)—is well above the classified pressure regime for neptunium and plutonium which begins at 0.002 TPa (20 kbar = 0.002 TPa), and is representative of the pressures encountered in a nuclear explosion.

In December of 1997 Secretary of Energy Frederico Peña held a press conference in which the results of the Fundamental Classification Review were presented. *The Report of the Fundamental Classification Policy Review Group*, chaired by former Sandia National Laboratory director Dr. Albert Narath, discussed the changing context of basic physics relevant to nuclear weapons:

> Classification of scientific information underpinning nuclear weapons design activities must be viewed in a somewhat different fashion. Limited resources have become and will likely remain a significant constraint in managing the acquisition of necessary scientific knowledge. However, the past 40 years have seen a large and sustained growth in areas of general science closely related to nuclear weapons technology—astrophysics, condensed matter, high temperature experiments, and computer design and applications. These resources can be leveraged [by the SBSS] by encouraging scientific exchange between U.S. researchers and the worldwide community.
>
> With no nuclear testing, the safety and reliability assurance of the stockpile will rest on the ability to attract and retain highly skilled scientists and engineers. Their willingness to center their careers in the nuclear weapons field may be enhanced to the extent that their scientific accomplishments can be recognized and rewarded by their peers in the open and unclassified arena.[67]

Until recently, lack of access to experimental facilities which can produce conditions similar to those encountered in a nuclear weapon explosion limited the amount of unclassified or non-governmental research in sensitive areas. However, the Policy Review Group stated that "general science" is expanding in bomb-relevant areas. In their judgment, retaining quality personnel in the nuclear weapons program necessitates permitting SBSS research to be published in the open scientific literature. Here one sees international proliferation concerns reflexively subordinated to an ostensible requirement to sustain and enhance unilateral U.S. nuclear capabilities. Better to disseminate our nuclear weapons science research, the Policy Review Group argues, than to compromise its quality by obscuring the technical achievements of weapons program personnel, thereby discouraging the best and brightest from devoting their professional lives to nuclear weapons work.

The Report of the Fundamental Classification Policy Review Group contains the following passages on the classification of equation-of-state measurements and theory:

> The relations between the thermodynamic variables of a material—density, temperature, pressure, energy, and entropy—are referred to as equations of state. Understanding nuclear weapon performance is dependent on good equation of state information at very high temperatures and pressures.
>
> Because of the importance of uranium and plutonium to weapon design, the equations of state for the actinides (atomic number greater than 89) should remain classified. All currently classified equation of state information used in weapons design calculations should remain classified because it may embody empirical information gained by comparisons with classified experiments. Otherwise, equation of state information for elements whose atomic number is less than or equal to 89 can be treated as unclassified.[68]

More specific information on the new classification guidelines for equations-of-state is relegated to a classified appendix of that report. The Caltech research may or may not overlap the recently revised classification guidelines. What should be noted, however, is that the trend towards open publication of crucial nuclear weapons data—basic physics in this instance—is not merely the direction "general science" is evolving towards, but a conscious process abetted by the "Science-Based" Stockpile Stewardship Program.

As was discussed above, the explosion of a nuclear weapon via the implosion technique is initiated through the basic mechanism of high-explosive-driven symmetrical compression of fissile material. The Caltech research program includes a study of what occurs when shock waves impinge on the interface between materials.

> An important component of the research to be carried out in the [Caltech] shock physics facility is the study of the interaction of strong shocks with material interfaces... Upon interaction with the shock, the material interfaces are impulsively accelerated and the resulting baroclinic generation of vorticity due to the misalignment of the resulting pressure and density gradients gives rise to the well-known Richtmyer-Meshkov instability and ultimately produces turbulent mixing that can contaminate or dilute the materials bordering the interfaces. The modeling and simulation of these Richtmyer-Meshkov instabilities and the resulting inhomogeneous anisotropic turbulence is a major thrust of the proposed research. *The instability process as well as the modeling of the resulting turbulence lies at the heart of many ASCI applications. An understanding of compressible turbulence and mixing is essential, for example, in important ASCI applications in which shock-driven implosion is a key step* (emphasis added).[69]

Here Caltech has subdivided this modeling effort into three stages: (1) the contact of the shock wave with the material interface, during which the initial vorticity is generated; (2) the growth of the layer at the material interface in which vortices have formed and mixing of the materials occurs; and (3) the ensuing compressible turbulent flow. These are some of the very complex phenomena, related to the turbulent mixing of plutonium and D-T in the primary (or lithium deuteride and uranium in the secondary), that had hitherto rendered computational modeling inadequate, forcing a continuing dependence on nuclear explosive testing to establish confidence in new or modified nuclear explosive package designs.

NOTES AND REFERENCE

1. Reportedly included in this purchase is an extensive library of plutonium and uranium equation-of- state (EOS) data gleaned from approximately 100 Soviet hydronuclear tests with nuclear yields under 100 kilograms. See Cochran, Paine, T.B. and C.E., *The Role of Hydronuclear Tests and Other Low-Yield Nuclear Explosions and Their Status Under A Comprehensive Test Ban*, Natural Resources Defense Council, Inc., Washington, D.C., (April 1995), p.16., and *USSR Nuclear Weapons Tests and Peaceful Nuclear Explosions, 1949 through 1990*, Physical Technological Center, Russian Federal Nuclear Center-VNIIEF, Sarov, (1996), p. 7., ISBN 5-85165-062-1.

2. Generally, "drivers" are external means of increasing the energy of fusion fuel, such as in the laser irradiation of a small capsule filled with a mixture of deuterium and tritium gas. If driven to a state where significant numbers of fusion reactions occur in the fuel, the energy released from the burned fuel may be deposited in the remaining unburned fuel, providing a second (potentially self-propagating) source of energy.

3. Research and development of more energetic high explosives within the SBSS program is discussed in "Transforming Explosive Art into Science," *Science and Technology Review*, Lawrence Livermore National Laboratory, (June 1997). (World Wide Web version: http://www.llnl.gov/str/06.97.html.)

4. *Sandia Lab News*, (September 15, 1995), p. 4.

5. *DOE This Month*, (October 1995), p. 5.

6. National Academy of Sciences Committee for the Review of the Department of Energy's Inertial Confinement Fusion Program, DOE Notes of Meeting held at Los Alamos and Sandia, (November 3–5, 1996), p. 4.

7. Referred to in this report as the "JASONs."

8. Cited in letter from JASON Members S. Drell and R.L. Garwin to Secretary of Energy Hazel R. O'Leary, (October 28, 1996), p. 2.

9. "Signatures of Aging," Study Leader: S. Drell, R. Jeanloz, JASON, The MITRE Corporation, (January 1998), JSR-97-320, p. 2.

10. "Our job is to help the U.S. Government to ensure that no one in the world doubts that the United States has the capability to project overwhelming force in the defense of its vital interests. Let me explain more fully what I mean by this statement.

The phrase "to ensure that no one in the world doubts" means that we are required to demonstrate the credibility of the science and technology that support our nation's nuclear stockpile. When the United States was conducting underground nuclear tests, any one in the world with a seismometer could measure the power of our weapons. These tests, along with missile flights and other systems tests, confirmed not only the capability of our weapons but also the strength of our resolve to maintain them in a safe and reliable condition. Now, in the absence of nuclear testing, some might be tempted to think that our capabilities and our resolve have deteriorated to the point where we would be unwilling or unable to use the weapons in our nuclear stockpile. We must not allow them that temptation.

The credibility of our stewardship activities has direct bearing on our nation's ability "to project overwhelming force in the defense of our national interests." Nuclear weapons are unique in their ability to inflict massive damage to a target—swiftly and surely. These criteria place them in a category fundamentally different from conventional weapons, or even chemical and biological weapons. Nuclear weapons are the "big stick" that defends our homeland and are the ultimate deterrent force against any potential aggressor." [Testimony of Siegfried S. Hecker, Director, Los Alamos National Laboratory, Hearing of the Subcommittee on Strategic Forces, Committee on Armed Services, United States Senate, March 19, 1997.]

11. Younger, Dr. Stephen, LANL Program Director, Nuclear Weapons Technology, *Weapons Insider,* (November/December 1996), pp. 1–2.

12. *Ibid.*

13. Program of the Thirty-Ninth Annual Meeting of the Division of Plasma Physics, Bulletin of the American Physical Society, Vol. 42, No. 10, accessible on the World Wide Web at http://www.aps.org/BAPSDPP97/.

14. Cauble, R., T. S. Perry, D. R. Bach, K. S. Budil, B. A. Hammel, L. B. DA Silva, P. Celliers, G. W. Collins, and R. J. Wallace, "Equation of State Measurements of NIF Ignition Capsule Ablator Materials," *Bulletin of the American Physical Society,* Vol. 42, No. 10, (1997), p. 2029.

In the experiments described by Cauble, the absolute equation-of-state (EOS) measurements for polystyrene (CH) at a pressures of 10–40 Mbar and beryllium (Be) at a pressures of 10–15 Mbar were performed by ablatively shocking the bromine(Br)-doped CH mounted directly in the hohlraum (a bromine dopant was used to increase the plastic's opacity for the back lighter x-rays, hence create a darker image relative to the sample). The images produced from the back lighter x-rays were two-dimensional, time versus position plots (position along the length of the Br-doped CH/CH or Be sample composite). The vu-graphs presented in Cauble's talk and Figure 2 in the *Physical Review Letters* article clearly show the shock front moving through the Br-doped CH, the shock front then moving through the sample, and the motion of the material at the Br-doped CH/sample interface. From this image, the shock wave velocity and particle velocity (after being shocked) can be extracted. These velocities serve to determine the Hugoniot (or shock adiabat) for a material which in turn can be used to determine the EOS.

15. Cauble, R., T. S. Perry, D. R. Bach, K. S. Budil, B. A. Hammel, G. W. Collins, D. M. Gold, J. Dunn, P. Celliers, L. B. Da Silva, M. E. Foord, R. J. Wallace, R. E. Stewart, and N. C. Woolsey, "Absolute Equation-of-State Data in the 10–40 Mbar (1–4 Pa) Regime," *Physical Review Letters,* Vol. 80, No. 6, (February 9, 1998), p. 1248.

16. QEOS is a Thomas-Fermi EOS model, referenced as More, R. M., K. H. Warren, D. A. Young, and G. B. Zimmerman, *Physics of Fluids*, Vol. 31, 3059 (1988). The SESAME EOS library is referenced as Lyon, S. P. and J. D. Jonhson, Los Alamos National Laboratory Report No. LA-UR-92-3407, (1992). "LLNL EOS" is referred to as "an extensively used EOS table" in the *Physical Review Letters* article, with a reference to the 1975 Livermore report by F. H. Ree, UCRL-51885.

17. Cauble, R. *et al., Bulletin of the American Physical Society,* Vol. 42, No. 10, (1997), p. 2029.

18. LANL, *Weapons Insider*, (March 1996), p. 2.

19. "ASCI Academic Strategic Alliance Program: Major Goals and Objectives," http://www.llnl.gov/asci-alliances/asap/goals.html, (Last modified November 27, 1996).

20. The list of attendees to the ASCI Alliances Pre-proposal Conference is given on the World Wide Web at http://www.llnl.gov/asci-alliances/asap/attendees.html, (Last modified December 20, 1996).

21. LANL, *op. cit.*, p. 2.

22. Representatives from the national nuclear weapons laboratories, the U.S. government, industry, and academia participated in the review process.

23. At the *Alliances Program* Pre-proposal Conference, Derrol J. Hammer (HPCC Group Leader, Procurement & Materiel, LLNL) listed "Relevance and practicality to ASCI goals" first on a vu-graph entitled "Preliminary Proposal Review." Hammer's vu-graph entitled "FINAL PROPOSALS" states that the "Unweighted evaluation will focus on strengths and deficiencies," but that the DOE will "Select Best Overall Combination of Disciplines to Meet ASCI Goals (We are not selecting "best proposals") (emphasis in original)."

24. "ASCI Strategic Alliances Program Research: Overview of the Background Papers," http://www.llnl.gov/asci-alliances/bb/001toc-bb.html, (Last Modified November 27, 1996).

25. Defense Programs would not make any information on these contracts available to Natural Resources Defense Council, beyond confirming that the University of California, Berkeley, had received Academic Strategic Alliances Program funding.

26. "Computer codes are special because they are central—they have it all together. It's obvious that we deny outsiders access to our [nuclear weapon] design information and [nuclear] test data; perhaps it is less obvious that for the same reasons we have to restrict what is said about the codes. Let me explain why that is and the kinds of questions an outside party, if he knew the evolution of our codes, would look at and exploit. He could ask, 'What are they working on new?' Or, 'What do they plan to develop?' He would infer that by which parts of the codes are markedly better than they were previously and which parts are the same. 'What physics topics are being improved and where is something being modeled not quite correctly and being improved?' This is important information to the other side, from which he might anticipate improvements in our weaponry. Finally, 'Which thing are they not doing correctly, and what does that imply in terms of design weaknesses of their weaponry that they may not even appreciate?;' " from Henderson, D. B., "Computation: The Nexus of Nuclear Weapons Development," in Metropolis, N., D. H. Sharp, W. J. Worlton, & K. R. Ames, eds., *Frontiers of Supercomputing*, University of California Press, (1986), p. 143.

27. The National Ignition Facility (NIF) and the Issue of Nonproliferation, Final Study Prepared by the U.S. Department of Energy, Office of Arms Control and Nonproliferation (NN-40), (December 19, 1995), pp. 26–27.

28. *Ibid.*

29. *Ibid.*, p. 57.

30. *Ibid.*, p. 41.

31. NAS Committee, DOE Notes for August 1–2, 1996, p. 10.

32. NAS Committee, DOE Notes for Nov. 3–5, 1996, p. 8.

33. Matzen, M. Keith, "Z Pinches as Intense X-ray Sources for High-Energy Density Physics Applications," *Physics of Plasmas*, Vol. 4, Number 5, (May 1997), pp. 1519–1527.

34. "September 1997 Highlights of the Pulsed Power Inertial Confinement Fusion Program," Sandia National Laboratory, http://www.sandia.gov/pulspowr/hedicf/highlights/hir9709.html.

35. "Z Machine on another dramatic climb toward fusion conditions," *Sandia Lab News*, (February 27, 1998), p. 1.

36. *Ibid.*, p. 4.

37. Singer, Neal, "Sandia formally proposes to design accelerator expected to produce high-yield fusion: Z machine achieves final milestone; proposed X-1 next big step," *Sandia Lab News*, Vol. 50, No. 7, (April 10, 1998), p. 1.

38. U.S. DOE, Pulsed Power Research Center, Sandia National Laboratories, undated (c. 1995).

39. Menikoff, R., K. Lackner, N.L. Johnson, S. Colgate, and J. Hyman, "The Design of Gifthorse (U)," Los Alamos National Laboratory document LA-11910-PR; *Defense Science*, (1990), pp. 20–28. Johnson, N. L., K. Lackner, J. Hyman, R. Menikoff, and A. Juveland, "History of Computations in Gifthorse (U)," Los Alamos National Laboratory document LA-11910-PR; *Defense Science*, (1990), pp. 23–24. Colgate, S., M. George, P. Gobby, B. Gillespie, R. Steele, L. Veeser, N.L. Johnson, K. Lackner, and R. Menikoff, "Construction and Testing of Gifthorse (U)," Los Alamos National Laboratory document LA-11910-PR; *Defense Science*, (1990), pp. 29–38. Menikoff, R., K. Lackner, N.L. Johnson, S. Colgate, and M. George, "Results from a Recent Gifthorse Experiment (U)," Los Alamos National Laboratory document LA-11910-PR; *Defense Science*, (1990), pp. 46–57. Johnson, N. L., K. Lackner, R. Menikoff, S. Colgate, and J. Colvin, "Future Directions for Gifthorse (U)," Los Alamos National Laboratory document LA-11910-PR; *Defense Science*, (1990), pp. 58–62.

40. Magraw, K., "Teller and the 'clean bomb' episode," *Bulletin of the Atomic Scientists*, (May 1988), p. 32.

41. *The III-rd Zababakhins Scientific Readings (abstract of reports)*, Dalnaya Dacha, Chelyabinsk region, Ural, USSR, (January 14–17, 1992).

42. "Russian Collaborations on Megagauss Magnetic Fields and Pulsed-Power Applications," http://www.p22web.lanl.gov/group/russian/html.

43. Statement of Robinson, C. Paul, Director, Sandia National Laboratories, Committee on Armed Services, United States Senate, (March 13, 1996), p. 10.

44. Jones, Suzanne L. and Frank N. von Hippel, "Transparency Measures for Subcritical Experiments Under the CTBT," *Science and Global Security*, Vol. 6, 1997, pp. 291–310. See also, Paine, C., "Memo to: Ralph Earle, Deputy Director, ACDA Concerning the Status of Gas-Dynamic (Impact) Fusion Experiments under a CTB," (February 22, 1996), p. 2, (unpublished memo in NRDC files).

45. JSR-94-345, JASON/The MITRE Corp., (August 10, 1994), pp. 17–22.

46. JSR-94-345, p. 20.

47. Kidder, R.E., Report to Congress: Assessment of the Safety of U.S. Nuclear Weapons and Related Nuclear Test Requirements, UCRL-LR-107454, (July 26, 1991), p. 6.

48. From 1990–92, Professor Drell advised the U.S. Congress and the defense establishment that further testing was needed to develop "safer" versions of several U.S. warheads prior to a test ban. Congress, the Joint Chiefs of Staff, and the incoming Clinton Administration determined that the recommended warhead and missile rework program, costing billions, would result in DOE contractor and military personnel radiation exposure and injury risks that equaled or exceeded the risks to the public from the postulated warhead plutonium dispersal accidents, the probability of which could be reduced (if not entirely eliminated) by modifications in handling and storage procedures. Under the terms of the Hatfield-Exon-Mitchell Amendment, the temporary moratorium imposed by Congress in September 1992, twice extended by the Clinton Administration, became permanent after September 30, 1996 unless the President certifies to Congress that another country has conducted a nuclear explosion after that date. The Comprehensive Test Ban Treaty was opened for signature at the United Nations in September 1996.

49. JSR-94-345, p. 17.

50. Sandia Report SANDS95-2751, *Stockpile Surveillance: Past and Future*, p. 8 and Figure 4.

51. Letter from Robert L. Puerifoy, former Vice- President for Technical Support, Sandia National Laboratory, to Senator Pete Domemici (R-NM), (December 17, 1997), Appendix 10, "Comments on Prepared Statement of Dr. Victor H. Reis, Assistant Secretary of Energy for Defense Programs, October 17, 1997," p. 1.

52. JSR-94-345, p. 17.

53. JSR-94-345, p. 18.

54. Katz, J.I., "The Case Against Scientific Stewardship," Department of Physics, Washington University, St. Louis Mo. 63130, (undated, circa late 1994).

55. "PBXs (Plastic Bonded Explosives) are typically used as maincharge explosives in nuclear weapons. PBXs in current use include LX-10 and LX-17. LX-10 is a very energetic explosive based on HMX that uses Viton A (vinylidine fluoride/hexafluoropropylene copolymer, made by DuPont) as a thermoplastic binder; it is used in the W68 and W79 weapons. LX-17 is a less energetic TATB-based explosive that uses thermoplastic Kel-F 800 (chlorotrifluoroethylene/vinyliding fluoride copolymer, made by the 3M co.) as a binder. LX-17 is considered an IHE (Insensitive High Explosive) because TATB is a highly insensitive explosive that does not readily detonate accidentally. It is used in several modern nuclear weapons, including the B83, W84, and W87." From "Formulating High Explosive Materials," *Energy and Technology Review*, Lawrence Livermore National Laboratory, (February 1988), p. 25.

56. "A Facility for Simulating the Dynamic Response of Materials," California Institute of Technology, (August 14, 1997), Section 2.2.1, p. 1. The Caltech Alliances Program proposal is available on the World Wide Web at: http://www.cacr.caltech.edu/~jpool/ASAP/proposal/. Note that this quote could also describe the overarching Stockpile Stewardship and ASCI problem: current weapons codes lack a full physics description and rely on test data for calibration. As high explosives play such an important role in nuclear weapons, the relevance of the quote to SBSS is more than just analogy.

57. Caltech refers to this as the "micromechanical level" of simulation.

58. "A Facility for Simulating the Dynamic Response of Materials," Section 2.2.1, p. 1.

59. AMRITA is an acronym for "Adaptive Mesh Refinement Interactive Teaching Aid."

On April 16, 1997, Professor James J. Quirk gave a lecture on AMRITA at his institution, Caltech. The talk abstract includes this descriptive information: "Although Adaptive Mesh Refinement (AMR) algorithms have matured to the point where they provide a robust, economical means of computing flows governed by disparate physical scales, because of their high development costs, they have failed to impact on the grass roots scientific community to the extent they deserve. In an effort to improve this situation, albeit in one small area of computational fluid dynamics (CFD), I have unified my own software tools to form an operating system (Adaptive Mesh Refinement Interactive Teaching Aid) which can be used as a jump-start by anyone interested in gaining a toehold in the world of AMR. AMRITA's web page is currently http://www.galcit.caltech.edu/~jjq/. Professor Quirk is a co-investigator on the Caltech *Academic Strategic Alliances Program* grant. In section 2.4 of Caltech's proposal ("Collaborations with ASCI Laboratories"), it states: "J. Quirk and J. Shepherd are investigating the application of AMRITA to detonation problems of interest to the DX (Dynamic eXperimentation) group at LANL."

60. "A Facility for Simulating the Dynamic Response of Materials," Section 2.2.1, p. 1

61. *Ibid.*

62. "Facility for Simulating the Dynamic Response of Materials," Section 2.2.2 Modeling dynamic response of solids, p. 1.

63. Caltech claims that beryllium and uranium modeling was not funded by the DOE. Even if true, however, extending the Caltech model to nuclear weapons materials is a simpler exercise than initially developing the model.

64. *Ibid.*, p. 2.

65. "Facility for Simulating the Dynamic Response of Materials," Section 2.2.3 First principles computation of materials properties, p. 1.

66.The following data were classified under U.S. classification rules for equation-of-state calculations and data prior to December 1997 (*Drawing Back the Curtain of Secrecy: Restricted Data Declassification Policy, 1946 to the Present,* RDD-1, June 1, 1994, U.S. Department of Energy (http://www.doe.gov/html/osti/opennet/document / rdd-1/drwcta.html):

h. The equation-of-state (EOS) studies for all elements under conditions other than those revealing classified information. (67-1)

i. Information on EOS and opacities of certain materials not of significance to weapon design. (72-11)

j. The calculated EOS data from theoretical models for certain materials (for Z less than 72 all materials; but for Z=72 and higher, only materials at pressures whose EOS data is not useful for designing nuclear weapons). (83-6)

k. Information concerning EOS:

(1) Static data for Z of 93 and 94 at pressures equal to or less than 20 kb. (89-1)

(2) Static data for Z greater than 94 at pressures equal to or less than 1 Mb. (89-1)

The classified versions of these classification rules are more specific. The set of elements heavier than lutetium (Z=71, where Z is the charge of the atomic nucleus or equivalently the number of protons or electrons in the atom) contains elements for which equation-of-state data is "useful for designing nuclear weapons." For neptunium (Z=93) and plutonium (Z=94), the range of pressures for which equation-of-state data and calculations are unclassified is explicitly defined. Caltech states in its Alliances Program research proposal (p.2):

> We propose to apply the method we used for Fe [Iron] to study a range of 3d, 4d, and 5d transition metal equation of state to ultra high pressure (1 TPa)... however, some systems [to which the method is applied] lead to enormous errors and problems are encountered with excited states and with actinides. We propose two approaches to solving this problem...

The 5d transition metals span hafnium (Z=72) through gold (Z=79): within the mass range for which classification guidelines may apply. As noted above, classification guidelines apply explicitly to actinides.

67. "Report of the Fundamental Classification Policy Review Group," Dr. Albert Narath, Chari, Unclassified Version (Classified Material Has Been Removed), Issued by the Department of Energy, (December 1997), pp. 30–31.

68. *Ibid.*, p. 31.

69. "A Facility for Simulating the Dynamic Response of Materials," Section 2.2.4 Compressible turbulence and mixing, p. 1.