SUBCRITICAL EXPERIMENTS

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JSR-97-300

March 1997

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1.1 Executive Summary

The authors, a subgroup of JASON, reviewed the first two sub-critical experiments (SCEs) now planned, called Holog and Rebound, to be performed underground at the Nevada Test Site (NTS). We conclude that:

a. They will add valuable scientific information for understanding physical properties of plutonium (Pu) under conditions relevant to the performance of primaries of nuclear weapons.

b. For these particular experiments, no conceivable scenario will lead to criticality. Therefore these experiments are consistent with the provisions of the CTBT signed by President Clinton on September 24, 1996.

c. While the peer review process was adequate for these two tests, we are not satisfied that the process is adequate as a model for future experiments.

While there is no question that US stockpile nuclear weapons would function today as designed, there are gaps in the scientific understanding of their performance. The Science Based Stockpile Stewardship and Management Program (SBSSMP) is charged to fill these gaps through "programs in theoretical and exploratory nuclear technology which will attract, retain, and ensure the continued application of our human scientific resources to those programs on which continued progress in nuclear technology depends."

A program of SCEs in SBSSMP properly inter-relates with other experiments, diagnostic studies, and simulations. Our subgroup did not review Holog and Rebound in this broad context. The nature of these particular tests makes the analysis of their potential criticality and containment straightforward. However, as part of our charge to examine the peer review process, we recognized that future SCEs could pose more complex questions. This led us to discuss issues that need to be addressed in developing the broader scientific program of SCEs and we comment on them in this report. Several important questions to be answered in developing program plans are the following:

a. What data will be valuable for retaining confidence in the safety, reliability, and performance of the enduring stockpile? More specifically, what gaps should be filled in our present knowledge of the equation of state, constitutive relations, surface properties, ejecta, spall effects, and phase changes of Pu under conditions of an explosion in order to improve predictions of the performance of a bomb primary?

b. If material changes due to radiation and possible corrosion are seen in aging bombs in the stockpile, what additional data relevant to the properties and behavior of the boost cavity during the primary implosion are required?

c. What data and understanding of physical properties of Pu relevant to weapon performance are required for predicting possible performance differences of new primaries that are manufactured by various methods of production?

The answers to such questions will provide guidance for developing an efficient, cost effective, and environmentally safe program of SCEs, some of which may be better performed above ground or at sites other than NTS.

1.2 Relevance of Holog and Rebound

Holog and Rebound are the first two proposed SCEs and the only ones that we reviewed. Both experiments will be performed underground at the U1A (formerly LYNER) facility at NTS. These two experiments involve limited quantities of plutonium and high-explosives in distributed configurations. They utilize well established techniques of materials science experiments. While we will continue to label these experiments as subcritical, in keeping with accepted usage, we note that they are not weapons tests at all, but weapons-related physics tests in which the nuclear properties of plutonium play no role.

In Holog there are two explosive-driven configurations with point initiation, designed to characterize ejecta production from shocked Pu in a flat plate geometry. Holographic measurements will be made of the size distribution and of the velocity vs size correlation of the emerging particles. One configuration will use close to 50 grams of high explosive to shock a flat plate target with an aggregate of 77.5 grams of plutonium on the surface. The other will use involve 50 grams of high explosive to shock a flat plate with 50 grams on the surface.

The Rebound configuration uses high-explosive driven flyer plates to generate planar-shock waves in an array of coin-sized samples of plutonium. The goal of these measurements is to obtain data over a range of high pressures as input for more accurate determination of the Pu equation of state. There will be three separate experimental stands. For the high pressure studies, 462 grams of Pu will be shocked by a metal flyer plate driven by 81 pounds of high explosive to create a maximum pressure of 2.3 megabars (Mbars); the corresponding numbers for medium pressure studies are 424 grams of Pu, 51 pounds generating 1.7 Mbars peak; and for low pressure studies, 589 grams of Pu, 28 pounds generating 0.8 Mbars.

There is no claim that the data from these experiments are needed immediately as part of the SBSSMP in order to retain confidence in the reliability and performance of the U.S. stockpile, but they are sensible ones to start with and there is merit in initiating them at existing facilities. The experience gained will help guide the future SBSSMP SCE program.

1.3 Program Aspects

In developing a program of SCEs over the long term, it will be important to identify and focus on those measurements critical to a successful stewardship program under a CTBT. The subcritical tests should be carried out within the context of a broader program including static and dynamic experiments above ground. It is only on the basis of numerous laboratory (above-ground) experiments investigating the material properties of a wide variety of analog materials, as well as static experiments on Pu, that the sub-critical experiments can be properly formulated and analyzed. A combination of laboratory experiments and materials theory must play a crucial role in supporting a program of science-based stewardship.

The scientific motivation for underground experiments is to examine the dynamic properties of Pu-containing sample assemblies. However, Pu can be studied over a significant portion of the appropriate pressure-temperature range in conventional static experiments, above ground. For thermodynamic properties, the static and dynamic results should be in close agreement; the two experimental approaches offer a means of independently validating the results. Because static experiments are far easier to perform than explosive-driven subcritical tests (with turn-around times of hours to days, rather than several weeks or months), there is much to be learned from experiments above ground, including determinations of phase diagrams (solid-solid and melting), equations of state and strength over a wide – and relevant – range of pressures and temperatures. The greater pace of laboratory experiments allows for quicker response to experimental findings.

Current regulations dictate that Holog and Rebound be performed at NTS. Possible changes in the rules imposed by regulatory authorities may affect how and where future SCE's are performed. For example, events involving the NTS at the local level, or of international agreements requiring full transparency of experimental facilities may make experiments at the NTS impossible. The stewardship program should be prepared for such changes of the rules and design a facility for above-ground subcritical experiments that could be built and put into operation, without undue delay.

We recommend that containment designs and processes be explored to reduce the cost of experiments and to provide more flexibility, subject to analysis of their safety and determination of their sub-critical nature. In this context, it is the possibility of forming jets, such as are produced by shaped charges in non-planar geometries, that increase the cost of containment and the difficulty of doing above-ground experiments. Nevertheless, the advantages of above-ground facilities are great and planning and design should go forward to make them available, should they be permitted.

To the degree that there is concern about relating static and dynamic measurements, for example of strength or other time-dependent mechanical properties, it is profitable to examine a variety of Pu analog materials under both static and dynamic conditions. Though more demanding than the static experiments, above-ground dynamic experiments are logistically far easier to perform than underground tests, and have much shorter turn-around times.

They are essential for developing a fundamental understanding of relevant material properties at a robust enough level to allow detailed simulation.

A broad understanding of material properties is required to address problems associated with either "aging," or surface preparation and texture of samples. The effects of surface preparation and texture need to be studied in a variety of materials in order to be reliably understood, for example via micromechanical models (e.g., atomistic and continuum models of defects). Similarly, radiation effects of aging can be examined in analog materials. As aging can involve the creation of new phases or compounds (e.g., through corrosion), there is a strong incentive for pursuing experiments on a wide variety of materials other than Pu.

Materials theory plays a crucial role in bolstering confidence in simulations. A basic understanding of the underlying processes is desirable, especially for simulations under new conditions. For example, it is necessary to develop quantitative models of radiation damage and corrosion if the effects of aging are to be reliably understood. A hierarchy of theoretical models, from ab-initio quantum theory to semi-empirical statistical mechanics (e.g., lattice dynamics and molecular dynamics) and micromechanics (e.g., atomistic and continuum) can, in principle, address this problem. Theoretical approaches require a basis of experiments on a wide variety of materials examined over a broad range of pressures and temperatures.

The three weapons labs have substantial expertise in condensed matter theory and materials science, and in associated computational simulation. Theory and simulation cannot obviate experiment in the forseeable future, but they provide a framework within which to lay out an experimental strategy, and help understand experimental results. Moreover, the ASCI program can be expected to enhance and deepen expertise in simulation over the coming years.

The value of integrating above-ground experiments and theory on the one hand, with the subcritical experiments on the other, is twofold. First, the diversity of approaches used and materials studied provide an important check on the reliability of results that are used as input for simulations: static and dynamic experiments should agree with each other when interpreted by theory; and it is important to understand why the results for different materials do or do not agree with each other. Second, because the objective is to have a robust understanding of material properties, experiments should be designed to test specific scientific questions.

Each subcritical experiment should answer specific questions that cannot be resolved by theory and above-ground experiments. The approach can be outlined in terms of a matrix designating studies of increasing difficulty, hence decreasing frequency:

			Difficulty →
	Samples:	Non-Pu	Pu
	THEORY	+	+
	EXPERIMENTS		
Difficulty ↓	Static (Lab)	+	+
	Dynamic (Lab)	+	–
	Underground	–	+

Studies not involving special problems are indicated by “+”. Those that do are indicated by “–”: above-ground dynamic experiments on Pu face major regulatory hurdles, whereas underground experiments on non-Pu targets are generally not cost effective. A combination of dynamic laboratory experiments on analog materials and static experiments on both Pu and analog materials should be used to refine the issues that can only be resolved by subcritical experiments. Support of static and dynamic laboratory experiments with a small fraction of the effort put into subcritical experiments would yield a major increment in basic understanding, and hence reliability of simulations.

1.4 Peer Review of Criticality

We are satisfied, on the basis of the evidence presented to us, that the experiments Holog and Rebound cannot result in the assembly of a critical configuration of Pu. The peer review of the Livermore experiment, Holog, by a Los Alamos expert, and of the Los Alamos experiment, Rebound, by a Livermore expert added to our confidence in the safety of these experiments. Although the process was adequate for these two tests, we are not satisfied that it is unambiguous and strict enough to handle future experiments which may come closer to the margin of criticality. The review process consisted of theoretical calculations of criticality of extreme configurations that are "obviously" closer to critical than any configurations that could arise in the course of an experiment that might go awry. The calculated configurations were found to be subcritical by a comfortably wide margin, and that was the end of the peer-review process.

This process is vulnerable to criticism on two counts: (1) No discussion was presented on the limits of error of the theoretical calculations. (2) No analysis was presented of possible ways in which specific experiments could go awry. It is not obvious "a priori" that with a limited quantity of explosive the most dangerous configuration necessarily has all the Pu lumped together. It would be helpful to apply to this peer-review process methods used in modern risk-based safety analyses. We recommend that, in future peer-review of subcritical experiments, various kinds of "maximum credible accidents" should be defined and analyzed in detail.

As requested, we assessed the process of peer-review only in the narrow context of assuring the subcriticality of experiments. In a wider context, an independent review process should also address the scientific importance and cost-effectiveness of proposed SCEs. By this process, inconsequential and redundant experiments could be discouraged, time and money could be saved, and the focus of the stewardship program could be sharpened.

1.5 Diagnostics and Criticality

The diagnostics on Holog will include three separate detectors that can place an upper limit on any unexpected nuclear yield, on the order of 1 mg HE-equivalent (or 1 nanoton). This limit appears to be the smallest yield that can be reliably measured with reasonable effort given the current state of the art. These detectors are well conceived, will add to the assurance that no unplanned nuclear processes occur, and should be included in possible future subcritical experiments. We look forward to reviewing results from them after this experiment. Detectors such as these may provide enhanced future transparency of treaty compliance, and should be located outside the containment barrier.

The planned detectors will be sensitive to prompt fission neutrons, prompt γ's produced in (n, γ) reactions, and delayed γ's arising from decay of fission products. They are within the state of the art and well chosen. It would be wise to carry out quantitative analyses on two fronts. First, it would be good to document the sensitivity of the detection system, *i.e.,* to determine the energy release threshhold for detection. Second, an analysis should be carried out concerning the possibility of false positive signals.

Given the redundancy of detectors, we have no reason to think that false positives will pose a real problem, but the threshhold of tolerability of false signals is likely to be low in a cooperative verification regime.

The CTBT, in accord with its negotiating record, forbids explosions that produce any nuclear yield. The U.S. interprets this to mean that experiments in which conventional high explosives assemble a critical mass of fissionable material are prohibited. However, it is difficult to measure the criticality of a briefly assembled, barely critical mass, as any self-generated nuclear energy will be many orders of magnitude less than the yield figure of 1 mg. Therefore any feasible diagnostic measuring the actual degree of subcriticality would require an external source of neutrons. In the current state of the art, a direct criticality measurement is not impossible but is fraught with difficulty; it would require irradiation of the sample by a strong external neutron source during the experiment. This would seriously interfere with other diagnostics, and could possibly produce a false positive measurement. We therefore believe that the omission of a criticality measurement on these two experiments is the correct choice.