NUCLEAR TESTING AND THE 1992 MORATORIUM

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PREFACE

Nuclear testing has been an issue for more than three decades. Currently there are four treaties that limit nuclear testing: the Limited Test Ban Treaty of 1963 which bans testing in the atmosphere, in space, and under water; the 1968 Treaty on Non-Proliferation of Nuclear Weapons; the Threshold Test Ban Treaty of 1974 and the Peaceful Nuclear Explosions Treaty which limit explosive yield to less than 150 kilotons of TNT. Of these, U.S. commitments under the Non-Proliferation Treaty are often cited as a reason for additional restrictions on nuclear testing.

The actual relationship between nuclear testing by the principal nuclear weapon states and proliferation to Third World nations would appear to be tenuous at best. Given the cost and commitment necessary for these nations to develop nuclear weapons, testing by the five principal weapon states in and of itself cannot constitute an adequate incentive to initiate a nuclear weapons program. On the other hand, if testing violated an internationally accepted norm, this would have to be an important factor in the decision of a nation to initiate a program.

Whatever the actual relationship between testing and proliferation, Third World nations are likely to use the test ban issue as part of a bargaining strategy at the 1995 NPT review. Consequently, the ability of the U.S. to enter into treaties imposing additional testing restrictions may be of significant *political* value. It is therefore important that the U.S.G. has technical guidance on the feasibility of additional testing restrictions that is free of institutional bias. It is hoped that this report may serve as a step in that direction.

EXECUTIVE SUMMARY

The body of this report lays out the political and technical issues surrounding nuclear testing in what is hoped is a relatively impartial manner. However, it would be a dereliction of responsibility to not explicitly discuss the implications of this study. The Hatfield Amendment, President Clinton's extension of the moratorium on testing, and the approaching 1995 Non-Proliferation Treaty (NPT) review conference mandate that this be done.

The first, and perhaps most important implication is that **nuclear stockpile reliability can be maintained into the indefinite future without *nuclear* testing.** It will be necessary, however, to maintain the availability of specific materials as well as a cadre of expert personnel to perform inspection and non-nuclear testing. There are a number of activities closely related to those of nuclear weapons design that could be used to maintain the expertise of weapons designers. If this is done, it will be possible to have confidence in the reliability of remanufactured nuclear weapons without nuclear-weapon design engineers and scientists who have benefited from direct experience with nuclear explosive tests.

The Hatfield amendment mandates that the President submit to the Committees on Armed Services of the Senate and House of Representatives reports containing: "A schedule for resumption of Nuclear Testing Talks with Russia [and a] plan for achieving a multilateral comprehensive ban on the testing of nuclear weapons on or before September 30, 1996." **There are three reasons why a comprehensive test ban (CTB) is currently in the national interest:**

I. Whatever the actual relationship between testing and proliferation, a group of NPT signatories has made extension of the NPT in 1995 conditional on the signing of a comprehensive nuclear test ban by the nuclear weapon states.

> Thus, while many believe the decision to initiate a nuclear weapons program and testing by the advanced weapon states are only remotely related, Third World nations are likely to use the test ban issue as part of a bargaining strategy at the 1995 NPT review. Consequently, the ability of the U.S. to enter into treaties imposing additional testing restrictions may be of significant *political* value.

The NPT, with 130 signatories, is the most widely adhered to arms control agreement in history. It constitutes the cornerstone of international efforts to prevent the further spread of nuclear weapons. Placing it in jeopardy for narrow institutional interests, or minor improvements in performance or "safety," does not make sense.

II. Without a nuclear test, few countries would be willing to invest in building a militarily significant arsenal.

> If the testing of nuclear weapons violated an accepted international norm, there would be considerable political cost to a nation performing a test. Indeed, the penalty could be raised under a CTB. But even the prospect of violating such a regime would be unlikely to affect existing nuclear weapon programs such as those in Iran and North Korea, although it might affect the decision to test.

III. It is not in the interests of the United States to have the Russians restart their test program.

> If the United States does not negotiate a nuclear test ban with the Russians under the timetable specified by the Hatfield Amendment, it is likely that a so-called "red-brown" coalition of elements of the former Communist party and the "National Patriotic Russian Front" will force a reinitiation of the Russian test program.

Much has been made of the issue of yield predictability for the primary of nuclear weapons. In fact, the record of yield predictability is remarkably good. This impressive record would not have been possible if U.S. weapons were not comfortably tolerant of the small variations in materials and manufacturing that accompany any practical production process. This is particularly well illustrated by the excellent performance of the new primary designs the very first time they were tested.

This does not mean, however, that changes should be introduced into weapons during a CTB to achieve minor improvements in performance or "safety." Such changes could contribute to the perception that the stockpile will degrade over time. *In the future, new delivery systems should be designed around the wide spectrum of existing nuclear weapon designs, thereby avoiding any possibility of degrading confidence in the stockpile under a CTB.*

1.0 NUCLEAR TESTING: WHY IS IT AN ISSUE?

Nuclear testing has again become an issue for both technical and political reasons. The political reasons are related to the Russian and French moratoria following the break up of the Soviet Union, the Hatfield Amendment, and the approaching 1995 Non-Proliferation Treaty (NPT) review conference; technical issues revolve around the safety, reliability and effectiveness of the nuclear weapons stockpile.

1.1 The Hatfield Amendment: Section 507 of the FY93 Energy and Water Development Appropriations Act (Public Law 102-377).

This law states that: "Hereafter, funds made available by this Act or any other Act for fiscal year 1993 or for any other fiscal year may be available for conducting a test of a nuclear explosive device only if the conduct of that test is permitted in accordance with the provisions of this section." In other words, all future nuclear testing must be conducted in accordance with this law.

The law imposes a nine month moratorium: "No underground test of a nuclear weapon may be conducted by the United States after September 30, 1992, and before July 1, 1993."

For each year after March 1, 1992 the Act requires the President to submit to the Committees on Armed Services of the Senate and House of Representatives reports containing: "A schedule for resumption of Nuclear Testing Talks with Russia [and a] plan for achieving a multilateral comprehensive ban on the testing of nuclear weapons on or before September 30, 1996." It furthermore specifies that: "No underground test of nuclear weapons may be conducted by the United States after September 30, 1996, unless a foreign state conducts a nuclear test after this date, at which time the prohibition on United States nuclear testing is lifted."

It may appear that the phrase "unless a foreign state conducts a nuclear test" would allow the U.S. to resume testing if France, China or a Third World proliferator conducted a test. Technically this may be true, but it is unlikely to be politically feasible to resume testing unless Russia breaks the moratorium.

During the period from July 1, 1993 to September 30, 1996, the Act allows very limited nuclear testing to introduce modern safety features (insensitive high explosive, fire-resistant pits or enhanced detonation-safety systems) into warheads where a cost-benefit analysis indicates the necessity. Only five tests may be conducted per year up to a total of fifteen for the four year fiscal period beginning with fiscal year 1993. Significant yearly reporting provisions are imposed on the President, and Congress may disallow tests even for introducing safety features if it passes a joint resolution disapproving of the President's report.

In addition, one test of the reliability of a nuclear weapon may be conducted during each reporting period until September 30, 1996, but only if the President certifies that it is vital to the national security interests of the United States and if Congress does not agree to a joint resolution disapproving the test.

One of the most important provisions of the Hatfield Amendment is the restriction that allows testing to introduce modern safety features only into warheads that will be in the *active* stockpile on September 30, 1996. This means that the Department of Energy cannot test to introduce safety features into weapons that will not be deployed by the Department of Defense. This conclusion derives from subparagraphs (C), (F), and (G):

> "(G) ... a total of 15 tests in the 4-fiscal year period beginning with fiscal year 1993, that are necessary in order to ensure the safety of each nuclear warhead in which one or more modern safety features are installed pursuant to the plan referred to in subparagraph (F)."
>
> "(F) A plan for installing one or more modern safety features in each warhead identified in the assessment referred to in subparagraph (C) ..."
>
> "(C) An assessment of the number and type of nuclear warheads that will remain in the United States stockpile of active nuclear weapons on September 30, 1996."

Thus, without a commitment from the services to deploy safety upgraded warheads, testing to introduce modern safety features will not be consistent with the provisions of the Hatfield Amendment.

1.2 The Test Ban Readiness Program: Section 1436 of the FY 89 National Defense Authorization Act.

The creation of a Test Ban Readiness Program was the principal recommendation of the October 1987 Kidder report (discussed in greater detail in Section 3.2). Kidder argued that what is needed today "is a Readiness Program whose purpose is to ensure that the U.S. is in good position to maintain the reliability of its stockpile of nuclear weapons in the absence of nuclear explosive tests."

Section 1436 of the FY 89 National Defense Authorization Act requires that the Secretary of Energy "establish and report a program to assure that the United States is in a position to maintain the reliability, safety, and continued deterrent effect of its stockpile of existing nuclear weapons designs in the event that a low-threshold or comprehensive ban on nuclear explosives testing is negotiated and ratified within the framework agreed to by the United States and the Soviet Union." Note the reference to "*existing nuclear weapons designs*."

The purpose of the program is:

"(1) To assure that the United States maintains a vigorous program of stockpile inspection and non-explosive testing so that, if a low-threshold or comprehensive test ban is entered into, the United States remains able to detect and identify potential problems in stockpile reliability and safety in existing designs of nuclear weapons.

(2) To assure that the specific materials, components, processes, and personnel needed for the remanufacture of existing nuclear weapons or the substitution of alternative nuclear warheads are available to support such remanufacture or substitution if such action becomes necessary in order to satisfy reliability and safety requirements under a low-threshold or comprehensive test ban agreement.

(3) To assure that a vigorous program of research in areas related to nuclear weapon science and engineering is supported so that, if a low-threshold or comprehensive test ban is entered into, the United States is able to maintain a base of technical knowledge about nuclear weapons design and nuclear weapons effects."

Under this program, the viability of the stockpile is to be assured by stockpile inspections, non-explosive testing, and maintaining the availability of special materials. A base of technical expertise is to be maintained by research into areas related to nuclear weapon science. The research proposed is not intended to augment the understanding of nuclear weapons science, or improve current "predictive capability."

1.3 Current Issues

There are two principal issues that can be summarized in the form of two assertions:

(1) The United States should negotiate a nuclear test ban with the Russians under the timetable specified by the Hatfield Amendment because:

- If this is not done, a so-called "red-brown" coalition of elements of the former Communist party and the "National Patriotic Russian Front" will force a reinitiation of the Russian test program. This is patently not in the best interests of the United States.

- Significant progress towards a comprehensive test ban must be achieved before the next NPT review in 1995.

(2) The United States should resume nuclear testing to:

- Assure the safety, reliability and effectiveness of the nuclear stockpile.

• Maintain the technical expertise needed to design and produce nuclear weapons.

• Develop the computational capability to predict with accuracy all aspects of nuclear weapon performance including effects on performance from changes in weapon design or configuration.

1.3.1 Restarting the Russian Nuclear Test Program

While arguments relating the proliferation of nuclear weapons and testing by the advanced weapon states may not be compelling to some (see Section 1.4), few would argue that the resumption of nuclear testing by Russia does not have significant national security implications.

The Commonwealth of Independent States (CIS) and Georgia, the U.S., Japan, the Russian Federation and the European Community have taken the unprecedented step of creating an International Science and Technology Center to provide weapon scientists in the CIS and Georgia, particularly those who possess knowledge and skills related to nuclear weapons, opportunities to redirect their talents to peaceful activities. Congress has appropriated $400 million to fund this activity under the Soviet Nuclear Threat Reduction Act. While there are differing views as to the underlying motivations for creating the Center, one effect of its existence and funding is to help reduce political pressure from the nuclear weapon laboratories, Chelyabinsk-70 and Arzamas-16, to resume testing.

If experience in the U.S. is pertinent, a reduction in political pressure from these laboratories may constitute a high leverage method of reducing the incentive to initiate other military programs. Consider, for example, the past relationship between the LLNL nuclear-pumped x-ray laser program and the initiation of the Strategic Defense Initiative; the current LANL effort to promote so-called "mini-nukes" or low-yield nuclear weapons for a special class of targets; and past efforts to promote enhanced EMP warheads despite the limited efficacy of these weapons against non-civilian systems or, from a military perspective, the obvious kill assessment issue.

1.3.2 The Safety, Reliability and Effectiveness of the Nuclear Stockpile

The assertion that one could not have confidence in the continued reliability and effectiveness of the nuclear weapon stockpile under a Low-Threshold Test Ban (LTTB) treaty or Comprehensive Test Ban (CTB) treaty has been made by the DOE and its weapon laboratories for many years. This position has become increasingly contentious since the mid-1980s. It is the subject of the October 1987 Kidder report which will be discussed in Section 3.2.

The Department of Energy has also addressed the issue of whether nuclear weapons could be remanufactured without nuclear testing. Section 3131 of the FY '90 National Defense Authorization Act required the Secretary of Energy to prepare a report on this issue. The language of the Amendment did not, however, specify that the remanufacture should be to original specifications. The DOE therefore assumed as a basis for the study[1] that "with the recent Congressional and Departmental (both Defense and Energy) emphasis on nuclear weapon safety, ... no existing design would be remanufactured without upgrades, where necessary, to incorporate modern safety features." The second phase of the study concluded that "remanufacture of most existing weapons could probably be accomplished." In some instances (for older weapons), "significant development engineering would be necessary to re-establish capabilities which no longer exist in the weapons complex. Also, to ensure reliability, at least one nuclear test would be required to certify any weapon which has been out of production for an extended period."

In general, the report concluded, "nuclear testing would be required in order to certify weapon performance for any remanufactured design, with or without safety upgrades." The key word is the term "certify." This means that the yield can be specified to within a small range. This is discussed in detail in Section 2.0.

Concerns about the safety of nuclear weapons in the U.S. stockpile became an issue with the publication of the Drell report which is discussed in Section 3.3. Subsequently, Kidder published his July 1991 report on the safety of U.S. nuclear weapons and related nuclear test requirements needed to upgrade the stockpile. This was updated in December 1991 to take account of

[1]Department of Energy, *Remanufacturing Study: Volume I - Unclassified Report*, December 1990.

the Bush Initiative and Defense Secretary Cheney's Nuclear Arsenal Reduction Order of September 28, 1991. The latter two Kidder reports are also discussed in Section 3.2.

The October 1987 Kidder report was written in response to a request by then Congressman L. Aspen, and others to R. Batzel, then the Director of Lawrence Livermore National Laboratory (LLNL). The laboratory agreed to make Dr. Kidder available for the requested study only if a second report was also submitted.[2] This report in turn referred to a study[3] conducted by the Scientific and Academic Advisory Committee for the President of the University of California, which was itself responded to by members of the physics faculty of the University of California at Santa Barbara.[4] While these reports (and many others) are of historical interest, they are not current policy drivers. For this reason, they will not be discussed further.

1.4 Nuclear Proliferation

Additional restrictions on nuclear testing are often cited as being necessary to strengthen the Nuclear Non-Proliferation Treaty. Indeed, a group of NPT signatories has gone so far as to make "extension of the NPT in 1995

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[2]G.H. Miller, P.S. Brown and C.T. Alonso, *Report to Congress on Stockpile Reliability, Weapon Remanufacture, and the Role of Nuclear Testing*, UCRL-53822, October 12, 1987.

[3]Lew Allen, et al., *Nuclear Weapons Tests: The Role of the University of California-Department of Energy Laboratories*, A Report to the President and the Regents of the University of California by The Scientific and Academic Advisory Committee, July 1987.

[4]J. Fulco and W. Kohn, *Nuclear Weapons Tests: The Role of the University of California-Department of Energy Laboratories*, A Response to the Report of The Scientific and Academic Advisory Committee to the President and the Regents of the University of California, September 3, 1987.

conditional on the signing of a comprehensive nuclear test ban by the nuclear weapon states."[5]

The perception that nuclear weapons testing and proliferation are closely linked was stressed by Sigvaard Eklund, then director general of the International Atomic Energy Agency, during the 1980 NPT review conference when he stated that "an effective treaty banning every kind of nuclear weapons test would be the most important single action that could be taken to strengthen and universalize the beneficial regime of non-proliferation of nuclear weapons." In a joint letter to the 1985 NPT review conference, representatives of Denmark, Finland, Iceland, Norway and Sweden said that "The conclusion of a comprehensive test-ban treaty would effectively enhance the non-proliferation regime....The Nordic Governments attach particular importance to the conclusion of a comprehensive test-ban treaty with universal adherence, which would be a most effective measure to halt further development of nuclear weapons and offer strong support for the purposes of the non-proliferation treaty."[6]

1.4.1 The Decision to Initiate a Nuclear Weapons Program

As mentioned in the Preface, the actual relationship between nuclear testing by the principal nuclear weapon states and proliferation to Third World nations would appear to be tenuous at best. This was emphasized by National Security Advisor Brent Scowcroft, Secretary of Defense Richard B. Cheney and Secretary of Energy James D. Watkins in a July 10, 1992 letter to J. Bennett Johnston, Chairman of the Senate Subcommittee on Energy and Water Development, Committee on Appropriations: "Despite what some may, claim, our nuclear testing does not hinder nuclear non-proliferation efforts. Recent

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[5]Zachary S. Davis, "Non-Proliferation Regimes: A Comparative Analysis of Policies to Control the Spread of Nuclear, Chemical and Biological Weapons and Missiles," Congressional Research Service 91-334 ENR, April 1, 1991.

[6]Review Conference of the Parties to the Treaty on the Non-Proliferation of Nuclear Weapons. Final Document, Part II, Geneva, 1985, p.2; as quoted in *Nuclear Weapons and Security: The Effects of Alternative Test Ban Treaties*, Report of the Congressional Research Service prepared for the Committee on Foreign Affairs, U.S. House of Representatives, June 1989.

accessions to the NPT underscore the vitality of the approach we have been taking in this regard. On the other hand, rogue nations such as Iraq, Iran and North Korea will not stop their nuclear programs if the U.S. ceases testing."

The leaders of Third World nations view nuclear, chemical and biological weapons as a logical extension of a conventional military capability.[7] These countries develop nuclear weapons in particular for two principal reasons: to deter, or achieve an advantage over, others in their region; or to prevent developed nations from interfering in the region.

The incentive for Third World countries to develop nuclear weapons may well be enhanced by the breakup of the Soviet Union and the reduction, if not elimination, of the adversary relationship between the U. S. and successor states to the Soviet Union. For example, in the past, both India and Pakistan exploited cold war tensions to achieve their own ends. Currently, the weakening of the alliance between the Soviet Union and India may well convince India to develop credible nuclear forces to deter a potential threat from China. This is true even though China's international relations have been evolving in the direction of normalization, and the Chinese threat, at least to external observers, has been declining for years. Since Pakistan's main motivation for the development of nuclear weapons has been to deter India, any decision by India to nuclearize its forces will almost certainly lead Pakistan to further develop and deploy nuclear weapons. The key question is whether or not additional restrictions on nuclear testing by the advanced weapon states would reduce this incentive. While it is by no means clear that they would, it is also not obvious that they would not.

If the testing of nuclear weapons violated an accepted international norm, there would be considerable political cost to a nation performing a test. But even the prospect of violating such a regime would be unlikely to affect existing nuclear weapon programs such as those in Iran and North Korea, although it might affect the decision to test. And without a test, few countries would be willing to invest in building a militarily significant arsenal.

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[7]These issues have been discussed in greater detail in: G.E. Marsh, *Non-Soviet Nuclear Threats: The Meaning of Deterrence in a Global Context,* Office of the Chief of Naval Operations, Strategy and Policy Division (N-51), December 1992.

1.4.2 The Non-Proliferation Treaty and the 1995 Review

Past NPT review conferences have often been contentious in nature. One of the principal sources of controversy has been the assertion by non-nuclear weapon states, signatory to the NPT, that a comprehensive test ban is necessary to meet the objectives of Article VI.[8] Many signatories to the NPT do not believe the U.S. has pursued negotiations for a comprehensive test ban "in good faith," although few could argue that recent strategic arms reductions were not major

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[8]In point of fact, it is the introductory part of the treaty, with reference to the 1963 Treaty banning nuclear tests in the atmosphere, outer space and under water, that refers to the "discontinuance of all test explosions of nuclear weapons for all time and to continue negotiations to this end...." However, it is reasonable to expect that such negotiations could fall under the purview of Article VI, which commits the parties to the Treaty to "...pursue negotiations in good faith on effective measures relating to cessation of the nuclear arms race at an early date and to nuclear disarmament...." One could legitimately question whether or not the preamble to a treaty is binding. In general, treaty interpretation is governed by the Vienna Convention on the Law of Treaties [U.N. Doc. A/CONF. 39/27, (1969), 63 A.J.I.L. 875 (1969), 8 I.L.M. 679 (1969); done in Vienna on May 23, 1969; entered into force on January 27, 1980]. Article 31 states quite explicitly that "The context for the purpose of the interpretation of a treaty shall comprise, in addition to the text, including its preamble and annexes: (a) any agreement relating to the treaty which was made between all the parties in connexion with the conclusion of the treaty; (b) any instrument which was made by one or more parties in connexion with the conclusion of the treaty and accepted by the other parties as an instrument related to the treaty." In addition, Professor M. Cherif Bassiouni, a renowned international law scholar at the DePaul University College of Law, has stated that "the preamble is binding unless it is so general or precatory in nature as to *obviously* not represent the parties' intent" (private communication). This is in direct contradiction to the testimony of Kenneth L. Adelman in 1986 when he was Director of the Arms Control and Disarmament Agency: "Preambulatory language is [sic] treaties, including the NPT and PNET , is horatory, and does not create legal obligations." (*Nuclear Testing Issues*, Hearings before the Senate Committee on Armed Services, April 29 and 30, 1986, p. 49.)

steps "relating to cessation of the nuclear arms race." As a result, as mentioned above, a group of NPT signatories has made "extension of the NPT in 1995 conditional on the signing of a comprehensive nuclear test ban by the nuclear weapon states."

Thus, while many believe the decision to initiate a nuclear weapons program and testing by the advanced weapon states are only remotely related, Third World nations are likely to use the test ban issue as part of a bargaining strategy at the 1995 NPT review. Consequently, the ability of the U.S. to enter into treaties imposing additional testing restrictions may be of significant *political* value.

2.0 NUCLEAR WEAPONS SCIENCE AND PREDICTIVE CAPABILITY

2.1 Where are the Uncertainties?

Classified Section

Classified Section

2.2 How good is the Current Predictive Capability?

Classified Section

Classified Section

Classified Section

Classified Section

Classified Section[9,10,11,12]

[9]Classified Section Footnote

[10]Classified Section Footnote

[11]Classified Section Footnote

[12]Classified Section Footnote

3.0 SAFETY ISSUES

This section begins with an attempt to establish a perspective by which to view potential safety enhancements. The four sections that follow deal with the technical aspects of nuclear weapon safety.

While there are numerous reports that deal with the nuclear safety and stockpile reliability issues, the Kidder reports and the Drell report will form the basis for the discussion to follow. This is both because of their high visibility and the fact that Kidder's reports, and his congressional testimony, were the technical basis for the Hatfield amendment.

3.1 Nuclear Safety Criteria

The Drell report is quite explicit in stating that "there is no clear answer to the question 'How safe is safe enough?'. What is called for is judgment, informed by careful analyses and an adequate data base, as to how far to push, or to relax, safety standards. Informed judgment on such an issue requires a realistic assessment of the risks and benefits." Such risk assessments, if performed at all, are usually qualitative in nature even though safety criteria are often stated in quantitative terms. In addition, they are usually restricted to narrow technical grounds.

A high yield nuclear detonation through accident is clearly not acceptable. But how much effort, cost, and political capital should be expended to reduce the overall system risk of such a detonation from say one in a hundred million to one in a billion? Is the introduction of incremental safety features into a few nuclear weapons worth the cost of Russia reinitiating its nuclear test program? Are these safety enhancements worth jeopardizing the 1995 NPT review? Can any perceived risks be reduced by a change in operational practices?

These questions cannot be answered by an analysis of the technical issues; they require a broadly constituted interagency process. The existing Nuclear Weapons Council[13] is simply too narrow in its focus to effectively

[13]The Nuclear Weapons Council (NWC) and an NWC Weapon Safety Committee were created in response to the 1985 Presidents Blue Ribbon Task Group on

address the broader implications of continuing nuclear testing to introduce enhanced safety features into the stockpile.

3.2 The Kidder Reports

There are three reports published by the Lawrence Livermore National Laboratory by R.E. Kidder:

(1) *Maintaining the U.S. Stockpile of Nuclear Weapons During a Low-Threshold or Comprehensive Test Ban*, UCRL-53821, October 1987 (CNWDI, Weapons Data Σ1). (Unclassified version is UCRL-53820, October 1987.)

(2) *Report to Congress: Assessment of the Safety of U.S. Nuclear Weapons and Related Nuclear Test Requirements*, UCRL-LR-107454, July 26, 1991.

(3) *Assessment of the Safety of U.S. Nuclear Weapons and Related Nuclear Test Requirements: A Post-Bush Initiative Update*, UCRL-LR-10953, December 10, 1991.

The principal findings of these reports are:

Maintaining the U.S. Stockpile of Nuclear Weapons During a Low-Threshold or Comprehensive Test Ban**:**

(i) It was concluded that "a high degree of confidence in the reliability of the existing stockpile is justified, and that it is sufficiently robust to permit confidence in the reliability of remanufactured warheads in the absence of nuclear explosive proof-tests."

(ii) The report reviewed the "problems encountered with the 14 nuclear weapon designs since 1958 that have been frequently and prominently cited as evidence that a Low-Threshold Test Ban (LTTB) or a Comprehensive Test Ban (CTB)

Nuclear Weapons Program Management, chaired by Judge William T. Clark, and the 1988 DOE Nuclear Weapons Safety Review Group, chaired by Gordon Moe.

would preclude the possibility of maintaining a reliable stockpile." It was concluded "that the experience has little if any relevance to the question of maintaining the reliability of the stockpile of nuclear weapons that exists in 1987."

Report to Congress: Assessment of the Safety of U.S. Nuclear Weapons and Related Nuclear Test Requirements**:**

(i) A projected future stockpile is defined by "deleting weapons currently scheduled for retirement and short-range, surface-to-surface tactical nuclear weapons that will likely be returned to the U.S. and placed in storage. With the exception of the Minuteman and Trident ballistic missile warheads, all warheads in this projected future stockpile will have both of the most important design features that contribute to nuclear weapon safety: enhanced electrical isolation (EEI) and insensitive high explosive (IHE)."

(ii) "It is argued that only a modest number (10-20) of nuclear tests would be needed to develop warheads with both EEI and IHE to replace existing Minuteman and Trident warheads (that lack only IHE) should that be deemed necessary."

Assessment of the Safety of U.S. Nuclear Weapons and Related Nuclear Test Requirements: A Post-Bush Initiative Update**:**

(i) "It is estimated that 11-13 nuclear tests would still be required to add IHE to those ballistic missiles not scheduled for retirement, namely the Minuteman III, C4, and D5 missiles. A total of 3-4 nuclear tests would be required for the Minuteman III upgrade alone."

(ii) "Incorporating IHE into the older W76 Trident I, II C4 missile warhead is problematical if Rocky Flats remains unavailable. The same is true of the W88 warhead. In the latter case, however, the W88 can be replaced by the W89, which has all the modern safety features and can be remanufactured with salvaged pits should Rocky Flats remain closed."

(iii) "Pit reuse is probably not a feasible option for further production of the W88 warhead. If Rocky Flats resumes operation, further production of unmodified

W88 warheads would require only 1 nuclear test to verify performance. A total of 3-4 tests would be required if the W88 is to be replaced by the W89; the smaller number would apply if Rocky Flats were operating. (Production of a new design incorporating IHE would be expected to require 5 nuclear tests.)"

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With regard to (ii) of the last report, note that no assessment is given as to whether the W89 can be substituted for the W88 without incurring the costs of additional flight tests. Note also that the third conclusion of this report differs from that of the Defense Science Board which concluded that pit reuse was a viable option.

The Defense Science Board Task Force[14] concluded that:

(i) "A pit-reuse designed warhead for the Mk-5 reentry body appears feasible. Possible risks due to less than optimal design constraints and aging of parts are deemed acceptable. Pit-reuse candidates could, except for yield, meet W88/Mk-5 military requirements and are compatible with the existing Mk-5 reentry body. Yield potential, although lower than the W88, appears to be in an acceptable range."

They also found that "development would take about five years and cost on the order of $750 million to $1 billion. However, much of these costs are opportunity costs associated with level of effort funding for the national weapons laboratories....The DoD cost would be driven by ensuring compatibility of the reused physics package with the existing Mk-5 reentry airframe, and the existing arming, fuzing, and firing system."

(ii) Another option, introduced by the Navy, was to adapt the existing W76 warhead to the Mk-5 reentry system on the D5 missile. The Task Force found that: "This option would not require development of a new warhead, nor would it rely upon production of new plutonium pits. Preliminary effectiveness studies using the W76/Mk-5 combination (combined with an updated Trident Guidance

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[14]February 1, 1992 memorandum from John S. Foster, Jr., Chairman of the Defense Science Board, Office of the Secretary of Defense, to the Director, Defense Research and Engineering forwarding the final report of the Defense Science Board Task Force on the Feasibility of Employing Pit-Reuse in the Production of Alternate Warheads for Trident II/Mk-5, and attached report. The Task Force was chaired by Dr. Donald A. Hicks.

System) show adequate single shot kill probabilities against the portion of the hard target base remaining after allocation of the existing number of W88/Mk-5 weapons. This option, although it requires further study, represents the least technical risk of the studied options, other than continued production of the baseline W88 -- because the W76 has already been qualified to the Trident II handling and flight environments, as well as the more severe environment of reentry."

3.3 The Drell Report

The Drell report is titled: *Nuclear Weapons Safety*, Report of the Panel on Nuclear Weapons Safety of the House Armed Services Committee, Sidney D. Drell (Chairman), John S. Foster, Jr., and Charles H. Townes, December 1990. There is a classified (SRD) Annex.

The Drell report recommended that the following priority goals for "improving the safety of the nuclear weapons systems in the stockpile, using available technology," be adopted and implemented as national policy (Appendix II contains definitions of the technical terms):

(i) "Equip *all weapons* in the stockpile with modern enhanced nuclear detonation safety (ENDS) systems."

(ii) "Build *all nuclear bombs loaded onto aircraft* - both bombs and cruise missiles - with insensitive high explosives (IHE) and fire-resistant pits. These are the two most critical safety features currently available for avoiding plutonium dispersal in the event of aircraft fires or crashes."

In addition, the report (and the Annex) raised serious concern about the fact that the "W88 is not equipped with IHE and is mounted in a through-deck configuration in close proximity to a third-stage rocket motor that uses a high energy propellant of the 1.1 class." The Annex did note, however, that it was necessary "to fill serious gaps in the data that are required in order to analyze risks resulting from the present design."

In discussing the issue of IHE, the Drell report pointed out that: "In contrast to its safety advantages, IHE contains, pound for pound, only about two-thirds the energy of HE and, therefore, is needed in greater weight and volume for initiating the detonation of a nuclear warhead. Hence the yield-to-weight ratio decreases for a nuclear warhead when IHE replaces HE." Thus, if the decision had been made in 1983 to deploy a warhead using IHE rather than the W88 with HE, "the military capability of the D5 would have had to be reduced by one of the following choices:

• retain the maximum missile range and full complement of 8 warheads, but reduce the yields of individual warheads by a modest amount.

• retain the number and yield of warheads but reduce the maximum range by perhaps 10%; such a range reduction would translate into a corresponding greater loss of target coverage or reduction of the submarine operating area.

• retain the missile range and warhead yield but reduce the number of warheads by one, from 8 to 7."

The Air Force has formulated a response to the Drell report.[15] Their principal findings are:

• "Bombs and cruise missiles with ENDS and IHE, but without FRP should not be modified to incorporate FRP." Although "FRPs are of primary, although limited, benefit for weapons on alert aircraft, risk with added handling, transportation, fabrication, and assembly outweighs FRP benefit."

• "No *significant* safety benefit is realized by using Class 1.3 instead of Class 1.1 in the Minuteman and Peacekeeper families."

• "The Mk 12A/W78 is the top Air Force candidate for safety upgrade" (The Mk 12A/W78 is used on the Minuteman III which uses a Class 1.3 propellant. The W78 has ENDS but not IHE or FRP.)

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[15]Lt Col John R. Curry (SAF/AQQS), *Air Force Response to the Drell Panel,* Nuclear Weapons Council Weapon Safety Committee, 1 August 1991.

3.4 Differences Between the Drell and Kidder Reports

The differences between the Drell (DR) and Kidder reports (KR) can be summed up as follows:

- The DR has been widely interpreted to imply that the need to improve the safety of U.S. nuclear weapons precludes the possibility of a nuclear test ban for the foreseeable future.

  The KR concludes that the safety of U.S. nuclear weapons can be brought up to modern standards in less than five years and requires only a small number of nuclear tests to do so.

- The DR proposes that existing nuclear bombs and air-launched cruise missiles be retrofitted with fire-resistant pits.

  The KR does not.

- The KR proposes that the transport of nuclear weapons by air in peacetime be prohibited.

  The DR does not.

- The DR suggests that the concept of separable components may provide a practical means of achieving significantly safer nuclear weapons.

  The KR considers the concept to be of doubtful practicality or necessity, and likely to result in a less robust and dependable nuclear weapons stockpile.

- The DR stresses safety concerns with the W88 Trident II (D5) SLBM, but not with the W76 Trident I, II (C4) SLBM of which far more have been deployed.

  The KR agrees with the DR with respect to the W88, but points out that the W76 presents safety concerns essentially identical to those of the W88.

These differences can be summarized in a table:

ISSUE	DRELL REPORT	KIDDER REPORT
Safety Improvements	Precludes a Test Ban in Foreseeable Future	Small Number of Tests over 5 Year Period
Fire-Resistant Pits	Should be Retrofitted in all Bombs and ALCMs	Not Required in all Bombs and ALCMs
Prohibition of Peacetime Air Transport	No	Yes
Separable Components	Yes	No
W88/D5 and W76/C4 Safety Concerns	Only W88/D5	Both

3.5 Implications for the Navy and the D5/W88

Section IV of the Drell report observed that, "With a reduced loading a safety-optimized version of the D5, equipped with IHE, non-detonable 1.3 class propellant and a fire-resistant pit, could fly to even longer ranges than at present....we note that a loading accident ... presents a safety concern only if the Trident missiles are moved and loaded onto submarines with the warheads already mated to the missile, as is standard U.S. Navy procedure. If the warheads are mated after the missile has already been loaded into the launch tubes there is no handling worry of this type."

Most of the safety concerns with the W88 Trident II (D5) SLBM have been alleviated by the cost effective Navy decision to load the W88 on to the D5 missile after it is placed in the launch tube of the SSBN.

4.0 WEAPON EFFECTS TESTING

Classified Section

Classified Section[16],[17],[18],[19]

[16]Classified Section Footnote

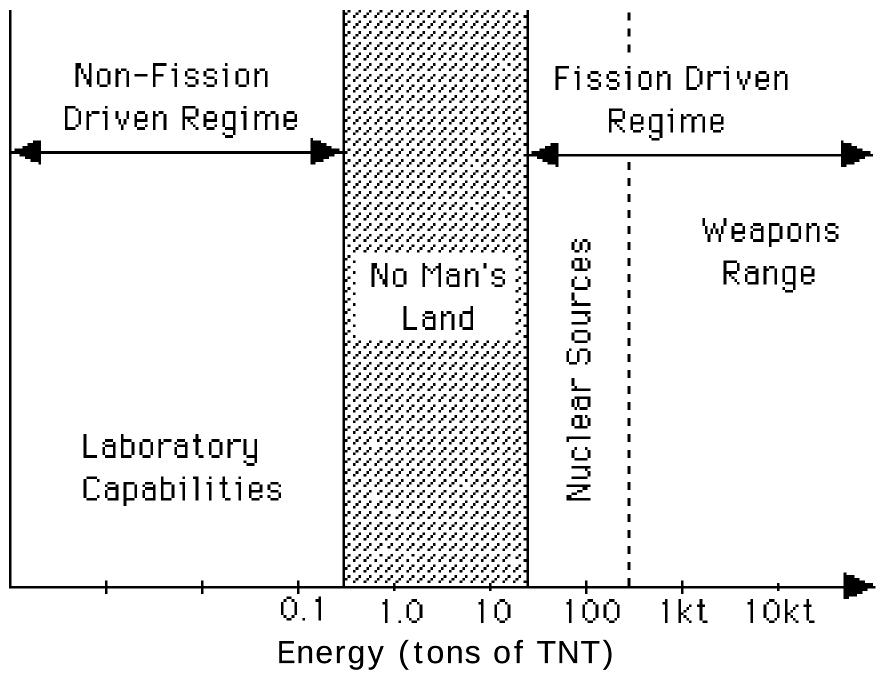
[17]Classified Section Footnote

[18]Classified Section Footnote

[19]Classified Section Footnote

5.0 FUTURE NUCLEAR TESTING LIMITATIONS: TYPES OF TEST BANS

Under any test ban regime, what constitutes a nuclear test is a key question. It is, for example, generally agreed that the laboratory-scale thermonuclear micro-explosions of inertially confined fusion (ICF) programs should not be prohibited. While these programs have often been touted in an energy context, the fact that they use lasers having a cycle time of hours means that laser-driven inertially confined fusion should primarily be viewed as a scientific program that could be a weapon effects hedge against a test ban. The yields that might be expected from imploding ICF capsules[20] are in the range of 1.4 X 10^{-4} kt. The following figure[21] gives some idea of the different energy ranges:



In the past, a low-threshold test ban assumed a yield threshold of between 1kt and 10kt, depending on verification limits (discussed in Appendix I). A

[20]J.D. Lindl, R.L. McCrory and E.M. Campbell, *Physics Today*, September 1992.

[21]Abstracted from a figure presented by R.E. Kidder at a hearing before the DOE Defense Nuclear Facilities Panel of the House Armed Services Committee concerning The Nuclear Test Ban Readiness Program on April 26, 1989.

comprehensive test ban might well set the yield limit[22] at the border between "No Man's Land" and "Nuclear Sources." However, this may not be in the best interests of continued progress in the study of the physics of high temperatures and pressures.[23]

There have been a number of proposals[24] for a high-energy density experimental facility that would operate in the "Fission Driven Regime," but not in the "Weapons Range." Such a reusable underground test chamber could be

[22]The issue of what constitutes a nuclear test has been addressed by Kidder and Evgeny N. Avrorin (Chief Scientist at the Institute of Technical Physics, Chelyabinsk 70) in a personal interchange of notes that took place in London early in 1993. Kidder had suggested that a nuclear yield exceeding 500 lbs HE equivalent be considered a nuclear test. Avrorin responded that on the basis of detectability, the threshold level should be set at 10 tons.

[23]See, for example: M.H. Hey, "The Physics of the Superdense Region," contained in *Laser-Plasma Interactions* Edited by R.A. Cairns and J.J. Sanderson (Scottish Universities Summer School in Physics, Edinburgh 1980).

[24]R.E. Kidder, A. Szoke and L.A. Glenn, "A Facility for High-Energy Density Experiments (U)," Lawrence Livermore National Laboratory, Research Monthly, March 1983, pp. 21-29 (SECRET-RD); C.E. Walter and P.B. Mohr, "High Energy Density Experimental Facility (HEDF)," Lawrence Livermore National Laboratory, UCID-19876, July 1983. See also the references cited in the latter report.

constructed under the aegis of both the United States and Russia and serve as an international users facility. As such, it could use unclassified fission sources. Careful thought should therefore be given to defining the allowable threshold under a comprehensive test ban.

APPENDIX I: VERIFICATION OF NUCLEAR TESTING LIMITATIONS

Allowable yield limits under a comprehensive or low-threshold test ban treaty are as likely to be set by political considerations as by the needs of science or verification. Nonetheless, verification capability is bound to play a significant role in any interagency process associated with negotiating either type of treaty. Because seismology is the primary means of detecting and estimating the yields of underground nuclear tests, it is important to include some background on the technical aspects of seismology and yield estimation in this report. An Appendix of this length cannot hope to do justice to either the long history of seismic monitoring of underground nuclear tests, or many of the seismological issues needed for an in-depth understanding of the subject. At best, it can hope to serve as an introduction, alerting the reader to some of the key issues.[25] The primary focus is on basic seismology and the evasion scenario based on the possibility of reducing the detectability of a nuclear explosion by testing in cavities. This Appendix will not discuss the historical controversy over the so-called m_b bias issue; it was primarily political in nature and has now been laid to rest.

UNDERGROUND NUCLEAR EXPLOSIONS AND SEISMOLOGY

An underground explosion in rock creates a radially symmetric shock wave. If the rock is previously in a state of near-zero pre-stress and if the rock is of uniform properties at all depths, the explosion-induced shock wave is the source of almost pure compressional or P-waves and Rayleigh waves. However, these simple conditions are not fulfilled by the earth: Nearly all rocks are in a state of measurable pre-stress (due to continuing processes of earth deformation) and the earth displays a pattern of marked discontinuous increase of elastic wave velocities (P and S) with increasing depth in the earth. Thus, other wave types are also generated by nearly all underground explosions, these

[25]Other, more extensive introductions are also available. See, for example: "Seismic Verification of Nuclear Testing Treaties," Office of Technology Assessment, OTA-ISC-361, (May 1988).

wave types being shear body waves (S-waves) and pure shear surface waves (Love waves), as well as additional Rayleigh waves.

Both Rayleigh and Love waves propagate only over the surface of the earth, amplitudes decreasing exponentially with depth beneath the surface layers. Particle motion in Rayleigh waves is a combination of vertical motion and motion in the direction of propagation, the particle describing a retrograde elliptical motion (moving towards the source at the top of the ellipse). The particle motion in Love waves is pure horizontal shear, the particle moving transverse to the direction of propagation in the plane of the ground surface.

Both P-waves and S-waves propagate through the body of the earth, decreasing in amplitude with increasing distance only due to spreading of their wave-fronts, wave-type conversion at elastic interfaces and losses due to anelastic processes in the earth. P-wave velocities are greater than those of S-waves ($v_p \approx \sqrt{3}\, v_s$), the ray paths of both wave types being concave upward in the earth due to the increasing velocity of propagation with increasing depth.

These various types of waves are shown in Fig. A1.

DECOUPLING OF UNDERGROUND EXPLOSIONS

The possibility of concealing underground nuclear explosions in large cavities was originally raised by Latter, et al. in 1961[26]. Since then much work has been done on this subject both in the U.S. and in the former Soviet Union. Currently, the definitive work on the verification issue is that of Evernden, et al.[27]

An underground explosion may be either "tamped" -- coupled or in close contact with the surrounding medium -- or "decoupled" in a large cavity with the result that the radiated signal is decreased in amplitude. The outwardly

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[26]A.L. Latter, R.E. LeLevier, E.A. Martinelli, and W.G. McMillan, "A Method of Concealing Underground Nuclear Explosions," J. Geophys. Res. **66**, 943 (1961); A.L. Latter, E.A. Martinelli, J. Mathews, and W.G. McMillan, "The Effect of Plasticity on Decoupling of Underground Explosions," J. Geophys. Res. **66**, 2929 (1961)

[27]J.F. Evernden, C.B. Archambeau, and E. Cranswick, "An Evaluation of Seismic Decoupling and Underground Nuclear Test Monitoring Using High-Frequency Seismic Data," Rev. Geophys. **24**, 143 (1986).

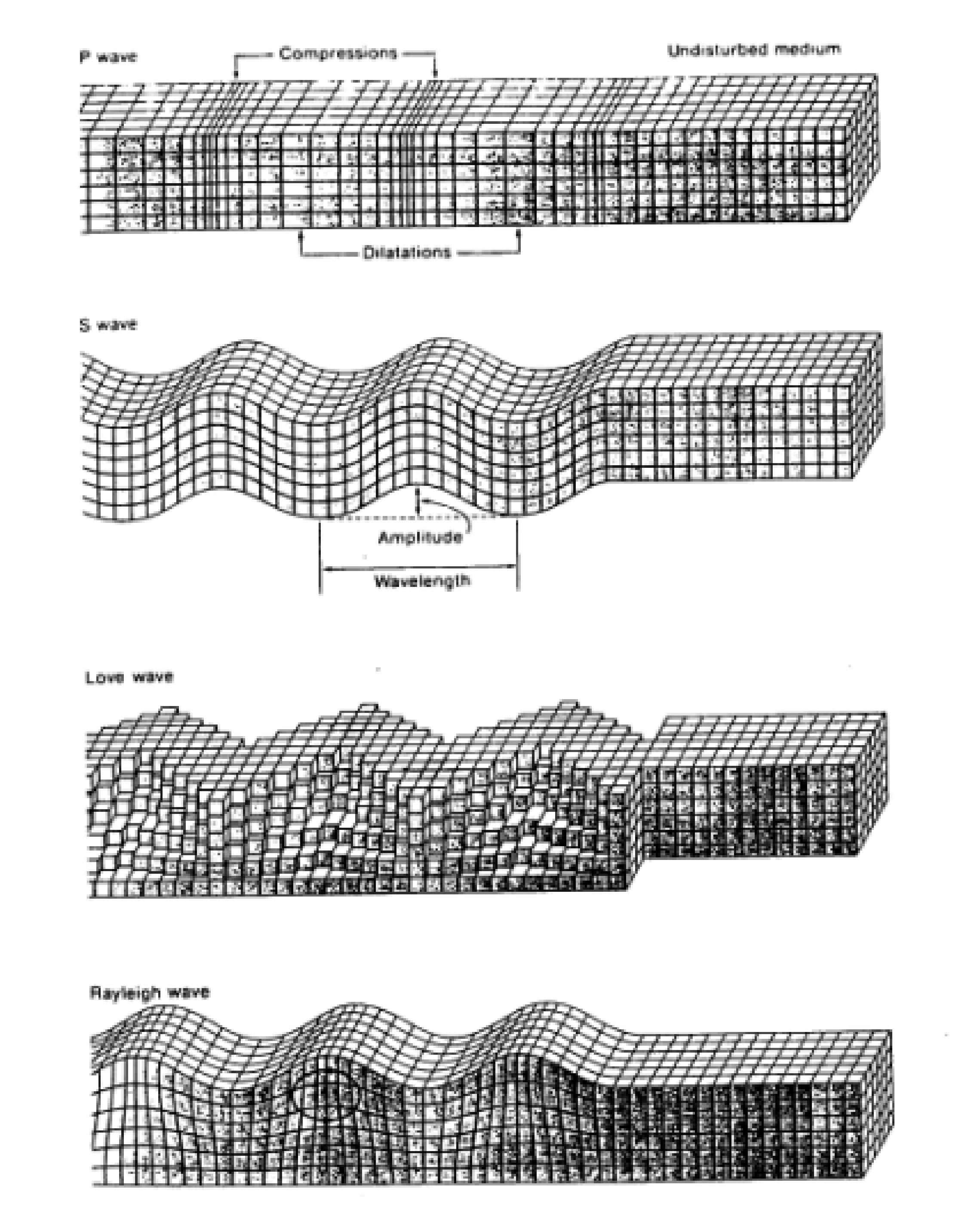

Fig. A1. Types of seismic waves propagated in an elastic medium. Direction of propagation is from left to right. [Adapted from: B.A. Bolt, "Nuclear Explosions and Earthquakes: The Parted Veil," (W.H. Freeman & Co., San Francisco 1976)] propagating shock wave produced by an explosion ultimately reaches a radial distance (the "elastic radius") where the surrounding medium behaves elastically or linearly. A "fully decoupled" explosion is one detonated in the smallest cavity required to achieve elastic response of the cavity walls (i.e., the "elastic radius" is the radius of the cavity). The radius of such a cavity depends on both the size of the explosion (Yield$^{1/3}$ scaling), the properties of the surrounding medium and the depth of the explosion.

When the shock wave reaches the elastic radius, it acts as a source of P-waves and Rayleigh waves with a time history similar to that of a δ-function.[28] The Fourier transform of such a source will give a flat frequency spectrum in the far field region. The features of a calculated explosion spectrum are shown in Fig. A2. Note the nearly flat spectral level at low frequencies up to a well-defined corner frequency -- which may peak somewhat in a narrow frequency band if the explosion is in a material of great strength -- and a spectral level decay varying as f^{-2} for higher frequencies. This reduction in amplitude for higher frequencies is a result of interference of waves radiated from different portions of the source. Fig. A2 shows the calculated displacement spectra for tamped and decoupled explosions of various yields; note that the spectrum of a decoupled explosion is identical to that of a tamped explosion (except possibly for spectral peaking near the corner frequency) with 1/200 the yield. In general, the spectra are flat for low frequencies, have corner frequencies lying on a line with f^{-3} slope,[29] and have high frequency decay proportional to f^{-2}.

The decoupling of an underground nuclear test by the use of large cavities is a strong function of frequency. Fig. A3 shows the decoupling factor for explosions in salt (the most probable medium within which to attempt to hide or reduce the apparent yield of an explosion) as a function of frequency and cavity radius. For yields other than 1 kt, frequencies scale as $Y^{-1/3}$ and the radius as

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[28]A more accurate explosion source model (the Sharpe Model) is discussed in Section 2 of the paper by Evernden, et al.

[29]That the corner frequencies lie on a line with slope f^{-3} can be seen as follows: Noting that the shock wave velocity, v, is approximately equal to the P-wave velocity, and that the radius of fracture, R_0, -- which corresponds to the source size -- is proportional to $Y^{1/3}$, the corner frequency $f_c \propto v/R_0 \propto Y^{-1/3}$ so that $Y \propto f_c^{-3}$. The f^{-2} decay for $f > f_c$ comes from the pressure step model of an explosion. Note that the falloff for earthquakes is f^{-3}.

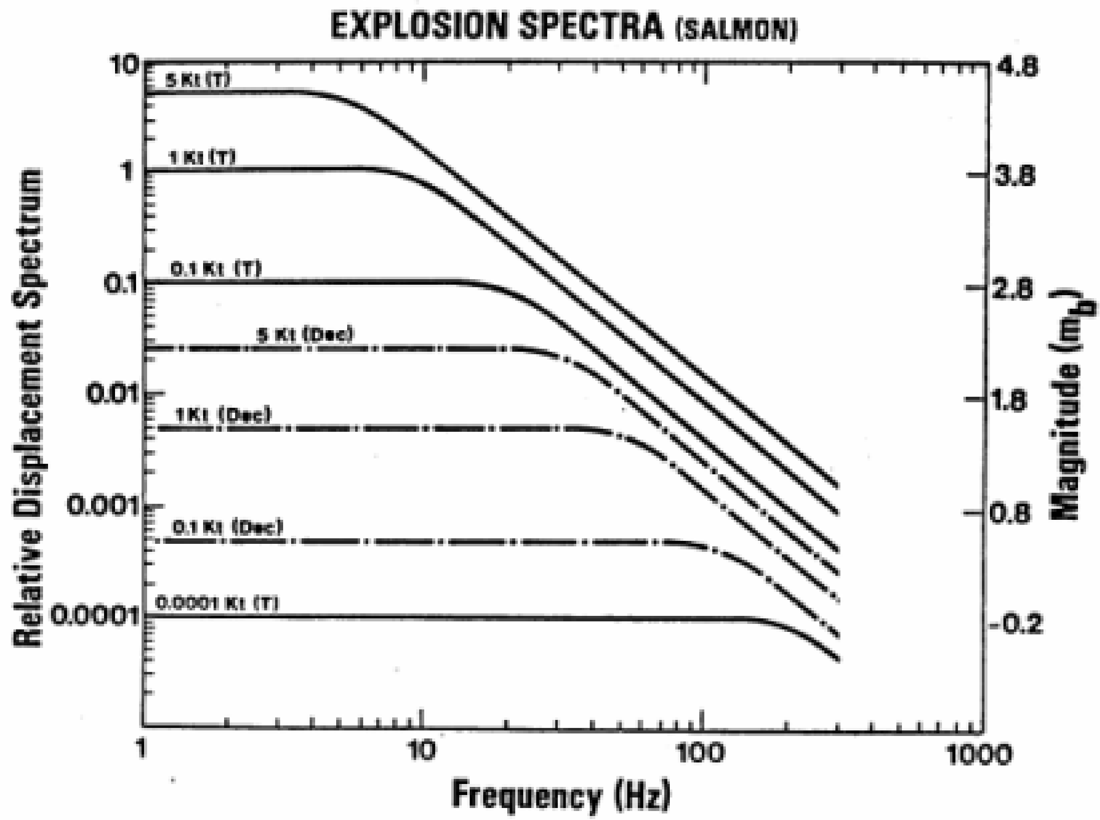

Fig. A2. Predicted displacement source spectra according to the Sharpe model for tamped (T) and fully decoupled (Dec) explosions in strong salt. [From: J.F. Evernden, et al., Rev. of Geophys **24**, 143 (1986)]

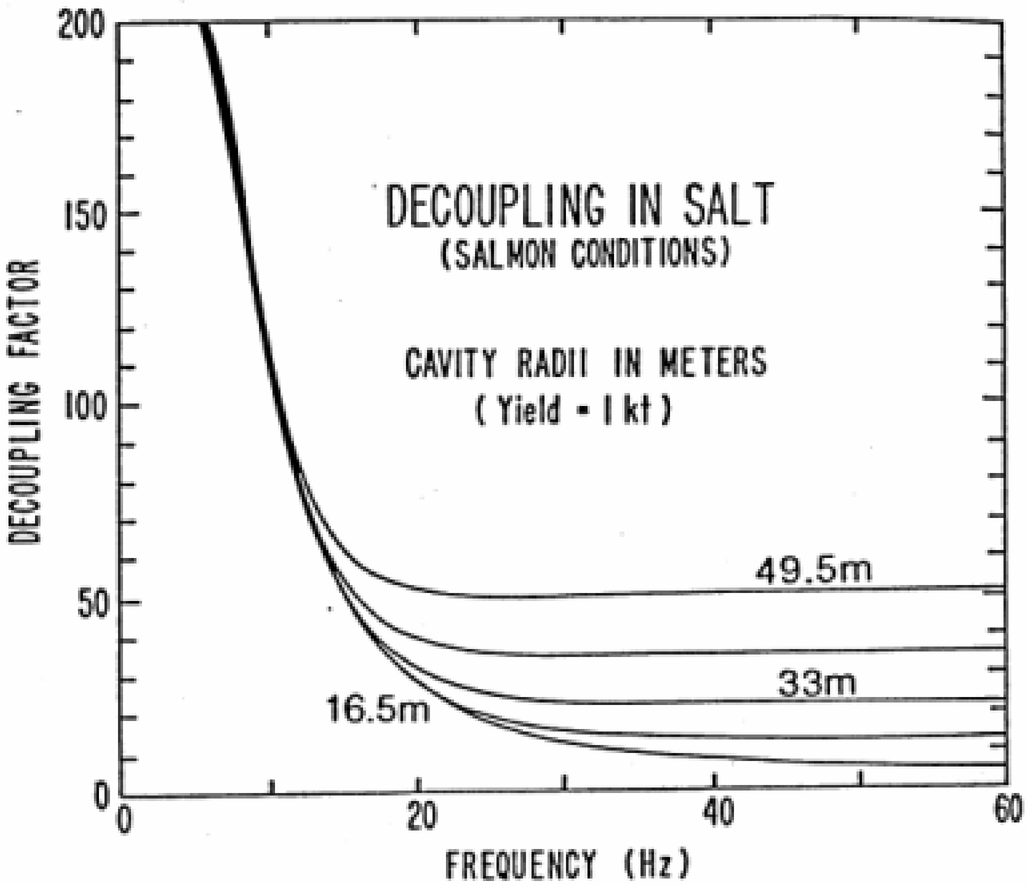

Fig. A3. Predicted P wave decoupling factors from the Sharpe model for 1 kt nuclear explosions in cavities of various radii (fully and over-decoupled explosions) in SALMON-like salt. The smallest radius is for a fully decoupled explosion. For yields (Y) of other than 1 kt, frequencies scale as $Y^{-1/3}$, and radii as $Y^{1/3}$. [From: J.F. Evernden, et al., Rev. of Geophys **24**, 143 (1986)]

$Y^{1/3}$ (where Y is the yield of the explosion). "Salmon Conditions" here means a *tamped* explosion in previously undisturbed salt. The Sterling 0.38 kt test in the cavity produced by the 5.3 kt tamped Salmon event only produced a 60-fold decoupling. Various explanations have been given for this observation. Apparently the salt surrounding the Salmon cavity was weaker at the time of the Sterling explosion than it was originally. Consequently, the cavity radius needed to achieve full decoupling for the 0.38 kt Sterling event was 20m while the cavity produced by Salmon had a 17.4m radius. The variation in decoupling versus frequency versus cavity size for the Sterling salt conditions is shown in Fig. A4. Note that the radius needed to fully decouple a 1 kt explosion is 27m rather than the 16.5m expected on the basis of pre-Salmon salt conditions.

Other analyses of the Salmon/Sterling pair show a decoupling generally smaller than a factor of 200. R. Blandford of the Defense Advanced Research Projects Agency (DARPA) found[30] a low-frequency decoupling of 70 and a high frequency decoupling of about 7.

The former Soviet Union also carried out test similar to the Salmon/Sterling pair. On March 29, 1976 an 8kt device was detonated in a somewhat elliptical salt cavity that had a minor axis of 66m and a major axis of 76m; i.e., a radius of approximately 35m. The cavity, which was created in 1971 by another nuclear explosion having a yield of 64kt, was located at Azgir and had a depth of 987m.

It is interesting to estimate from Fig. A3 and Fig. A4 what size cavity would be required to achieve full decoupling at Azgir. To do this one takes the radius for full decoupling from each figure and multiplies times the yield of the March 29, 1976 test at Azgir to the one-third power (that is, $8^{1/3} = 2$). From Fig. A3, the value is R_0 = 33m, and from Fig. A4, R_0 = 54m. If Fig. A3 were correct the cavity radius at Azgir of 35m would have been adequate to achieve full decoupling. In fact, Adushkin, et al. calculate a low frequency limit for the decoupling factor of only about 20.[31] It is clear that the salt at Azgir behaves somewhere in between Fig. A3 and Fig. A4. Adushkin, et al. conclude that "The actual strength of salt,

[30]The paper by R. Blandford can be found in: D.B. Larson, Ed., "Proceedings of the Department of Energy Sponsored Cavity Decoupling Workshop," Pajaro Dunes, California, Department of Energy Conf. 850779, July 29-31, 1985, p. V-3.
[31]V.V. Adushkin, I.O. Kitov, O.P. Kuznetsov and D.D. Sultanov, submitted to Geophys. Res. Lett.

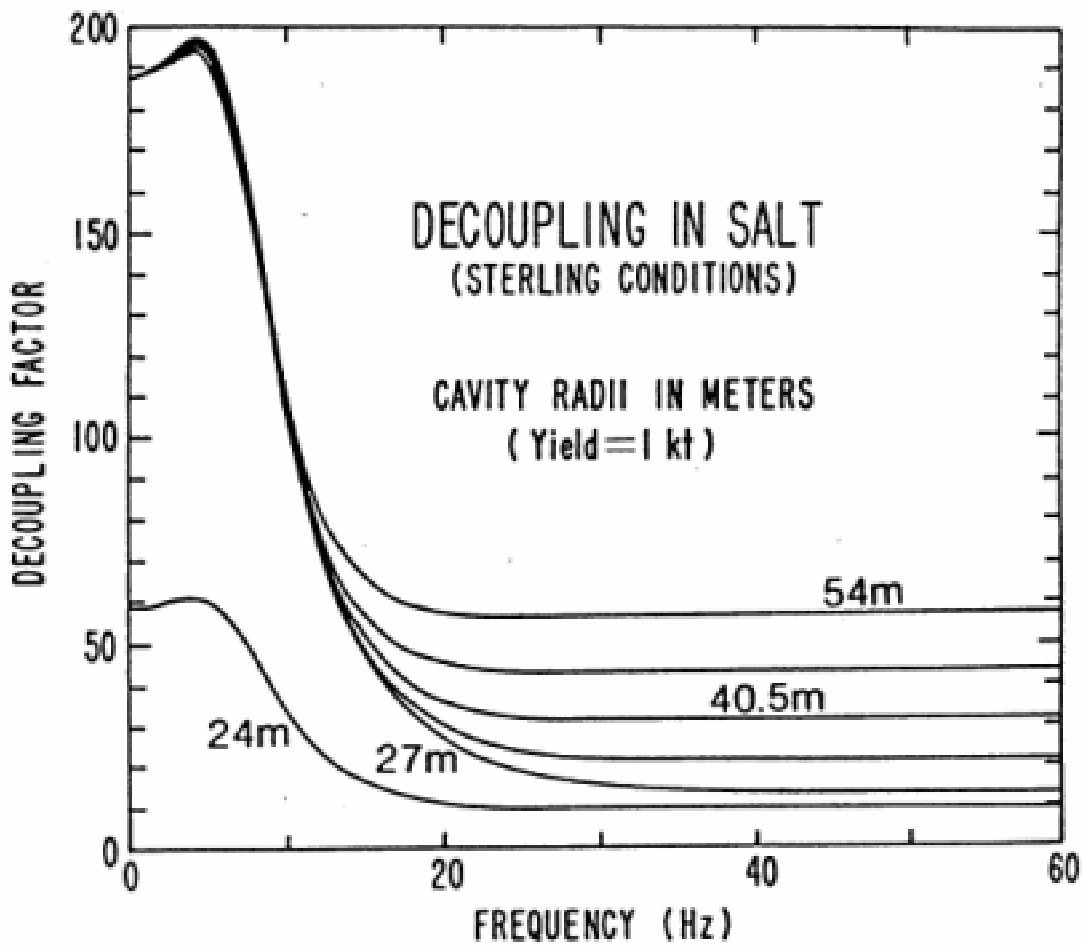

Fig. A4. Predicted P wave decoupling factors from the Sharpe model for 1 kt nuclear explosions in cavities of various radii in Sterling-like salt. The radius of 24m is for the partially decoupled conditions observed at the time of Stirling. For yields (Y) of other than 1 kt, frequencies scale as $Y^{-1/3}$, and radii as $Y^{1/3}$. [From: J.F. Evernden, et al., Rev. of Geophys **24**, 143 (1986)] which effectively controls decoupling, is much less than that previously used in theoretical studies to estimate the maximum decoupling factor. Hence, the maximum decoupling factor may not be more than about 100 in agreement with the findings of Denny and Goodman[32] and the experimental data currently available." Denny and Goodman concluded that "The decoupling value of 72 obtained by Springer et al. (1968) is confirmed.[33] A revision of Patterson's (1966) partial decoupling curve[34] shows that the value for full decoupling in a shot-generated cavity would be only slightly higher."

Another possible evasion scenario is the use of unconventional cavities.[35] A Cavity Decoupling Workshop in 1985 concluded that "It does not appear, however, that cavity shape alone (i.e. without tectonic release) could make an explosion look like an earthquake but it may affect detection in some directions."[36]

LIMITATIONS ON THE DETECTION OF UNDERGROUND EXPLOSIONS BY SEISMIC MEANS

In spite of the evidence supporting a maximum decoupling factor of about 100, Evernden, et al. in their extensive studies assumed the more conservative value of 200 consistent with Fig. A4. Their basic conclusion is that with an in-country network the capability exists today to identify explosion-generated seismic signals at least as small as those from a fully decoupled 1kt explosion at

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[32]M.D. Denny and D.M. Goodman, J. Geophys. Res. **95**, 19,705 (1990).

[33]D. Springer, M. Denny, J. Healy, and W. Mickey, J. Geophys. Res. **73**, 5995 (1968).

[34]D. Patterson, Lawrence Livermore National Laboratory, UCID-5125 (1966); J. Geophys. Res. **71**, 3427 (1966).

[35]L.A. Glenn, "Unconventional Cavity Decoupling," Lawrence Livermore National Laboratory, UCID-19830, June 29, 1983.

[36]D.B. Larson, Ed., "Proceedings of the Department of Energy Sponsored Cavity Decoupling Workshop," Pajaro Dunes, California, Department of Energy Conf. 850779, July 29-31, 1985.

all potential decoupling sites within the former Soviet Union.[37] A range of 1-3 kt is now generally accepted within the seismic community.

The capabilities of seismic monitoring networks discussed by Evernden, et al. are based on the use of high-frequency data up to 30 or 40 Hz. It is the use of such relatively high frequencies (where decoupling factors are far less than the low frequency limit) that allow seismic networks to achieve the stated sensitivity even against a determined evader.

Studies have also been performed for the case where the assumption is made that no detecting stations can be located within the former Soviet Union. If one postulates a worldwide network of 25 high-quality (small array) stations located completely outside the former Soviet Union, the ability to detect a fully decoupled 10 kt explosion is shown[38] in Fig. A5. The probability of getting the indicated amount of data is 0.9. This figure assumes a decoupling factor of 200. If one uses the more realistic factor of 60-70, this figure would represent the capability to detect a fully decoupled 3 kt explosion. Note that the figure also assumes that the monitoring stations are capable of detecting 15 Hz signals (well within current capabilities). The reason for this is that the signal to noise ratio is about 1 at 9 Hz and 5 at 20 Hz, so that multiple station detection would be expected at frequencies above 10 Hz. This can be seen in Fig. A6.

It is often stated that for small explosions one could negotiate the right to perform on-site inspections (OSI). Unfortunately, the scenario of drilling at a "suspect site" to confirm the occurrence of a nuclear test is overblown. One must locate the suspect site quite accurately if drilling is to be useful. Unless there are obvious surface features, which can be avoided, this is not an easy task. In

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[37]Hannon [W.J. Hannon, Science **227**, 251 (1985)] has published results which are somewhat more conservative. However, in his analysis, Hannon assumes the possibility of full decoupling throughout all regions of the USSR, an assumption that is certainly unsupportable. In addition, Hannon's identification of explosions is based almost entirely on comparison of amplitudes of 1-Hz P and 0.05 Hz Rayleigh waves. This makes his calculated capabilities unattainable against a determined effort at evasion based on hiding in an earthquake.

[38]This figure, and the following one, are taken from: D.B. Larson, Ed., "Proceedings of the Department of Energy Sponsored Cavity Decoupling Workshop," Pajaro Dunes, California, Department of Energy Conf. 850779, July 29-31, 1985, p. VI-67 and VI-66.

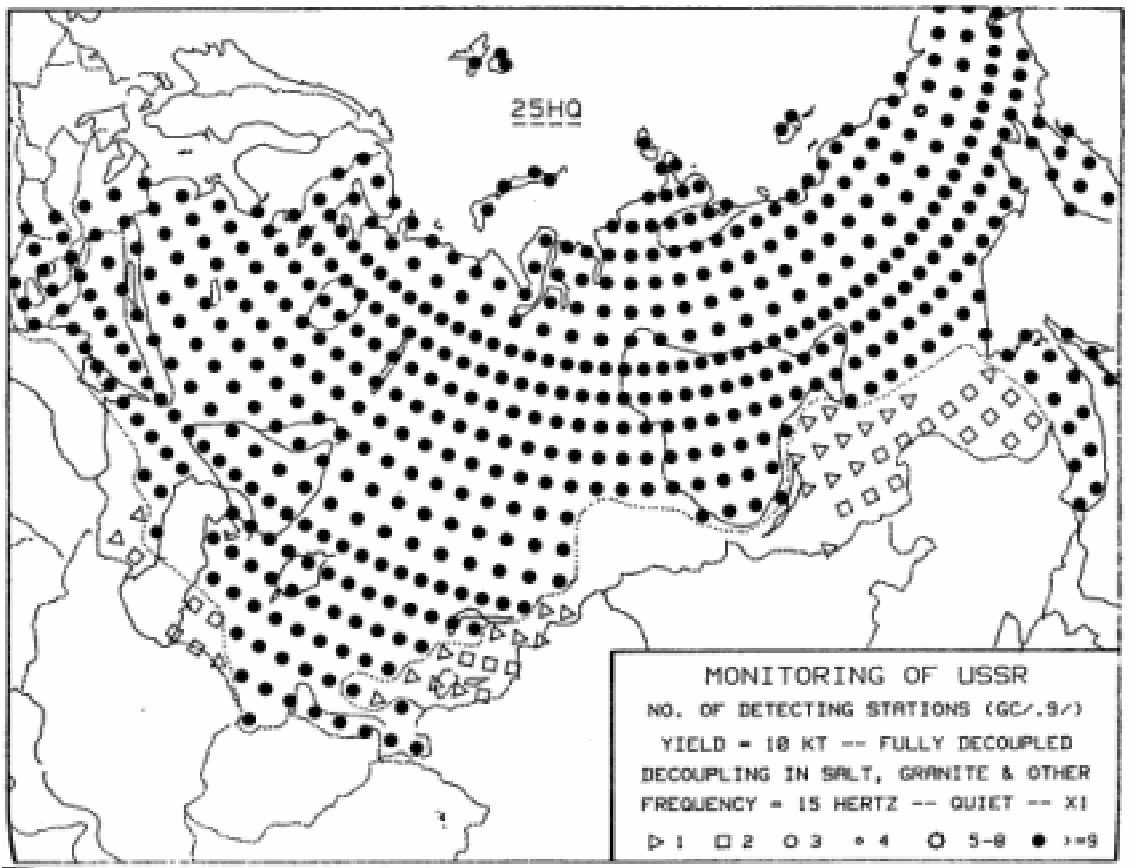

Fig. A5. The ability of 25 High Quality (HQ), or small arrays, external to the former Soviet Union to detect a fully decoupled 10 kt explosion. The figure assumes a decoupling factor of 200 and the ability to detect 15 Hz signals. If decoupling is a more realistic factor of 60 to 70, the figure would apply to a 3 kt explosion. [From: J.F. Evernden, "Selected Comments on the Decoupling Conference." (Footnote 29)]

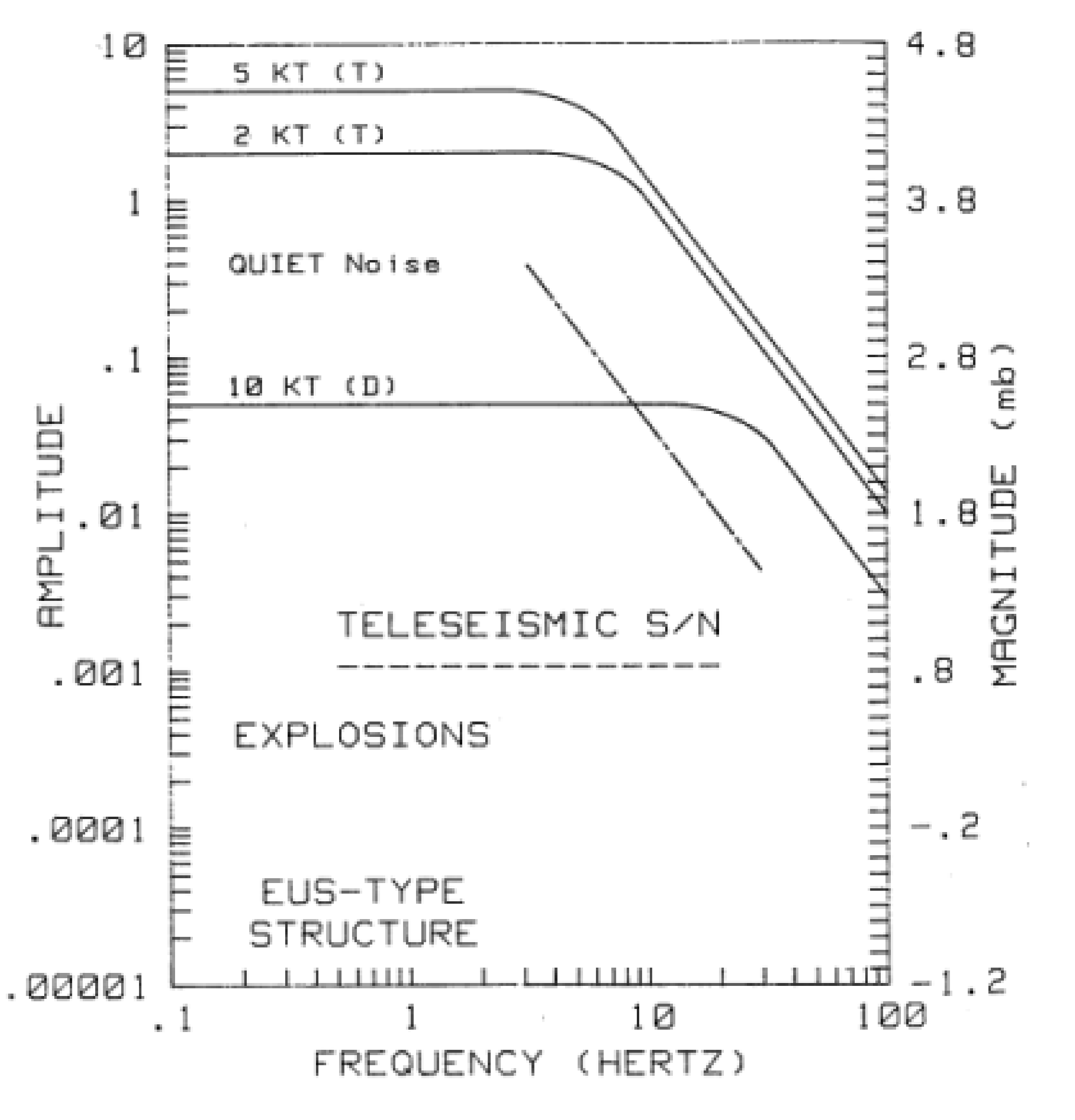

Fig. A6. Teleseismic signal to noise ratio assumed in calculating the monitoring capability shown in Fig. A5. Multiple station detection by a properly designed network external to the former Soviet Union would be expected at frequencies above 10 Hz. [From: J.F. Evernden, "Selected Comments on the Decoupling Conference." (Footnote 29)] general, without extensive path calibration one cannot hope to locate an explosion by seismic means to better than 5-6 km. Even with an in-country network, estimates are still only about 3 km. (One does better at Semipalatinsk because the paths have been very well calibrated.) Also note that ACDA sponsored some field experiments many years ago that showed the limited utility of OSI.

APPENDIX II: NUCLEAR SAFETY DEFINITIONS

To a large extent, the following is taken from Section IV of the Drell Panel Report on Weapon Safety.

Enhanced Nuclear Detonation Safety (ENDS):

The concept of a modern ENDS system was developed at the Sandia National Laboratories in 1972 and introduced into the stockpile starting with the Air Force B61-5 bomb in 1977.

The ENDS system is designed to prevent premature arming of nuclear weapons subjected to abnormal environments. The basic idea of ENDS is the isolation of electrical elements critical to detonation of the warhead into an exclusion region which is physically defined by structural cases and barriers that isolate the region from all sources of unintended energy. The only access point into the exclusion region for normal arming and firing electrical power is through special devices called strong links that cover small openings in the exclusion barrier. The strong links are designed so that there is an acceptably small probability that they will be activated by stimuli from an abnormal environment. Detailed analysis and tests give confidence over a very broad range of abnormal environments that a single strong link can provide isolation for the warhead to better than one part in a thousand. Therefore, the stated safety requirement of a probability of less than one in a million requires two independent strong links in the arming set, and that is the way the ENDS system is designed. Both strong links have to be closed electrically -- one by specific operator-coded input and one by environmental input corresponding to an appropriate flight trajectory or spin motion appropriate to its flight profile -- for the weapon to arm.

In addition to the strong links, there is one weak link also located in the exclusion region. The weak link would be open or broken, thereby preventing arming, if environmental conditions exceeded set bounds; for example, if there were a temperature excursion due to fire. Weak links are functional elements critical to the normal detonation process that are designed to fail, or become irreversibly inoperable in less stressing environments than those that might bypass and cause failure of the strong links.

Insensitive High Explosive (IHE):

The following table[39] shows several measures that are indicative of the different detonation sensitivities of conventional and insensitive high explosives:

Sensitivity Measure	Conventional HE	IHE
Minimum explosive charge to initiate detonation (ounces)	~ 10^{-3}	›4
Diameter below which detonation will not propagate (inches)	~ 10^{-1}	1/2
Shock pressure threshold to detonate (kilobars)	~ 20	~90
Impact velocities required to detonate (miles/hour)	~ 100	~1200-1300

Fire Resistant Pits (FRP):

The *pit* of a nuclear weapon is that part of the *primary*, or first stage of the weapon, that contains the plutonium. If the plutonium is encased within a ductile, high melting-point metal shell that can withstand prolonged exposure to a jet fuel fire (~1000 ^{o}C) without melting or being eaten through by the corrosive action of molten plutonium, it qualifies as a FRP. The plutonium itself may melt, but will remain contained within the encasing shell and not be dispersed into the environment.

FRPs may fail to provide containment against the much higher temperatures created by burning missile propellant. They would also fail in the event of detonation of the high explosive surrounding the pit.

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[39]This table and the following one are adapted from the presentation to the Drell Panel by Lawrence Livermore National Laboratory on June 19, 1990.

Missile Propellant:

Two classes of propellants are used in long range ballistic missiles in the U.S. One is a composite called the "1.3 class" and the other is a high energy propellant called the "1.1 class." Their relevant properties are listed in the table below:

Property	1.3 Composite	1.1 High Energy
Minimum explosive charge to initiate detonation (ounces)	›350	~ 10^{-3}
Diameter below which detonation will not propagate (inches)	›40	~ 10^{-1}
Shock pressure threshold to detonate (kilobars)	(1)	~ 30
Specific impulse (seconds)	~ 260	~ 270

(1) No threshold established.