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Transparency Measures for Subcritical Experiments Under the CTBT

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This paper outlines transparency measures that could be taken to build international confidence that "subcritical experiments" conducted underground by the U.S. or any other country do not violate the Comprehensive Test Ban Treaty. Our calculations suggest that on-site measurement of the integrated radiation output from these experiments should be adequate to verify that nuclear yields greater than grams of TNT equivalent had not occurred, even allowing for the possibility of substantial shielding. However, our calculations also indicate that a pure fission experiment that remained strictly subcritical for its entire duration should have a yield no greater than 0.1 microgram TNT equivalent, even given irradiation by an external deuterium-tritium neutron source. Experiments involving chemical-implosion-induced deuterium-tritium fusion could have yields above this limit, and may require fission product measurements in addition to prompt radiation measurements to rule out a supercritical test.

INTRODUCTION

In October 1995, the Department of Energy (DOE) announced a series of experiments which it said would help determine the impact that aging plutonium and new methods of producing replacement plutonium components for warheads will have on the reliability of the U.S. nuclear weapon stockpile. This series of "subcritical experiments" is to be conducted underground at the Nevada Test Site. In a 1996 article in *The Bulletin of the Atomic Scientists*, we suggested that the need for each proposed subcritical experiment be reviewed by an independent panel; that a study of above-ground alternatives be conducted; and, in the event that any experiments go forward, that arrangements be made for transparency measures sufficient to build international confidence that the experiments are subcritical.[1] Subsequently, the DOE decided that the need for the experiments had already been adequately reviewed by the JASON group of consultants,[2] but that it would support a study of

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above-ground options by the JASONs.[3] At the time of this writing, it has not agreed to provide the international community with any physical data bearing on the subcriticality of the experiments.

THE NEED FOR TRANSPARENCY

The Comprehensive Test Ban Treaty (CTBT) will ban both full-scale and low-yield nuclear tests, including so-called "hydronuclear" tests which were defined by the U.S. government in the CTBT negotiations as having a nuclear yield of less than 4 lb (1.8 kg) TNT equivalent. However, according to the United States' interpretation, the CTBT would permit the proposed subcritical experiments in which conditions for an exponentially growing fission chain reaction would not be created. The controversy surrounding the proposed tests originates in the fact that they will involve both fissile material and high explosives, and will be conducted underground at the Nevada Test Site in the "Low-Yield Nuclear Experimental Research" (LYNER) facility. Although its official name was recently changed to "U1a," the LYNER facility was designed for hydronuclear tests.

One reason for building the LYNER facility below ground is the difficulty associated with predicting the yield of hydronuclear tests and therefore the possibility that they might significantly overshoot their design yield. This possibility arises from the fact that the yields of hydronuclear tests are extremely sensitive to certain design parameters. Although concerns about overshoots should not apply to experiments that are designed to be safely subcritical, the DOE would like to use the LYNER facility for subcritical tests, now that hydronuclear tests are prohibited.

Seen from space, activity at the test site associated with an underground subcritical test would be virtually indistinguishable from that for any other underground experiment, including a hydronuclear test. Seismic measurements can place an upper limit on the total explosive yield of a test, adequate to rule out the possibility that a full-scale nuclear test had been conducted. But seismic data would be of no use in determining what fraction of the energy from an explosion was nuclear. If other countries wished to know whether a subcritical or hydronuclear experiment had taken place, how could they tell the difference?

Evidence that this question is not purely academic is provided by alleged activities at the Russian nuclear test site Novaya Zemlya, near the Arctic Circle in January 1996. According to leaks to the *Washington Times*, intelligence information on these activities led some U.S. officials to suspect that a nuclear test had occurred. One government official was quoted as saying that "many Pentagon officials have few doubts and believe Moscow set off a small nuclear

weapon." In the same article, however, State Department spokesman David Leavy was quoted as saying, "It is the view of the United States that the Russian moratorium on nuclear testing is continuing."[4]

The confusion may have arisen in part from the fact that a seismic array in Norway detected a magnitude 2.5 event in the Novaya Zemlya region on January 13, 1996. A seismic signal of this magnitude would correspond to a well coupled[5] underground explosion of a few tons of TNT, or about a thousand-ton decoupled explosion.[6] Later data analysis by the independent Incorporated Research Institutions for Seismology determined, however, that the event was an earthquake—not at the test site, but under the sea.[7]

RADIATION OUTPUTS

If the subcritical experiments are performed underground, the only way to assure the international community that they are in fact subcritical would be through on-site monitoring. This could be accomplished by allowing an international organization to measure the intensity of neutron and gamma-ray radiation from the experiments. Using above-ground detectors to monitor the radiation from underground experiments would not be effective because, for example, the tunnels in which the U.S. tests are to be conducted are 300 meters deep, while the attenuation lengths of 1 MeV neutron and gamma rays in rock are on the order of 10 cm. Any radiation monitoring would therefore have to take place underground in the experimental facility.

We have estimated an upper bound on the nuclear yield that could be achieved from a sample of fissile material assembled to near-criticality by high explosives, and compared the resulting radiation to that from a typical hydronuclear experiment. As will be seen below, these radiation fluences are likely to differ by many orders of magnitude. We have used MCNP, a Monte Carlo transport code, in making our estimates, though nearly all can be checked with simple "back of the envelope" calculations.[8]

4 LB HYDRONUCLEAR EXPERIMENT

An experiment at the upper end of the hydronuclear range, with a fission energy yield equivalent to the detonation of 4 lb of chemical explosives, would release 5.2×10^{19} MeV (8.4×10^{6} joules) of energy.[9] When a Pu-239 nucleus is fissioned by a fast neutron, it releases about 3 fission neutrons of average energy about 2 MeV each, about 7 prompt gamma rays of average energy about 2 MeV each, and fission fragments carrying about 165 MeV for a total prompt energy release of approximately 185 MeV. About 3×10^{17} fissions are therefore required to generate the 5.2×10^{19} MeV of a 4 lb explosion.

Some of the neutrons and gamma rays will be captured in the plutonium or the high-explosive material and others will escape. MCNP finds that about one gamma ray and one neutron, each carrying about 1 MeV on average, will escape per fission from a 5 kg sphere of weapon-grade plutonium[10] surrounded by a spherical shell of high explosive 10 cm thick.[11] Thus, about 3×10^{17} neutrons and 3×10^{17} gamma rays would escape from a 4 lb hydronuclear test. A detector placed 2 m from the experiment would see fluences of about 6×10^{11} gamma rays or neutrons per cm^2.

SUBCRITICAL EXPERIMENTS

We have estimated *upper limits* on the radiation outputs from subcritical experiments, with and without an external neutron source, using the following simple model: a 7.5 kg solid sphere of weapon-grade plutonium of radius 4.81 cm surrounded by a 10 cm thick shell of high explosive weighing 25 kg. According to MCNP, $k_{eff} = 1$ to within 0.1 percent for this system.[12] We imagine that this system has been assembled to $k_{eff} = 1$ by the high explosives and remains so for one microsecond, or about 100 neutron generations.[13]

It should be emphasized that during a real experiment, k_{eff} would not remain constant, but would rise to a peak value and then fall. Therefore, a subcritical experiment could not hover just below criticality for this long. The assumption that $k_{eff} = 1$ for 100 generations has been made in the interests of obtaining a conservative upper limit.

In the absence of an external neutron source, there would be some neutrons and gamma rays emitted by the plutonium due to spontaneous fissions of Pu-240 and Pu-242. One kilogram of weapon-grade plutonium, containing 6 percent Pu-240, emits about 5.5×10^4 spontaneous neutrons (resulting from 2.8×10^4 spontaneous fissions) per second.[14] The 7.5 kg of plutonium we are considering would therefore have 2.1×10^5 spontaneous fissions per second, or 0.2 per microsecond. Although the probability is only 0.2 percent, if we assume for the purposes of establishing an upper bound that a spontaneous fission occurs within 10 nanoseconds (one neutron generation) of the sphere reaching criticality, then if $k_{eff} = 1$ for 100 generations, 100 fissions (less than a picogram TNT equivalent) will take place and about 100 neutrons and 100 gamma rays, both of average energy 1 MeV, would escape. A detector placed 2 m from the experiment, would see fluences of 2×10^{-4} γ/cm^2 and 2×10^{-4} neutrons/cm^2 from these fissions. Any effort to detect these small neutron or gamma-ray fluxes during the one microsecond period of interest would likely yield a null result.

In addition to these neutrons and gamma rays of fission origin, there would be a background of gamma rays as a result of alpha and beta decays of Pu-240 and Am-241. These decays would also contribute fluences at 2 m of about 10^{-4} γ/cm^2 with average energies of a few hundred keV each in the one microsecond measurement interval.[15] The terrestrial gamma ray background would contribute roughly another 10^{-5} γ/cm^2 of average energy several hundred keV in one microsecond.[16]

An external neutron source would increase the number of fissions and therefore of neutrons and gamma rays emitted. Typical industrial pulsed neutron sources generate neutrons by colliding 50 keV deuterons (D) and/or tritons (T) with a fixed target containing deuterium and/or tritium to give the fusion reaction: $D + T \rightarrow He^4 + n + 18$ MeV.[17] The neutron carries about 14 MeV of kinetic energy and is emitted nearly isotropically. Commercially available neutron sources can produce 10^8 neutrons in a 3.5 μs pulse.[18] Our estimates assume a source size of 10^8 neutrons emitted in a pulse of negligible width—again in the interests of an upper limit.[19]

We assume that such a neutron source is placed 0.5 m from the center of the subcritical experiment. Our MCNP simulation then calculates a yield of 1.5×10^7 fissions (0.09 μg TNT) and radiation fluences from the critical assembly of 38 neutrons/cm^2 and 35 γ/cm^2 2 m away. The neutron and gamma-ray energy spectra are shown in figures 1 and 2. The neutrons and gamma rays have average energies of 1.0 MeV each. If the 14 MeV neutron source is 2 m from the detector and there is a clear line of sight between them, then the neutron fluence directly from the source is simply $10^8/4\pi(200)^2 =$ 200 neutrons/cm^2.[20]

Though quite low themselves, these upper limits on the yield and radiation output from a subcritical experiment are conservatively high. A more realistic estimate may be made by scaling the size of the subcritical experiment down such that $k_{eff} = 0.8$.[21] The lower criticality and the smaller volume exposed to the neutron source would reduce the yield to 3.7×10^5 fissions (2.3 ng TNT) for fluences of 1.2 neutron/cm^2 and 0.8 γ/cm^2 2 m away.[22] All of the above results are summarized in table 1.

In principle, the DT neutron source assumed here could be replaced by a fast critical assembly that could deliver as much as 10^6 times more neutrons in a microsecond.[23] Although it is unlikely that a reactor of this type would be licensed for this application in the U.S., other countries might use one. The results presented here would have to be scaled to account for such a case.

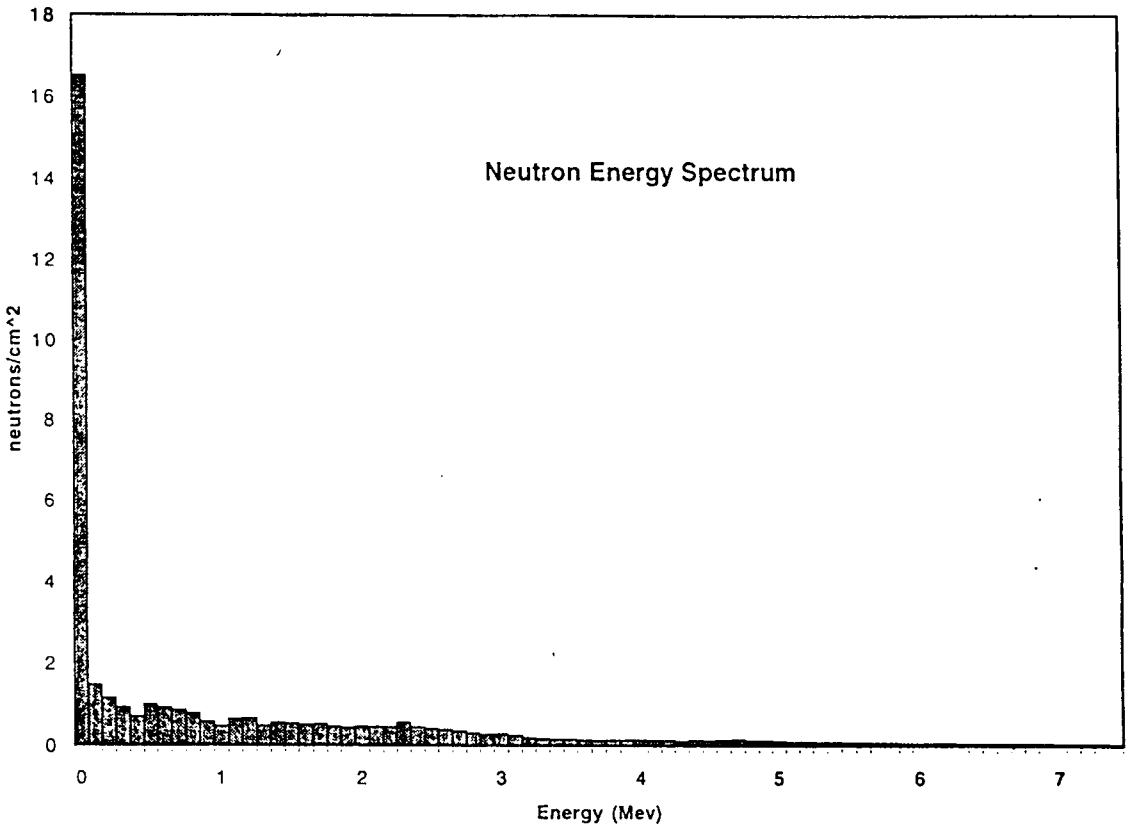

Figure 1: MCNP result for neutron fluence versus energy at 2 m from the subcritical experiment (k_{eff}=1 for 100 neutron generations) with external source. Neutron moderation by the high explosive around the plutonium has severely distorted the original fission spectrum. About 40 percent of the entries in the first bin (15 percent of the total spectrum) fall below 1 eV.

DT IMPLOSION

In 1992, an international conference on implosion physics was held in honor of the Russian implosion designer, E. I. Zababakhin, at Chelyabinsk-70 in Russia. The topics addressed included experiments involving the implosion of DT gas using high explosives. Such experiments are known to have been conducted by the U.S. weapons labs as well, and are asserted by some to be a class of "subcritical experiment" permissible under the CTBT.

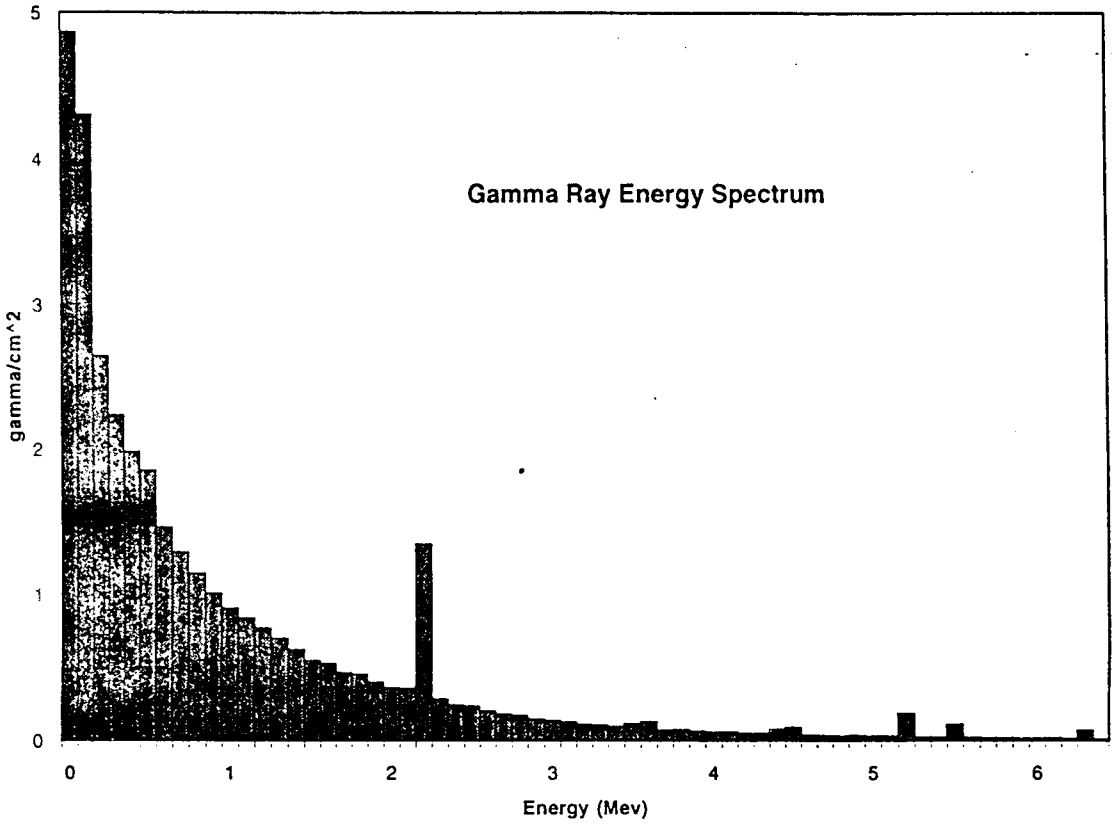

Figure 2: MCNP result for gamma-ray fluence versus energy at 2 m from the subcritical experiment (k_{eff} = 1 for 100 neutron generations) with external source. The peak at 2.3 MeV is from neutron capture in hydrogen in the high explosive.

According to abstracts from papers presented at the Zababakhin conference, the largest number of fusion reactions attained in Russian experiments involving the high-explosive-induced implosion of DT gas was on the order of 10^{13}.[24] Such yields appear to have been attained using rather elaborate techniques involving multiple concentric shells of materials of different densities. At 18 MeV released per fusion and 3×10^{16} MeV/gTNT equivalent, 10^{13} fusion reactions correspond to a fusion yield of 6 mg TNT. To estimate the radiation output from such an experiment, we have used MCNP to simulate a 14 MeV neutron point source at the center of a 100 kg HMX sphere. Note that we have neglected other materials, such as shells of heavy metal. As the neutrons pass

Table 1: Yields, particle fluences (n/cm^2 or γ/cm^2) and average particle energies ($\bar{E}_n$ or $\bar{E}_\gamma$) that would result at 2 m from the subcritical experiments (SCE), hydronuclear experiments (HNE), and DT implosions described in the text. The energy fluence (MeV/cm^2) reaching the detector can be obtained by multiplying the particle fluence by the average particle energy.

Scenario	Yield (TNT eqv.)	n/cm^2 ($\bar{E}_n$ MeV)	γ/cm^2 ($\bar{E}_\gamma$ MeV)
SCE, spont. fission only	<1 pg	$<2 \times 10^{-4}$ (1)	$<2 \times 10^{-4}$ (1)
SCE w/ext. source, $k_{eff} = 0.8$†	2.3 ng	1.2 (1.0)	0.8 (1.0)
SCE w/ext. source $k_{eff} = 1$†	0.09 μg	38.0 (1.0)	35.0 (1.0)
DT Implosion†	6 mg	9.2×10^6 (6.8)	8.7×10^6 (2.3)
DT Implosion Inside Pu†	162 mg	9.6×10^7 (1.9)	6.7×10^7 (1.1)
4 lb HNE	1.8 kg	$\approx 6 \times 10^{11}$ (1)	$\approx 6 \times 10^{11}$ (1)

†. Indicates that yield, fluences, and energies were calculated by MCNP.

through the high explosive, gamma rays are produced as a result of inelastic scattering and neutron capture. MCNP finds fluences of 9.2×10^6 neutrons/cm^2 and 8.7×10^6 γ/cm^2 2 m away (see table 1). The average energies of the neutrons and gamma rays are 6.8 MeV and 2.3 MeV respectively. The energy spectra are shown in figures 3 and 4.

DT IMPLOSION INSIDE PLUTONIUM

Another possible subcritical experiment could involve the implosion of DT inside a plutonium shell. Some fusions would take place and could serve as an internal neutron source or perhaps be relevant to the study of plutonium-boost-gas mixing during the implosion.[25] The number of fusion reactions that could be produced by a simple chemical implosion system is unclear, but presumably considerably less than achieved by the complex designs described in the Zababakhin proceedings. We will assume 10^{13} fusions (6 mg TNT), but the results may be scaled for lower fusion yields. Using MCNP to simulate a point source of 10^{13} 14 MeV neutrons at the center of our subcritical model with $k_{eff} = 0.8$, we found a fission yield of 2.5×10^{13} fissions (156 mg TNT). Fluences of about 1.1×10^7 neutrons/cm^2 and 8.6×10^6 γ/cm^2 of fusion origin would result at 2 meters, with average energies of 9.0 MeV and 1.7 MeV per particle, respectively. In addition, fluences of about 8.5×10^7 neutrons/cm^2 and 5.8×10^7 γ/cm^2 of fission origin would result at 2 meters, with average energies of 1.0 MeV each. The total fluences and average particle energies are given in table 1.

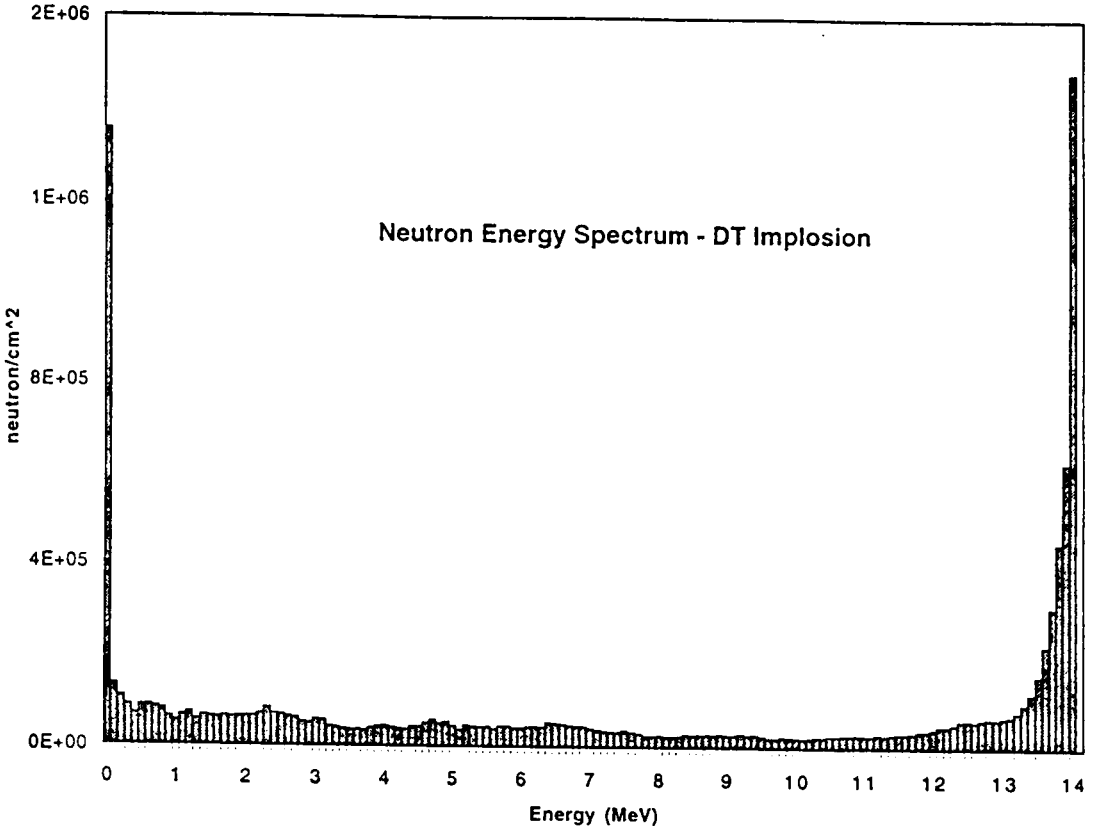

Figure 3: MCNP result for neutron fluence versus energy at 2 m from the pure DT implosion experiment described in the text.

MEASUREMENTS

Measurements of the prompt radiation from the experiments considered above could be made using a plastic scintillator coupled to a photomultiplier or photodiode (see Appendix A). Such a detector would provide a value for the energy fluence striking the detector which, when combined with estimates of the average energy per particle and losses suffered between the experiment and detector, could be used to calculate a yield. Alternatively, prompt radiation

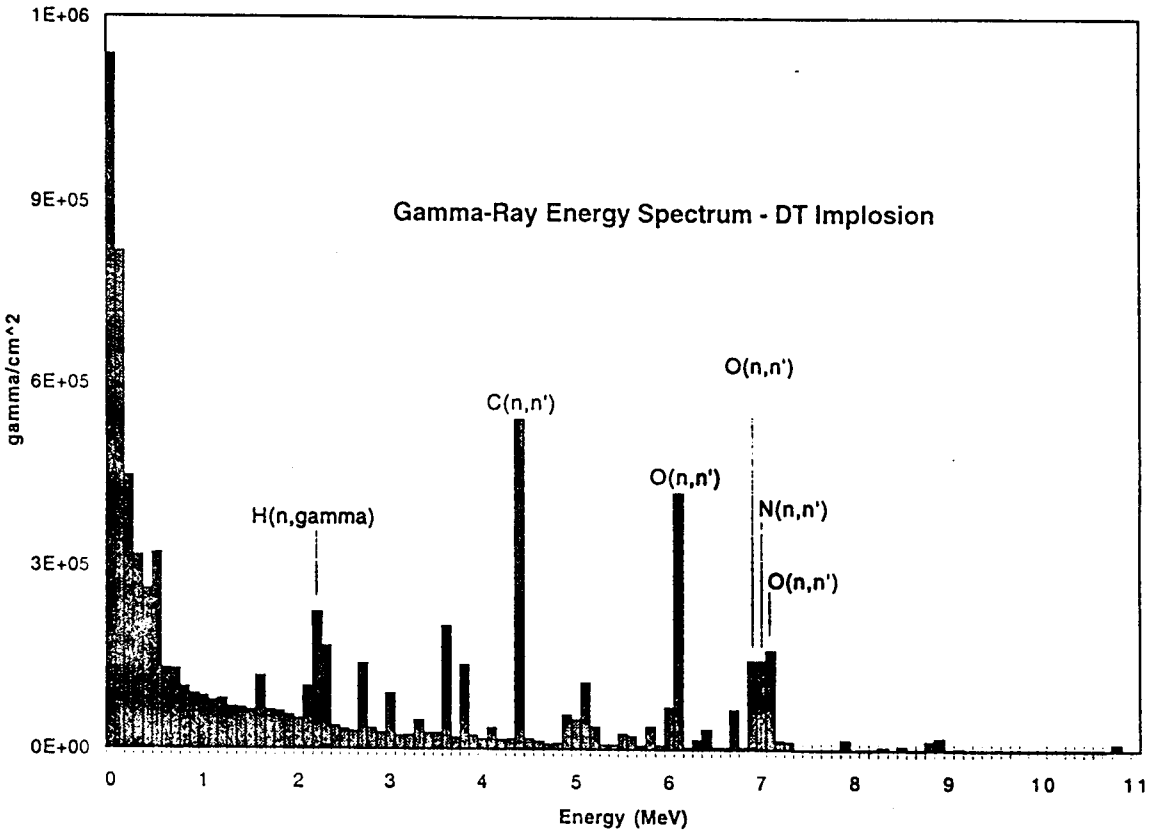

Figure 4: MCNP result for gamma-ray fluence versus energy at 2 m from the pure DT implosion experiment described in the text. The characteristic spikes arise from inelastic scattering and radiative capture of the high-energy neutrons in the high explosive.

could also be measured by including a sample of material, such as dosimetry film or activation foil, that could be recovered and analyzed after the experiment.

Measurements of radiation from any fission products present could also be useful. For example, one might measure the gamma-ray energy spectrum in the region of a gamma-ray line expected from a fission product such as I-131. This isotope has a half life of 8 days and emits a 364 keV gamma ray in 79 percent of its decays. Our estimates suggest that this line should be readily detectable for yields as small as one milligram (see Appendix B). Such a mea-

surement could be used to estimate the yield, or, if combined with a prompt radiation measurement, to distinguish a fission experiment from a pure-DT implosion experiment, from which no fission products would result.

PROTECTION AGAINST DECEPTION

Possible deception is a concern, particularly if the on-site monitors are not the last people out of the experimental area before the test takes place. Efforts to evade detection of a CTB-violating test could include the following: (1) interruption of power to the detectors or interruption of or substitution for the signal during the measurement; (2) movement of the detector or experiment; (3) destruction of verification instrumentation by high explosives just before the experiment takes place (if the monitoring equipment is expected to be destroyed by the experiment); and (4) the emplacement of shielding around the experiment to reduce the radiation flux reaching the detector.

The first class of possibilities represents standard concerns for fissile-material safeguards. The detector could be equipped with a battery-operated device, similar to those included with many electric clocks, that would flag a power interruption. The integrity of the signal line between detector and readout electronics could be ensured by transmitting a periodic fiducial signal, perhaps every tenth of a second or so, that would set off an alarm were it interrupted.

The second concern might be addressed by placing the signal cable and detector inside a rigid pipe. Verifying that the location of the experiment remained fixed would be more difficult. Perhaps seismic detectors placed in the corridor outside the test chamber could, by triangulation, verify the position of the explosion.

The third possibility could be handled by using a sample of recoverable material as discussed earlier. Alternatively, the scintillation detector could be hardened against the explosion, perhaps by also placing it inside a steel pipe.

We have studied the fourth possibility by looking at the shielding capacity of a number of materials. The closer the detector is placed to the experiment, the more confidence one would have that the experiment was not heavily shielded. As we have assumed that the detector would be within 2 m of the experiment, we have considered shields with a maximum thickness of 50 cm.

A good neutron shield combines a light element for moderation with an element of high thermal neutron absorption ability. LiH is a good example. Li-6 makes up 7.5 percent of natural Li and has a thermal neutron cross section of 940 barns (940×10^{-24} cm^2). Li-7, which has a thermal cross section of about 0.04 barns, makes up the other 92.5 percent. The high thermal neutron

Table 2: Particle fluence, average particle energy, and energy fluence shielding factors for various materials calculated using MCNP. The shielding factor is an estimate of the reduction in energy fluence that would occur when a high-explosive-driven pure-fission experiment is surrounded by a shielding material. MCNP was used to calculate the effect of a spherical shell of material 20 cm or 50 cm thick on the model subcritical experiment for which $k_{eff} = 1$. The particle fluences were then scaled up to correspond to a 4 lb hydronuclear experiment. Fluences are given 2 m away from the experiment. Values for unshielded 1 g and 0.1 μg experiments are given for reference at the bottom of the table. Statistical errors are a few percent.

	n/cm^2(E_n MeV)	n shielding factor	γ/cm^2(E_γ MeV)	γ shielding factor
4 lb HNE	6×10^{11} (1)	1	6×10^{11} (1)	1
LiH				
20 cm	8.4×10^{9} (1.7)	42	5.3×10^{11} (0.7)	1.6
50 cm	2.8×10^{7} (2.6)	8,240	3.2×10^{11} (0.6)	3.1
TiH_2				
20 cm	3.5×10^{9} (1.6)	107	2.2×10^{11} (2.1)	1.3
50 cm	4.6×10^{6} (3.0)	43,500	8.3×10^{9} (2.3)	31
Steel/H_2O)/B†				
20 cm	6.3×10^{10} (0.8)	12	2.0×10^{10} (1.2)	25
50 cm	1.5×10^{9} (0.5)	800	3.5×10^{8} (1.0)	1,714
Pb				
20 cm	4×10^{11} (0.6)	2.5	3.6×10^{9} (2.0)	83
50 cm	3×10^{11} (0.3)	6.7	9.0×10^{8} (2.6)	256
Reference Cases:				
0.1 μg SCE	38 (1.0)	1	35 (1.0)	1
1 g HNE	$\approx 3 \times 10^{8}$ (1)	1	$\approx 3 \times 10^{8}$ (1)	1

†. Assuming a 96:3:1 steel to water to boron weight ratio.

absorption cross section of Li-6 means that once a fission neutron has been moderated by collisions with hydrogen nuclei, it is very likely to be absorbed, even for relatively small concentrations of Li-6.[26] The neutron energy shielding factors from LiH and several other materials are given in table 2. Also shown are the neutron fluences that would result from a shielded 4 lb (TNT) hydronuclear experiment.

A good gamma-ray shield contains elements of high mass number (Z) because of their high density, large photoelectric cross sections at low gamma ray energy, and large pair production cross sections at high gamma-ray energy. However, the threshold for inelastic neutron scattering decreases with Z, so that high-Z shields will lead to production of additional gamma rays. This effect can be seen from the data in table 2. Although lead is an excellent gamma-ray shield, its effectiveness in this case is compromised by the production of gamma rays from neutrons. Despite its smaller gamma-ray attenuation coefficient, the iron in the steel/water/boron mixture has better overall gamma-shielding properties than lead when equal numbers of neutrons and gamma rays are incident on the shield.

None of the shields in table 2 provides the ten orders of magnitude reduction necessary to make the fluences from a 4 lb hydronuclear experiment appear to be consistent with those expected from a subcritical experiment. However, an optimized shield that included a layer of neutron-moderating/absorbing material and a layer of gamma-ray-absorbing material might be able to provide the roughly six-order-of-magnitude reduction necessary to bring the radiation fluences from a one gram test into the realm of those from a subcritical test. Such a shield might also be able to reduce the fluences from a 4 lb hydronuclear experiment by four or five orders of magnitude to levels comparable to those calculated for the DT implosion experiments. Therefore, if underground DT experiments were planned, transparency measures would need to be chosen such that they could distinguish these experiments from hydronuclear tests, for example, by combining prompt radiation measurements with fission product detection.

ACKNOWLEDGMENTS

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APPENDIX A: INSTRUMENTATION FOR PROMPT RADIATION DETECTION

As we have seen, one would expect the yield from a safely subcritical test to be less than a tenth of a microgram TNT equivalent, even if irradiated with a burst of neutrons. Ideally, any on-site monitoring method would be able to obtain a reasonably precise measurement of the yield down to this upper limit. One would also want to be able to measure higher yields, in the case of a treaty-violating event. A detection range of 0.1 micrograms (TNT) up to 10 grams (TNT) would be desirable. It is unlikely that a single detector would be able to cover a dynamic range this wide, however. Multiple detectors with a range of sensitivities would be necessary. The following appendix gives a basic description of the instrumentation required to detect the prompt radiation from an experiment and determine the yield.

Plastic scintillators are an appropriate choice for this application. Plastic scintillators have very short decay times (about a nanosecond), and they are sensitive to both gamma rays and neutrons. Gamma rays arriving at a rate of 35 $\gamma/cm^2\mu s$ striking a scintillator of area 100 cm^2 would each be separated by about 0.3 ns. Individual pulse counting would be impossible and the detector would have to be operated in "current mode." Current mode operation implies that traditional methods, such as pulse shape discrimination, by which one might separately resolve the gamma-ray and neutron signals will not be possible.

The sensitivity of a scintillation detector to a given particle type may be specified by the amount of output charge produced per unit energy incident on the detector. Parameters that determine this sensitivity include the energy deposition efficiency, the scintillation efficiency, the collection efficiency of the scintillation light on the photocathode, the quantum efficiency of the photocathode material, and the gain of the photomultiplier tube (PMT).

The energy deposition efficiency ε is calculated using the interaction cross section of the incident radiation in the scintillator material and the size and geometry of the material. The scintillation efficiency S of a material is defined as the fraction of the kinetic energy deposited by the particle that is converted to scintillation light. The scintillation efficiency for gamma rays in common plastic scintillators such as Bicron BC-400 and BC-404[27] is about 3 percent[28] and is linear (i.e., independent of the energy of the incoming particle) above about 125 keV.[29]

The collection efficiency C refers to the fraction of scintillation light that strikes the photocathode coupled to the photomultiplier. It is determined by the following: the photocathode area; the probability that scintillation light

will be absorbed and reemitted at a wavelength to which the photocathode is relatively insensitive; and the success with which reflective materials on the sides of the scintillator, optical coupling fluid between the scintillator and the window of the PMT, and light guides are used to minimize losses.

The quantum efficiency q of the photocathode is defined as the ratio of the number of photoelectrons produced at the photocathode to the number of incident photons. The quantum efficiency varies with the wavelength of the incident scintillation light; it is quoted at the wavelength of peak response of the photocathode, usually in the range 200–500 nm. Photocathode quantum efficiencies are in the range 20–30 percent for bi-alkali photocathodes whose spectral sensitivities are well matched to the emission spectra of plastics.[30]

Modulo corrections for nonlinearity in the response of the scintillator material[31] or in the photomultiplier tubes,[32] the overall sensitivity of the detector, defined as the output charge per unit incident neutron energy, may be estimated by the product:

$$\text{Sensitivity (Coul/MeV)} = \varepsilon \times S \times C \times G \times q\, e/E \qquad (1)$$

where G is the gain, E is the average energy of scintillation photons, q is the quantum efficiency at the wavelength corresponding to E, and e is the electron charge in coulombs. For example, taking $\varepsilon = 0.1$, $S = 0.03$, $C = 0.1$, $G = 10^6$, $q = 0.2$, and $E = 3.2$ eV, we find a sensitivity of 3×10^{-12} Coul/MeV. Given a detector area of 100 cm^2, the average output current from gamma rays of average energy 1.0 MeV from our 0.1 μg (TNT) subcritical experiment would be:

$$I = (3 \times 10^{-12}\ \text{Coul/MeV})\ (1.0\ \text{MeV})\ (35\ \gamma/\text{cm}^2)\ (100\ \text{cm}^2) / (1\ \mu\text{s}) = 0.01\ \text{A}$$

The contribution to the current from neutrons can be estimated in the same way, but the sensitivity must be calculated using values for ε and S specific to neutrons. In practice, this sensitivity would be determined by calibrating the detector using known sources.

Because the measured current is proportional to the energy fluence striking the detector, it will vary in time with the rate at which the radiation arrives. For a detector placed 2 m away from the experiment, gamma rays will arrive within 7 ns. Thus, their arrival over the one microsecond interval of interest will occur essentially instantaneously. The neutrons, in contrast, will have a range of speeds. The 14 MeV neutrons from a source 2 m away would require about 40 ns to reach the detector. One MeV neutrons would reach the detector in about 150 ns. Neutrons with energy below about 5 keV (over 30

percent of the neutrons that escape from the experiment) will require 2 μs to reach the detector. If the active time window of the detector is smaller than a few μs, these slow neutrons, which make up a small fraction of the total neutron energy fluence, will be lost.

A waveform digitizer or digital oscilloscope could be used to measure and store the voltage across a resistor through which the output current from the PMT or photodiode was sent. For instance, LeCroy makes a digital oscilloscope (9384 Series) with a maximum sample speed of 4 Gigasamples per second, 8-bit vertical resolution, and memory sufficient to store 8 million records, or 2,000 μs of data measured at 0.25 ns intervals.

Detectors spanning a range of sensitivities would be needed to obtain a measurable current from a wide variety of possible incident neutron fluences. One way this could be achieved would be by coupling multiple PMTs with various gain settings to the scintillator. A silicon photodiode might also be coupled to the scintillator to cover the high end of the dynamic range, as photodiodes have small areas and no gain.

Given complete knowledge of the experiment and the absence of significant background, a yield as low as 0.1 μg (TNT) should produce a measurable signal. However, uncertainties are likely to arise as a result of a lack of information about the experiment, which may be cloaked. For example, the distance between the detector and experiment may be poorly estimated, or the average energy assumed for the outgoing radiation might be incorrect due to incomplete knowledge of the thickness, geometry, and type of material through which the radiation passes before reaching the detector. Background radiation from a neutron or gamma-ray source would be comparable to the signal from a 0.1 μg (TNT) experiment, and would almost certainly require that the detector be shielded. Electromagnetic pulses (emps), to which PMTs and cables (though not photodiodes) would be sensitive, would be created by the detonation of high explosives and would make electromagnetic shielding necessary.[33] Although we believe that an experiment that seriously violated the subcritical threshold (by a gram or more) would be difficult to hide, very low-yield, but perhaps prohibited, experiments may not be measured with high confidence.

APPENDIX B: FISSION PRODUCT DETECTION

An estimate of the fission yield of an experiment could be made by searching for gamma rays from fission products. Gamma rays could be detected using a high-resolution detector such as high-purity germanium (HPGe).[34] One approach would be to measure the decay rate of a particular fission product relative to the decay rate of Pu-239. This ratio is related to the fission efficiency which, when multiplied by an estimate of the total amount of plutonium used in the experiment, would give the yield. Alternatively, one could use the measured decay rate of a given fission product to estimate the number of nuclei of that isotope present, the result of which would be proportional to the fission yield that had occurred. We explore the second approach in the following simple example.

There are many candidate fission products for detection, but here we will use I-131 which has a half life of 8 days, emits a 364 keV gamma ray 79 percent of the time, and makes up about 3.9 percent of the fission products created as a result of Pu-239 fission by fission-spectrum neutrons.[35] The number of I-131 atoms produced per TNT-equivalent gram of fission is:

$$(0.039 \text{ I-131/fission}) \times \frac{3 \times 10^{16} \text{ MeV/gTNT}}{185 \text{ MeV/fission}} = 6.3 \times 10^{12} \text{ I-131/gTNT} \quad (1)$$

With a mean lifetime of 10^6 s, the decay rate per gram of TNT equivalent is

$$\frac{dN_{\text{I-131}}(t)}{dt} = 6.3 \times 10^6 \, e^{-t/10^6 s} \text{ I-131 decays/gTNT} \quad (2)$$

For simplicity, let us imagine that a test with a nuclear yield equivalent to one milligram TNT occurred in a room with a combined floor and ceiling area of 100 m^2 over which the fission products were evenly spread and into which about half of the radiation is emitted. The flux in the room from the 364 keV line of I-131 would then be roughly:

$$(0.79) \times (0.5) \times \frac{6.3 \times 10^6 e^{-t/10^6 s}}{50 \text{ m}^2} \times 10^{-3} \text{ gTNT} = 50 \, e^{-t/10^6 s} \, \gamma/\text{m}^2\text{-s-gTNT} \quad (3)$$

HPGe detectors have a gamma-ray energy resolution of about 1 keV (FWHM) at 300 keV.[36] The terrestrial background rate in the region of 364 keV is about 40 γ/m^2-s-keV.[37] If we require a I-131 signal of 5σ significance, then we need the number of signal counts registered in the detector to be greater than or

equal to five times the statistical fluctuations in the background in the signal region:

$$A_S \varepsilon_S S t \geq 5\sqrt{A_B \varepsilon_B B t} \tag{5}$$

where A_S and A_B are the effective areas of the detector for signal and background, ε_S and ε_B are the efficiencies for signal and background events, S is the signal flux, B is the background flux, and t is the measurement interval. Approximating $A_S = A_B$ and $\varepsilon_S = \varepsilon_B$ and solving for t we find,

$$t \geq \frac{25B}{A_S \varepsilon_S S^2} \tag{6}$$

If a measurement is taken one day after an experiment with a fission yield of one milligram TNT equivalent, equation (3) gives S = 46 γ/m^2s. Taking a signal region of width 2 keV, we have B = 80 γ/m^2s. For $A_S = 0.003$ m^2 and $\varepsilon_S = 0.2$ we find that a signal of 5σ significance would be obtained after about 10^3 seconds of counting.[38]

NOTES AND REFERENCES

1. von Hippel, F. and S. Jones, "Take a Hard Look at Subcritical Tests," *The Bulletin of the Atomic Scientists*, (November/December 1996), p. 44.

2. *Nuclear Testing*, JASON report #JSR-95-320, McLean, VA:Mitre Corp., (August 3, 1995).

3. *Subcritical Experiments*, JASON report #JSR-97-300, McLean, VA:Mitre Corp., (January 21, 1997).

4. Gertz, B., "U.S. Officials Suspect Russia Staged Nuclear Test This Year," *The Washington Times*, (March 7, 1996), p. A3.

5. "Decoupling" refers to the reduction in seismic signal that can result when an explosion is detonated in a large underground cavity.

6. van der Vink, G. and T. Wallace, "The Political Sensitivity of Earthquake Locations," *IRIS Newsletter*, Vol. XV, No. 3, (Fall 1996), pp. 20–23.

7. *Ibid.*

8. MCNP, "A General Monte Carlo Code for Neutron and Photon Transport," Version 4A, Los Alamos National Laboratory, (1994).

9. The standard assumption is made that the detonation of one short ton (2,000 lb) of chemical explosive yields 10^9 calories (4.2×10^9 J) of energy. Therefore, about 3×10^{16} MeV are released per gram of TNT detonated.

10. Assumed throughout the paper to be δ-phase weapons grade plutonium of density 16 g/cc, though in fact the implosion would result in a higher density. For isotopic composition see *Reversing the Arms Race: How to Achieve and Verify Deep Reductions in the Nuclear Arsenals*, F. von Hippel and R. Sagdeev, eds., Gordon & Breach Science Publishers, New York, (1990), p. 266.

11. Assumed throughout the paper to be HMX of chemical composition $C_4H_8N_8O_8$ and density 1.9 g/cc, though in fact the explosive would have expanded somewhat as a result of the explosion. See *Reversing the Arms Race*, p. 299.

12. The quantity k_{eff} represents the neutron multiplication factor, i.e., the ratio of the number of neutrons in successive generations. See S. Glasstone and A. Sesonske, *Nuclear Reactor Engineering*, 4th Ed., Chapman & Hall, New York, (1994), p. 151.

13. This value corresponds approximately to the number of generations in a fission explosive in which $k_{eff} \approx 2$ and may be seen as follows: if one neutron sets off a chain reaction in a system in which $k_{eff} = 2$ throughout, then the nth generation of neutrons will contain 2^{n-1} neutrons. In this case, about 81 generations would be required to fission the 2.5×10^{24} nuclei in one kilogram of plutonium ($2^{81} = 2.4 \times 10^{24}$). For the supercritical assembly whose early hydrodynamics are being simulated in the subcritical experiments, the velocity of a 2 MeV neutron is $\approx 2 \times 10^9$cm/s and its mean free path in weapon-grade plutonium between fissions is about 10 cm, so that the time between fissions is on the order of 10^{-8} s. At 10^{-8} s per generation, a 100-generation chain reaction would take less than one microsecond. For further discussion see Robert Serber, *The Los Alamos Primer*, University of California Press, Berkeley, (1992), pp. 9–10, and C. Mark, "Explosive Properties of Reactor-grade Plutonium," *Science and Global Security*, Vol. 4, (1993), p. 118.

14. About 2 neutrons are produced per spontaneous fission. *Reversing the Arms Race*, p. 315. We have neglected the additional neutrons from (α, n) reactions in the plutonium, a roughly 2 percent correction. *Ibid.*, p. 269.

15. Ten year old weapon grade plutonium emits about 130,000 γ/g-s of average energy about 400 keV (*Reversing the Arms Race*, p. 384). If we assume that half of those gamma rays produced within one mean free path (≈ 0.2 cm for 400 keV gamma rays in Pu) of the surface of the plutonium sphere escape from it, then about $0.5 \times (4\pi/3)(4.81^3 - 4.61^3$ cc$) \times 16.0$ g/cc $\times$ 130,000 γ/g-s $= 6 \times 10^7$ γ/s will escape for a fluence at 2 m of 10^{-4} γ/cm^2 per 1 μs.

16. The terrestrial gamma ray background at sea level is about 10 γ/cm^{2}s, and would be somewhat larger deep underground. It may also diverge from this value due to variations in the local uranium concentration. The cosmic gamma-ray flux at sea level is only about one percent as large as the terrestrial gamma ray background there, and would be in any case negligible 300 meters underground. Similarly, charged cosmic rays would not be significant during the 1 μs time interval of interest, as their flux at sea level is about 200 particles/m^{2}s.

17. The D-T reaction cross section is near maximum at 50 keV. See *A Physicist's Desk Reference*, American Institute of Physics, (1989), p. 118.

18. See *Reversing the Arms Race*, p. 367, note 3.

19. In the case of the 3.5 μs pulse emitting 10^8 neutrons, this assumption over-estimates the upper limit by a factor of about 7. This may be seen by assuming a square pulse: 1/3.5 fewer source-induced fissions would actually occur during the 1 μs window of criticality and would do so on average halfway through the experiment for a total of 50 generations at $k_{eff} = 1$ rather than 100 generations ($3.5 \times 2 = 7$).

20. These source neutrons would complicate efforts to measure the fluences from an experiment of such a small yield unless shielding or some other means were employed to reduce the source fluence reaching the detector.

21. In this case, the experiment becomes a 3.5 kg solid sphere of weapon-grade plutonium of radius 3.75 cm surrounded by a 10 cm thick shell of high explosive weighing 20 kg.

22. The fact that $k_{eff} = 0.8$ means that each neutron causes $(1 - k_{eff})^{-1} = 5$ additional generations instead of 100, for a factor of 20 reduction in yield. Another factor of 1.6 reduction can be attributed to the smaller effective area of the sphere: $4.81^2/3.75^2 = 1.6$. Finally, a larger fraction of the fast neutrons pass through the smaller mass of plutonium without causing fissions for an overall factor of about 35.

23. The Sandia Pulse Reactor II delivers a burst of about 10^{16} fission neutrons in a pulse 40 μs FWHM. See, "Radiation Facilities," Sandia National Laboratory, (brochure), (December 1989), p. 11.

24. 3rd Zababakhin Scientific Readings (Abstracts), (January 14–17, 1992), Chelyabinsk-70.

25. It is believed that the fission yields of most or all modern fission primaries are "boosted" by internal D-T fusion. See, e.g., T. Cochran, W Arkin, and M. Hoenig, *U.S. Nuclear Forces and Capabilities*, Cambridge, Bellinger, (1984).

26. If the natural LiH is replaced with 100 percent Li-6-enriched LiH, the neutron shielding effect is the same, implying that in natural LiH, the shielding effect is already limited by the elastic scattering cross section in hydrogen.

27. Formerly NE-102 and PILOT-B, respectively.

28. Clark, D., "The Intrinsic Scintillation Efficiency of Plastic Scintillators for ^{60}Co Gamma Excitation," *Nuclear Instruments and Methods*, Vol. 117, (1974), p. 295.

29. Knoll, G., *Radiation Detection and Measurement*, Wiley, New York, (1989), p. 248.

30. Plastic scintillators, such as BC-400 and BC-404, have emission spectra that peak between 400–440 nm. The spectral response of typical bialkali photocathodes, Sb-K-Cs, for example, peaks between 400–450 nm.

31. Leo, W., *Techniques for Nuclear and Particle Physics Experiments*, Springer-Verlag, Berlin, (1987), pp. 130–3.

32. Knoll, pp. 290–1.

33. PMTs are traditionally protected from magnetic fields by surrounding them with μ-metal. Dark currents in the PMTs are about a nanoamp and would not be significant compared to currents of the size expected from a 0.1 μg (TNT) test.

34. See G. Knoll, *Radiation Detection and Measurement*, Wiley, New York, (1989), Ch. 13, for a discussion of these detectors.

35. Rider, B.F., "Compilation of Fission Product Yields," NEDO-12154-3C, ENDF 322, 1981.

36. Knoll, p. 500.

37. Based on data taken from R.R. Finck, K. Liden, and R.B.R. Persson, "In Situ Measurements of Environmental Gamma Radiation by the Use of a Ge(Li)–Spectrometer," *Nuclear Instruments and Methods*, Vol. 135, p. 559, (1976). The background rate at the site of the experiment should be measured beforehand to adequately account for the radioactivity of the local rock. The plutonium dispersed throughout the room will also give rise to a set of characteristic gamma-ray lines; fission product signals must be chosen such that they are well enough separated from these plutonium lines so as to be resolved by the detector.

38. Values for A_S and ε_S taken from *Reversing the Arms Race*, p. 273 and R.R. Finck, *et al.*, respectively.