Hydronuclear Testing or a Comprehensive Test Ban?

by

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ABSTRACT

Hydronuclear tests--tests of nuclear weapons at yields less than about two kilograms of TNT equivalent--are useful for the assessment of new designs and the safety of existing designs.

Hydronuclear tests can serve a useful role in the development of the full spectrum of unboosted fission weapons, including first generation nuclear weapons of the implosion type with yields in the 10 to 30 kiloton range, more sophisticated designs with yields up to about a megaton, and advanced micro-nuclear weapons with yields of 5 to 500 tons. Since hydronuclear tests do not generate sufficient yield to create the conditions for fusion of deuterium and tritium in the core, such tests do not provide a reliable means if extrapolating the performance of new "boosted" fission weapons and thermonuclear primaries, or advanced thermonuclear secondaries.

In negotiating the Comprehensive Test Ban Treaty (CTBT) the current strategy of the U.S. Government is not to define in the treaty what constitutes a nuclear test. If this strategy is successful and the treaty is ratified, the U.S. Government will interpret the CTBT to permit hydronuclear testing if such a test is conducted by any other country. A program of hydronuclear testing by any of the weapon states will encourage the others to conduct similar tests, with the results of undermining the purpose of the treaty.

If hydronuclear tests are permitted under a CTB, the nuclear test sites of declared nuclear powers may be maintained, in part, to facilitate the conduct of hydronuclear tests. Such tests will make verification of the CTBT increasingly difficult. Since the marginal value of hydronuclear tests to insure the safety and reliability of existing stockpiled weapons is very small, they should be explicitly banned under the CTBT.

I. Introduction.

Hydronuclear tests are nuclear weapons tests, or high explosive driven criticality experiments, limited to subcritical, or slightly supercritical, neutron multiplication. As a consequence they release an insignificant, or at most a very small, amount of fission energy. The prefix "hydro" means in this instance that the fissile core of the nuclear device behaves like a fluid under compression by the chemical high explosive, and also if sufficient fission energy is released to melt the core; but the nuclear energy released is kept sufficiently small so that the core does not rapidly heat to plasma temperatures and explode "like a bomb." Thus, hydronuclear tests are generally limited to total nuclear energy releases, or "yields," of less than a few kilograms of TNT equivalent.

There are two categories of very low-yield nuclear weapon tests of interest. The first is for engineering development of new or modified nuclear warhead designs, and the second is to assess the safety assess of nuclear warheads. In conducting a hydronuclear test for weapon development, some of the fissile material in the core is removed--and perhaps substituted with non-fissile materials to preserve the geometry of the core--in order to substantially reduce the yield of the device. The rate of development of the chain reaction during the hydronuclear test can be measured experimentally and scaled to determine the rate of development of the chain reaction of the device with its full complement of fissile material. In conducting a safety test, the full complement of fissile material is included, but the chemical high explosive is initiated at a single point, rather than simultaneously at many points, to insure that the weapon will not explode like a bomb if the chemical high explosive is detonated accidentally.

In Section II we review of the physics of nuclear explosions and hydronuclear tests. Those who are less mathematically inclined may wish to proceed to Section III, which is a discussion of the most common types of nuclear warhead designs, to better appreciate which types of designs require nuclear testing and where hydronuclear testing would be beneficial under a Comprehensive Test Ban (CTB). This is followed by a discussion of hydronuclear testing as it relates to warhead safety (Section IV); then a discussion of the value of hydronuclear testing, if permitted under a CTB, in countries known to possess nuclear weapons (Section V). In Section VII we demonstrate that the United States is presently prohibited by law from conducting hydronuclear testing under the 1992 "Hatfield-Exon-Mitchell" Amendment. Finally, we conclude by arguing that the CTB Treaty (CTBT) should ban hydronuclear testing, and we propose CTBT language that would accomplish this.

II. Physics Primer on Fission Explosions and Hydronuclear Tests.[1]

To appreciate the difference between nuclear weapon explosions and hydronuclear tests, we begin by reviewing the basic equation describing the neutron chain reaction that applies to both situations. We then look at the time sequence of the energy released during the nuclear explosion to better understand the changes in the physical properties of the fissile material during the rapidly multiplying chain reaction. And finally, we examine how the hydronuclear tests differ from more powerful nuclear explosions.

In an actual weapon, a hydronuclear test device, or a reactor, it is necessary to achieve a chain reaction; whereby, neutrons emitted by fissioning nuclei induce fissions in other fissionable nuclei. The neutrons from these fissions, in turn, induce fission in still other fissionable nuclei, and so on. Prompt neutrons from fission are emitted with a continuous energy spectrum over several Mev, with an average energy of about 2 Mev.[2] The neutrons are slowed by collisions before being re-absorbed.

The average number of neutrons released per fission is denoted by ν. For fission by 1 Mev neutrons, $\nu = 2.95$ for plutonium-239, and 2.52 for uranium-235.[3] In a nuclear chain reaction a portion of these neutrons are captured by nuclei that do not fission, and a much larger fraction escape the material without being captured. The remaining portion cause further fissions.

We denote by f the fraction of neutrons that go on to cause fission, and define $k \equiv \nu f$, the average number of prompt neutrons at time t that go on to cause fissions. If there are N neutrons at a given instant, there will be Nk neutrons at the end of one generation. The increase in the number of neutrons is $Nk - N = N(k-1)$. Thus, the increase in the number of neutrons per neutron generation is (k-1). In a nuclear fission explosion, after the fissile core is assembled or compressed, (k-1) exceeds zero and a rapidly expanding chain reaction is initiated. In the case of hydronuclear tests, (k-1) is slightly positive (close to zero), and the chain reaction progresses much more slowly, or (k-1) is negative (between 0 and -1) in the case of subcritical experiments, and the chain reaction dies out unless it is maintained by an external source of neutrons.

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[1] Much of this discussion is derived from Robert Serber, *The Los Alamos Primer* (Berkeley: University of California Press, 1990; an annotated revision of Serber's 1943 lecture notes); J. Carson Mark, "Explosive Properties of Reactor-Grade Plutonium," *Science and Global Security*, 1993, Vol. 4, pp. 111-128; and Samuel Glasstone and Philip J. Dolan, *The Effects of Nuclear Weapons*, United States Department of Defense and Energy Research and Development Administration, 1977, Chapter 1.

[2] Serber, *The Los Alamos Primer*, p. 19.

[3] Serber, *The Los Alamos Primer*, p. 20. The kinetic energy of the neutron is expressed in units of million electron volts (Mev), where 1 Mev = 1.6×10^{-13} joules (j).

As the fission process releases energy the fissile material itself progresses through several states of matter depending on the amount of energy released. The material first heats up, then melts, then vaporizes, and finally ionizes as electrons are progressively stripped from the nuclei. The expansion of the fissile material results in greater neutron losses and fewer neutron captures and fissions, eventually resulting in (k-1) falling below zero if it were initially positive, at which point the chain reaction begins to die out.

To achieve a high efficiency in a nuclear explosion, a very rapid growth in the number of fissions is sought--that is, (k-1) needs to be larger than zero, and is typically between 0.2 and 1. In a hydronuclear test some of the fissile material is removed, and non-fissile isotopes can be substituted for them to preserve the original geometry. The value (k-1) is reduced to only a few percent, or less, of its value in a weapon, resulting in a chain reaction that takes considerably longer but releases significantly less energy.

For a quantitative understanding, it is convenient to express the rate of change in the neutron population during the chain reaction as

$$\frac{dN}{dt} = \alpha(t)\, N(t)\,, \qquad (1)$$

where $\alpha = (k\text{-}1)/\tau$, and τ is the mean time between fissions.[4] α is a measure of the rate of neutron multiplication at time t, or stated another way, $1/\alpha$ is proportional to the neutron doubling time.[5] While k, τ, and therefore α are all functions of time, it is often convenient to examine situations, which we do subsequently, where one or more of these parameters are constant in time.

As noted in *The Los Alamos Primer*, the speed of a 1 Mev neutron is 1.4×10^9 centimeters per second (cm/sec) and the total track length of a neutron between fissions in uranium-235 metal at normal density is about 13 cm, so the mean time between fissions, τ, is on the order of 10^{-8} seconds.[6] The first measurements of the mean time between fissions in uranium-235 metal, made at Los Alamos in 1944-45, found that $\tau = 1.25 \times 10^{-8}$ seconds, and only gradually decreased with increasing neutron speeds between 5×10^8 and 1×10^9 cm/sec. The value of τ varies inversely with the density of the fissile isotopes in the material. Consequently, the slightly larger value of τ may be due to the fact that the uranium manufactured for *Little Boy*, the bomb dropped on Hiroshima, was enriched to only about 80 percent in the fissile isotope U-235.

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[4] For those not mathematically inclined, $\frac{dN}{dt}$ is the calculus notation for the derivative of N with respect to t, and $\alpha(t)$ means α is a function of t.

[5] The instantaneous neutron doubling time is actually $T_d = \ln(2)/\alpha = 0.693/\alpha$.

[6] Serber, *The Los Alamos Primer*, p. 12.

In δ-phase plutonium metal at normal density the total mean track length is about 15 cm, so τ is about 1.1×10^{-8} seconds.[7] Since τ varies inversely with the density of the material, τ would be about 0.6×10^{-8} seconds for U-235 metal, and 0.7×10^{-8} seconds for δ-phase plutonium metal, when compressed on average to 1.5 times their normal density--densities typically achieved in an implosion type weapon. As the fissile nuclei are depleted by the fission process, τ increases. Also, during the disassembly phase of a weapon explosion the density of the material is considerably reduced and eventually drops toward zero, and τ becomes even larger. But for illustrative purposes, we will follow the lead of others by assuming $\tau = 10^{-8}$ seconds, and ignoring any variations in its value during the course of the nuclear explosion.

The period, 10^{-8} seconds, turns out to be a convenient unit of time, and it was defined during the Manhattan Project as one "shake." When time is measured in shakes, α is measured in shakes^{-1}; and when time is measured in micro-seconds (μs), α is measured in μs^{-1}.

In designing *Little Boy*, which used about 50 kg of 80%-enriched uranium surrounded by a thick tamper, α was estimated to be 0.2 per shake (20 μsec^{-1}), which implies (k-1) = 0.25 after assembly and prior to disassembly of the supercritical mass. Since the average number of neutrons released per fission of plutonium-239 nuclei by 1 Mev neutrons is about 0.4 higher, relative to the fission of uranium-235 nuclei, and α values between 0.7 and 1 per shake (70-100 μsec^{-1}) are readily achievable in plutonium fission weapons where the core is compressed on average up to 1.5 times the normal density. As will be discussed further below, in boosted fission weapons, once deuterium-tritium (DT) boosting is initiated α values even 10 times larger can be achieved for a fraction of a shake.

To simplify the mathematics we assume the chain reaction is not initiated until the core is fully compressed, and α is constant, at least during the initial phase of the chain reaction. Integrating equation 1, gives

$$N = N_o \, e^{\alpha t} , \qquad (2)$$

where N_o is the initial number of neutron.[8] The number of neutron generations is $t/\tau = \alpha t/(k-1)$. The rate of fissions is N/τ, and the rate of energy released, the power, is $E_f N/\tau$, where E_f is the energy released per fission. E_f equals 180 Mev per fission, or 6.89×10^{-24}

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[7] Mark, "Explosive Properties of Reactor-Grade Plutonium," p. 116. The density of δ-phase and α-phase plutonium are 15.7 and 19.6 g/cm^3, respectively. Since the track length is inversely proportional to density, the track length in α-phase plutonium is 15x(19.6/15.7) = 19 cm. The speed of a 1 Mev neutron is 13,800 kilometers per second (= 1.38×10^8cm/s).

[8] e is the constant irrational number 2.71828..., familiar to those who have had differential calculus. For convenience e^{at} is sometimes written, $\exp(\alpha t)$.

kilotons (kt) per fission.[9] The total energy released to time t, i.e., the weapon yield, is the integral of the power, or

$$W = E_f (N_o/\alpha\tau)\, e^{\alpha t} . \qquad (3)$$

We are now in a position to examine the sequence of events that take place during the course of a fission chain reaction occurring during a nuclear weapon explosion. For convenience we will assume that we have an efficient plutonium implosion weapon, such that $\alpha = 1$ per shake (or 100 μsec^{-1}). Note, that if we also assume $\tau = 1$ shake, then (k-1) = 1, and the number of neutron generations, t/τ is numerically equivalent to αt, since $t/\tau = \alpha t/(k-1) = \alpha t$, and both are equal to the period of time measured in shakes. In Table 1 we show the power and total energy released as a function of time measured in shakes (or as a function of αt), assuming the chain reaction is initiated by a single neutron at $\alpha t = 0$, i.e., No/(k-1) = 1.

As seen from Table 1, as a function of time measures in shakes, the following yields are realized:

Time (shakes)	Yield (TNT equivalent)	
0	0	chain reaction starts
39.6	1	kilogram
46.4	1	ton
53.3	1	kiloton
55.6	10	kiloton
57.9	100	kiloton

For different but still constant values of α, the values in both columns above would have to be divided by α. In any case, the larger the value of α the more quickly the chain reaction proceeds to a given energy release.

At any time t, 95 percent of the total energy released is released in the last three neutron generations (i.e., the last three units of αt). It is also noted that if the neutron source supplies e^x neutrons within the first αt, then the number of neutron generations is reduced by x. In effect, the first x neutron generation are skipped. Thus, by using a strong pulsed source of neutrons that can be delivered within a few shakes, the initiation of the chain reaction can be timed so that the desired degree of supercriticality is achieved before the supercritical mass starts disassembling due to the energy buildup in the core. If the

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[9] We can measure the energy released per fission in units of choice, e.g., ergs, joules, calories, or TNT equivalent in pounds, kilograms, tons or kilotons, by using the appropriate conversion factor: E_f = 180 Mev/fission = 2.88×10^{-4} ergs/fission = 6.89×10^{-12} calories (cal)/fission = 1.38×10^{-17} pounds of TNT equivalent/fission = 6.25×10^{-18} kilograms of TNT equivalent/fission = 6.89×10^{-21} tons of TNT equivalent/fission = 6.89×10^{-24} kilotons (kt)/fission. The convention is to assume that 1 kiloton of TNT equivalent = 10^{12} calories.

chain reaction starts sooner than the optimum time due, for example to neutrons generated by spontaneous fissions in plutonium, the yield of the device will be less than optimum. The effect of preignition of the chain reaction on the yield distribution of fission weapons has been reviewed by Carson Mark.[10] This is a separate topic relevant to the weapons usability of reactor-grade plutonium.

As energy is released during the chain reaction a number of physical changes take place as a function of the energy density. If we neglect the energy produced and/or absorbed in other weapon components, e.g., in the fissionable U-238 tamper, and the energy that escapes from the core, then the average energy density is W/M, where M is the mass of the fissile core. In Table 1, we have assumed M = 10 kilograms (kg).

Plutonium melts at 641 °C. Complete melting occurs when the energy density reaches about 107-117 kj/kg (25-28 calories/gram).[11] For our 10 kg core, as seen from Table 1, this occurs at about αt = 38.2. Plutonium vaporizes at 3235°C. Vaporization is complete when the energy density reaches about 1.56 Mj/kg (373 calories/gram).[12] In our 10 kg core, this occurs about 2.6 shakes later, at about αt = 40.8. At 2 Mj/kg (500 calories/gram)--at αt = 41.1 for our 10 kg core--the electrons in the outer most shells begin to be stripped from the plutonium (or uranium).[13] As noted by Carson Mark, one kilocalorie per gram is typically released by the detonation of high explosives. During the next few αt considerable energy is utilized in stripping additional electrons from the nuclei. The ionization energy required to strip all 94 electrons from a plutonium nucleus is about 785,150 ev, or 70 kg of TNT equivalent/gram of plutonium.[14] For a 10 kg core this amounts to 750 tons of TNT equivalent. Since the fission energy released is not all absorbed by ionization, but is shared by the photons (X- and gamma-rays) and the kinetic energy of the nuclei and free electrons, not all of the electrons are freed, even when the total energy released reaches a few kilotons.

Since the energy density in the core is inversely proportional to the mass of the core, the energy density would be 2.5 times higher for a fission primary with a 4 kg core, rather

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[10] Mark, "Explosive Properties of Reactor-Grade Plutonium."

[11] The specific heat of plutonium is about 9 cal/mol, and the latent heat of transformation is 454 cal/mol for the phase transformation $\delta \rightarrow \epsilon$, and 676 cal/mol for $\epsilon \rightarrow$liquid; *The Plutonium Handbook*, pp. 37-38. We assume the plutonium core is initially between 25 °C and 90 °C, the higher temperatures due to internal heating caused by radioactive decay.
[(641 °C - 25°C) x 9 cal/°C-mol + (454 cal/mol + 676 cal/mol)]/239 g/mol = 27.9 cal/g.
[(641 °C - 90°C) x 9 cal/°C-mol + (454 cal/mol + 676 cal/mol)]/239 g/mol = 25.5.9 cal/g.

[12] The specific heat of liquid plutonium is 10 cal/°C-mol, and the heat of vaporization of plutonium is 80 kcal/mol. See previous footnote for sample calculation.

[13] It takes 5.113 electron volts (ev) to strip the most loosely bound plutonium electron.
$(5.113 \times 10^{23}$ nuclei/mol)(1 mol/239 g)$(1.60219 \times 10^{-19}$ j/ev)$= 2.064 \times 10^{3}$ j/g (493 calories/g).

[14] Some 785,150 electron volts (ev) of energy are necessary to strip all 94 electrons from a plutonium nuclei.
(785,150 ev/nuclei)$(6.022 \times 10^{23}$ nuclei/mol)(1 mole/239 g)$(1.60219 \times 10^{-19}$ j/ev)(0.238846 calories/j)$(2 \times 10^{-6}$ lb TNT/calorie)(1 kg/2.20462 lb) = 69 kg TNT/g.

than for a 10 kg core considered above. At this higher energy density the melting point, boiling point, and ionization level would be reached about 0.9 shakes earlier. Similarly, a 27 kg core would take an additional shake to reach the corresponding conditions. But these are only approximations in any case, since we are ignoring the energy absorbed in other components, i.e., the tamper and chemical high explosive, and the energy that escapes from the system.

By incorporating thermonuclear fuel, typically a mixture of deuterium and tritium gas (or lithium hydrides) directly into (or proximate to) the core of fissile material, the efficiency of the fission bomb can be improved; that is, one can obtain a much higher yield from a given quantity of fissile material, or alternatively, the same yield from a much smaller quantity. This process is called "boosting." The fusion process itself may add only slightly to the yield of the device. Far more important to the yield is the extra quantity of free neutrons produced as a result of the fusion reaction. These in turn increase the efficiency by producing additional fissioning in the fissile material of the core.

We will examine the behavior of boosting in a modern warhead where the boosting is provided by a mixture of about one mol of deuterium and tritium (DT). The tritium is typically stored in an external steel flask and injected into the hollow core just prior to detonating the device. To achieve fusion the DT mixture must reach about 20 million degrees Kelvin (or about 2 kev, where 1 ev in temperature units is 11,604 °K). It is also necessary that the product of the confinement time and plasma densitybe about 10^{14} s/cm^3 or higher, the so-calles Lawson Criterion. At a typical burn temperature of 20 kev, the product of the confinement time and plasma density on the order of 10^{15} s/cm^3 is required for 30 percent of the DT to fuse--to achieve 30 percent burnup. In a modern boosted primary with a 4 kg plutonium core the temperature of the core reaches 2 kev and burning is initiated when the total energy released reaches about 250-300 tons, or at about $\alpha t = 52$; and substantial burning taken place before one kiloton has been released within the next shake or two. At $\alpha t = 52.5$ there are $e^{52.5} = 6.3 \times 10^{22}$ neutrons, about 0.1 mol of neutrons. If one-half the DT burned, then an additional 0.5 mol, or 3×10^{23} neutrons, are added to the core by the fusion reaction

$$D + T \rightarrow n + {}^4He + 17.6 \text{ Mev.} \qquad (5)$$

Assuming the neutron population can be increased through boosting by roughly a factor of 5-10, and the yield increased by about the same amount even though the energy released directly from the fusion of the 0.5 mol of DT is only about 175 tons of TNT equivalent.

This, of course is an idealized picture of the boosting process. For our purposes, it is important to note under the best of circumstances, boosting does not commence until about 300 tons of energy have been released. As will be seen below this is beyond the hydronuclear test regime.

To summarize, assuming a constant $\alpha = 1$ per shake, as the chain reaction proceeds the following yields and conditions are realized:

Time (shakes)	Yield (TNT Equiv.)	Condition in a 4 kg Pu core.
0	0	chain reaction starts
38	0.2 kg	Pu melted
40	1.4 kg	Pu vaporized
41	4.0 kg	energy density typical released by the detonation of a chemical high explosive
43	30 kg	ionization initiated
52.1	300 ton	initiation of DT fusion reaction

Depending on the design, the chain reaction may be initiated by a pulse of neutrons and α will not be constant, and of course the chain reaction does not go on forever, but stops when α declines to -1. To show just one design alternative, we offer in Table 2--also displayed in Figures 1 and 2--an idealized version of a low technology fission weapon having a solid 20 kg U-235 core, surrounded by a 180 kg U-238 tamper and enough chemical high explosive to provide a 4 km/s imploding shock wave, sufficient to generate an $\alpha = 0.5$ per shake.[15] We assume the chain reaction is initiated by a pulse of $e^{12} = 1.6 \times 10^5$ neutrons at $t = 0$, which shortens the chain reaction time by $\alpha t = 12$, or 24 shakes, since our α is now 0.5 per shakes. Also, with α now 0.5 instead of 1 per shake, the chain reaction takes roughly twice as long to achieve the same increase in the energy released.

When the yield reaches a ton, or so, sufficient to overcome the pressure from the imploding shock, the core starts expanding, initially at a small rate. The core expansion, and the rate of decrease in α, become appreciable in a few more shakes when about 0.5 kt of energy has been released within the core. In our idealized case, we have assumed that within 10 shakes--between 80 and 90 shakes--α drops from 0.5 to zero per shake. As seen in Table 2 (and Figure 2), only 1.5 percent of the energy is released prior to 80 shakes, when the core is still fully compressed. Fifty percent of the energy is released prior to returning to prompt critical at 90 shakes, and the other half is released after the chain reaction has become subcritical at 90 shakes. Thus, for untested designs, accurate modeling of the disassembly phase of the explosion is critical to accurately predicting the yield.

Hydronuclear tests are limited in yield, but permit testing the initiation and the early phase of the chain reaction. To keep the yield below, let us say, four pounds of TNT equivalent, α must be reduced to a few percent of its original value. To test a new design by hydronuclear testing, the objective is to reduce α by a known amount without changing the way the materials behave under compression before significant energy is released. As noted previously this is achieved by substituting non-fissile isotopes for fissile isotopes,

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[15] Based on the modeling of Andreas Pritzker and Walter Hälg, "Radiation Dynamics of a Nuclear Explosion," *Journal of Applied Mathematics and Physics (ZAMP)*, 1981, Vol. 32, pp.1-11.

otherwise keeping the design the same. If the desired hydronuclear test yield is W_2, and the original yield is W_1, the ratio of the yields for our constant α case is from equation 3:

$$W_2/W_1 = (\alpha_1/\alpha_2) \exp(\alpha_2 t_2 - \alpha_1 t_1) . \quad (5)$$

To obtain an approximation of α_2 for our 20 kg U-235 design, we assume W_1, α_1, and t_1 are 35.5 kt, 0.5 per shakes, and 100 shakes, respectively. We assume that we want to limit W_2 to about 2 lb (0.9 kg) of TNT equivalent = 10^{-6} kt; and we further assume that the core expansion, or rebound, time is two to three times the compression time, or about 15 μs = 1500 shakes for the core. Plugging these values into equation 4 above, gives $\alpha_2 = 0.02$ per shake, or four percent of the original value. In Table 3--also displayed in Figures 3 and 4--we present an idealized version of this hydronuclear test. The yield is 3.7 pounds (1.7 kg) of TNT equivalent.

To approximate the amount of fissile material in the hydronuclear test core, we let $\epsilon \equiv M_{f2}/M_{f1}$, the ratio of the fissile isotopes in the hydronuclear core to that in the respective nuclear weapon core. Since $\alpha = (k-1)/\tau$, $k \equiv \nu f$, $f_2 = \epsilon f_1$, and $\tau_2 = \tau_1/\epsilon$, then

$$\alpha_2/\alpha_1 = \epsilon(\epsilon k_1 - 1)/(k_1 - 1). \quad (6)$$

For $\alpha_1 = 0.5$ per shake, $\alpha_2 = 0.02$ per shake, and $\tau = 1$ shake, we find $\epsilon = 0.69$.[16] In other words about 30 percent of the fissile isotopes must be removed to reduce α from 0.5 to 0.02 per shake, thereby reducing the yield from 35.5 kt to a few kilograms of TNT equivalent.

These are rather crude approximations of α_2 and ϵ, since most of the energy is released during disassembly, when α is not constant. In actuality, these values would be calculated using sophisticated weapon codes. To insure that the hydronuclear yield has not been miscalculated, a series of hydronuclear tests can be conducted beginning with less fissile material and then progressively adding more. Such a series of hydronuclear tests would permit more accurate scaling to determine the value of α for the weapon with its full complement of fissile material.

III. Engineering Development of New Nuclear Warhead Designs.

In order to discuss which types of nuclear warheads require testing and where hydronuclear testing may be beneficial, it is useful to review the various types of warhead

[16] This give only an approximate answer because we have assumed α is constant. Also, the fissile material would likely be replaced by a fissionable material, for example, U-235 replaced by U-238, which would fission, albeit less frequently than U-235.

designs that are typically found in the arsenals of nuclear weapons states.[17] These can be categorized as either pure fission, boosted fission, or thermonuclear devices. The latter, also referred to as "fusion" or "hydrogen" weapons, are usually defined as nuclear weapons in which at least a portion of the release of energy occurs through nuclear fusion. In a strict sense, boosted fission weapons could be categorized as thermonuclear weapons since they use utilize fusion materials. However, since only a small fraction of the yield of a boosted fission weapon is derived directly from the fusion reaction, boosted fission weapons are more often treated as a distinct weapon category.

Thermonuclear weapons (and even fission weapons) can be categorized as having one, or more than one, stage. Single stage pure fission designs are further characterized as either gun-assembly or implosion types. The fissile core of an implosion type fission device can vary in sophistication from the low-technology *Trinity* type device--also called a "solid pack"--first tested by the United States in 1945, to the more sophisticated "levitated pit" design used in modern fission warheads and the fission primaries of thermonuclear warheads. A two-stage thermonuclear weapon has a fission or boosted fission primary, also called a "trigger,"and a separate component called the secondary, both contained within a heavy casing. Very high yield thermonuclear devices may have a third stage--a tertiary. In a modern staged device, the primary is likely to be boosted. The secondary usually contains a composite of fusion and fissile materials, although it is possible to construct secondaries from purely fissile or fusion materials. The outer casing of a staged device can be made of some type of fissionable material--depleted, natural, or enriched uranium, or even thorium.

A. Gun-assembly pure fission designs. The simplest weapon design is the pure fission gun-assembly device. Here two subcritical masses of fissile material are brought together to form a single supercritical mass. An explosive propellent is used to fire one of the subcritical masses down a "gun barrel" into the other. Plutonium cannot be used as the fissile material because the speed of assembly is too slow to achieve a significant nuclear energy yield. Therefore, gun-assembly weapons are made with high-enriched uranium (HEU), typically, uranium enriched to more than 80 percent in the isotope U-235.

The relevant physics needed to construct a workable gun-assembly weapon is widely available in the open literature as are most of the design details of *Little Boy*, the first U.S. gun-assembly weapon. It is notable that the design of *Little Boy* predated the use of computers. *Little Boy* was not tested before it was used in combat--at Hiroshima on August 6, 1945. Similarly, the six warhead arsenal of South Africa, since dismantled, were all gun-assembly type warheads; and none were tested.

The yield of a gun-assembly device is a function of the number of critical masses of the final HEU assembly, which in turn depends on several key parameters, including the enrichment of the uranium, the type and amount of tamper/reflector material that surrounds

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[17] We do not discuss here the full spectrum of possible designs. We omit, for example, a discussion of neutron warheads and various theoretical directed energy weapon designs.

the assembled HEU, and the geometry of the final HEU and tamper/reflector assembly. Although the yield of the design can be predicted using modifications of commercially available nuclear hydrodynamic computer codes, there is no guarantee that the prediction would be closer than a factor of two or so unless one had good equation of state data and high confidence in the computer modeling. On the other hand, it is public knowledge that the *Little Boy* design used about 50 kilograms of 80%-enriched uranium; the target uranium was housed within a thick tungsten carbide reflector/tamper surrounded by a much thicker steel tamper; the final supercritical assembly was on the order of 2.5 critical masses; and its yield was on the order of 15 kilotons. Any country can copy this design; or if a modified design is chosen the number of critical masses of the final HEU/reflector assembly can be accurately estimated by conducting subcritical assembly measurements in the laboratory. Hence, there is no need for nuclear testing to have high confidence of achieving a yield in the ten to fifteen kiloton range. While hydronuclear testing can be used in developing gun-assembly designs, the marginal value of these tests is considerably less than the value of hydrotesting implosion designs.

B. "Solid-pack" implosion type pure fission designs. In an implosion type fission weapon a subcritical mass of fissile material is compressed by a chemical high explosive. The fissile material is typically either plutonium, or HEU, or a composite of the two. In the most straightforward design the core of fissile material is a solid sphere or cylinder, surrounded by a tamper, which in turn is surrounded by the chemical high explosive. A sphere has the smallest surface to volume ratio, and therefore the smallest neutron losses and smallest critical mass. Cylindrical symmetry is used where the diameter of the device must be kept small--to fit, for example, in an artillery shell--and of course other shapes are theoretically possible. Considerably less fissile material is needed for an implosion weapon relative to a gun-assembly device.[18]

The Gadget, the first nuclear weapon tested (by the U.S. at the Trinity Site on July 16, 1945), was a low-technology, "solid-pack" design with a 6.1 kg plutonium core.[19] The yield of this device was 22 kilotons. Once weaponized into a bomb, then called *Fat Man*, it was dropped by the U.S. on Nagasaki on August 9, 1945, and tested twice in Operation Crossroads in the Pacific in the summer of 1946. Mark III bombs, the first production model of *Fat Man*, were introduced into the U.S. nuclear arsenal in 1947 and the last was retired in 1950. The first Soviet test on August 29, 1949 was almost an exact copy of the U.S. *Fat Man* design, the Soviets having obtained the design through espionage.

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[18] For uniform compression the critical mass of the fissile material is inversely proportional to the square of the density [$M_c \propto (1/\rho)^2$]. If the critical mass of a fissile assembly is M_{oo} at normal density, and if 2.5 crits is needed to achieve the desired yield, a gun assembly-weapon would require an initial fissile inventory = 2.5 M_{oo}. In an implosion weapon the same 2.5 crits can be achieved by uniform compression of just under one M_{oo} to $2.5^{½} = 1.6$. In this example, the fissile material requirement for the implosion device would be 40 percent of that required for the gun assembly device.

[19] Although the plutonium core had a 2 cm diameter hole in the center to house the neutron initiator, it is classifies as a solid core design.

By today's standard, *Fat Man* is a very large, heavy, low-technology design. It was 60.25 inches in diameter, 128 inches long, and the various models weighed between 10,300 and 10,900 pounds (4672-4944 kg). The total weight of the nuclear device was about 7600 pounds (3447 kg), primarily because it included a very heavy tamper. To compress the core and the tamper an even larger quantity of chemical high explosive was needed.[20]

Similar to the gun-assembly device, the yield of a solid-pack implosion device is a function of factors, including the number of critical masses of the final assembly and the timing of the initiation of the chain reaction. The number of critical masses depends in turn on several other key parameters, including the size and enrichment of the fissile core, the type and amount of tamper/reflector material, and the geometry of the final assembly. Although the yield of the design can be predicted using modifications of commercially available nuclear hydrodynamic computer codes, accurately predicting the yield is somewhat more difficult than predicting the yield of a gun-assembly device. On the other hand, the basic design of *Fat Man* is publicly available, and any country can copy this design. Hence, there is no need for nuclear testing to have high confidence of achieving a yield in the ten to twenty kiloton range. Hydronuclear testing could be of limited value in confirming the validity of the design and the computer modeling to predict the yield. However, if a nation's nuclear weapons program were sufficiently advanced to be conducting hydronuclear tests, it is more likely that its nuclear weapons designs would be more sophisticated than this low technology solid-pack design.

C. Levitated pit and core designs. The levitated pit design is an implosion weapon where there is a gap between a "flying plate" and the fissile core. The fissile core is supported, or "levitated," in the center of the device. As described by Ted Taylor, if you want the drive a nail you do not rest the hammer on the nail and push; rather, you hit the nail with the hammer. The flying plate--in this case a thin metal shell--is analogous to the head of the hammer. Driven by the chemical high explosive, it gains momentum as it accelerates through the free space before striking the tamper or fissile core. By achieving greater compression levitated pit designs can be lighter and use less fissile material to achieve the same yield, or alternatively achieve a greater yield for the same device weight.

In the U.S. weapons program levitated pits (and composite cores) were first tested in Operation Sandstone in April-May 1948. The first two tests of the series, X-Ray and Yoke, achieved yields of 37 kt and 49 kt, compared to the 20 kt yield of the Mark III bomb, a production model of the earlier *Fat Man* design.

The flying plate can serve as the tamper, part of the tamper, or it can be made of fissile material. In addition, the fissile core geometry may be solid, a hollow shell, or it may be solid fissile core levitated within a fissile shell.

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[20] The plutonium core was surrounded by a uranium tamper weighing some 110 kg, inside a 120 kg aluminum layer, inside about 2300 kg of high explosive, inside a 520 kg duralumin casing.

The relevant physics for basic levitated pit designs is available in the open literature. Imploding hemispheric and hemicylindric flying plate systems, without the fissile materials, are used commercially to shape metals and for conducting materials research. Relative to the solid-pack nuclear warhead designs, the physics and nonnuclear experiments required to verify levitated pit and levitated core designs are more complicated, and the possibility of error is greater. Without nuclear explosive testing one could have confidence that a conservatively designed weapon would work, although one would not know the exact yield and the design would not be optimal in terms of yield-to-weight or yield-to-volume. Hydronuclear tests could be used to calibrate computer design codes, give greater assurance of achieving a minimum yield closer to the design yield, and optimize the design, if higher yield tests were not permitted under a CTB or for political reasons.

D. Boosted fission and other single-stage thermonuclear designs. As noted above, by incorporating thermonuclear fuel, typically a mixture of deuterium and tritium gas (or lithium hydrides) directly into (or proximate to) the core of fissile material, the efficiency of the fission bomb can be greatly improved; that is, one can obtain a much higher yield from a given quantity of fissile material, or alternatively, the same yield from a much smaller quantity.

Boosting is most advantageous in lower yield single-stage weapons and in the primaries of multi-stage thermonuclear weapons. High-yield single-stage designs can be made very efficient without boosting. The quantity of high explosive and fissile material in a boosted device having a yield in the few kiloton range can be made sufficiently small to be made very safe from the standpoint of single-point asymmetric detonations; that is, the yield of a single-point detonation can be made extremely small. Single-point safety tests are taken up in Section IV below.

Boosted fission devices are likely to incorporate many of the features of levitated pit design. Since boosting does not take place until the energy release has reached at least 300 tons of TNT equivalent, hydronuclear testing is essentially of no value in gaining confidence that the boost phase of a nuclear device operates as designed. If a boosted primary had been previously tested in the kiloton range, hydronuclear testing could confirm successful operation of the device up to a point just prior to when boosting is initiated.

E. Staged thermonuclear designs. In a staged thermonuclear device the X-radiation from a fission or boosted fission primary is largely contained within a heavy metal case. The initial X-radiation from the primary heats up the inner surface of the casing turning it into an opaque plasma. Subsequent x-radiation from the primary is absorbed by the plasma surface and re-irradiated into the cavity. Some of the radiation trapped within this blackbody cavity, also called a "hohlraum," is absorbed by the surface of the secondary component which heats up in a manner similar to the case. The radiation absorbed at the surface of the secondary causes the surface of the secondary to ablate, that is, to "boil

away." The reactive force from the ablation produces a rapid compression of the secondary. The density of the secondary material, achieved by compression with radiation from a fission primary having a yield in the kiloton range, can be ten or more times greater than that achievable using chemical high explosives. Thus, the fission and fusion processes that take place in the secondary are generally much more efficient than the those that take place in the primary.

Early thermonuclear primaries of the implosion type probably had thick tampers and high yields. Since the objective is to utilize the X-radiation from the primary, in modern weapons the heavy tamper has probably been replaced by a thin beryllium reflector. This pit, now much lighter, requires much less chemical high explosive to achieve the desired compression. The lack of a heavy tamper is partially offset by the fact that the radiation that escapes from the primary does not contribute to the disassembly of the primary core. The amount of high explosive needed can be reduced even further by boosting. A typical modern thermonuclear primary might consist of a 4 kg plutonium core in the form of a thin shell about 7 cm in diameter, a beryllium reflector and about 50 kg, or so, of high explosive.

In a multi-stage device the secondary can be made entirely of fusion, or fissionable material, or typically both. The casing can be made of fissile material (enriched uranium) or fissionable material (enriched, natural or depleted uranium, or thorium), or in the case of early British thermonuclear designs, lead bismuth.

Early conservative thermonuclear designs used heavy unboosted primaries with primary yields of a few hundred kilotons. Modern staged thermonuclear warheads use boosted fission primaries with primary yields on the order of a few to about 15 kilotons.

A number of technologically advanced nations are capable of producing thermonuclear weapons without nuclear tests or test data. But these are likely to be heavy single staged devices, or possibly two-stage devices with heavy high-yield primaries. The United States and the Soviet Union produced workable, conservatively designed, multi-staged thermonuclear weapons before the advent of high speed computers. The first U.S., Soviet, and Chinese tests of two-stage thermonuclear devices were all successful. The first British two-stage thermonuclear test demonstrated staging, in that the fissile material in the secondary fissioned, but the fusion materials apparently did not burn and therefore the desired yield was not achieved. Only after the third attempt did the British achieve a successful test of a two-stage thermonuclear device. Nevertheless, a conservatively designed staged thermonuclear design produced without testing would represent a credible threat.

Implosion of the secondary of a staged thermonuclear weapon can be verified only with nuclear explosive testing. Hydronuclear tests are of no value in this regard, since the energy of the radiation emitted from the primary is far less than the energy released by the primary's chemical high explosive and is totally inadequate to compress the secondary.

IV. Safety Assessments of Nuclear Warheads.

A safety criterion for U.S. nuclear weapons is that the accidental detonation of the chemical high explosive at a single point must not result in a fission energy release exceeding 4 pounds (1.8 kg) of TNT equivalent. Other weapons states presumably utilize the same, or a similar, criterion. Whether a particular design meets this criterion can be determined either by computer calculations, or through experimental "one-point safety" tests. Whether these one-point safety tests are included within the definition of hydronuclear tests is a matter of semantics. In any event, if hydronuclear tests are prohibited under a CTB, the single-point safety tests would be excluded as well, because there are no external characteristics of either the device being tested or the energy released that distinguish the two.

The United States conducted 1051 nuclear tests between 16 July 1945 and 23 September 1992. Of these 34 have been categorized by the Department of Energy (DOE) as safety experiments (Table 4). All but one of these announced safety tests took place between 1955 and 1958. Additional hydronuclear experiments were conducted by the United States during the 1958-1961 nuclear test moratorium, and the existence of these tests was kept secret until the late 1980s. The number of such experiments still has not been revealed. It has been revealed that there were nine experiments in the first series of tests in 1960, followed by several additional series.[21] After the moratorium the only announced safety test occurred in 1988. Additional safety tests may have occurred in conjunction with other announced tests. The United States defines an underground test as either a single explosion, or two or more explosions fired within 0.1 second of one another within an area delineated by a circle having a diameter of two kilometers. Multiple devices were sometimes emplaced in the same shaft (known as a "string of pearls") and fired simultaneously, or in rapid succession. The DOE still keeps secret the number of such "pearls" and their purpose.

One reason so few one-point safety tests have been conducted by the United States in recent years is because modern boosted fission primaries use so little fissile material. Even if a high explosive detonation is accidentally initiated at a single point, the asymmetric compression of the fissile material will release very little nuclear energy. Modern boosted primaries are inherently one-point safe.

Under a CTB regime the only weapons that will be retained in the U.S. stockpile are those that will have already been fully tested and demonstrated to be one-point safe. While rare, there have been instances in the past where more recent computer analyses indicated that the design, or the way in which it is deployed, appeared less safe than previously had been believed under certain accident scenarios. If at some time in the future it were judged that a particular warhead type was unsafe as then deployed, changing the nuclear design and conducting additional one-point safety tests would not be options under a CTB. Safety

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[21] Robert N. Thorn and Donald R. Westervelt, "Hydronuclear Experiments," Los Alamos National Laboratory, (LA-10902-MS) February 1987, p. 5.

concerns, nevertheless, could be resolved by substituting a safer warhead type, or by altering the manner in which the warhead is deployed.

V. The Value of Hydronuclear Testing in Specific Countries.

The value of hydronuclear testing to a weapon state under a CTB regime depends upon a number of factors, including the maturity of the states' nuclear weapons program and the extent to which full yield tests have already taken place. In this section we examine the situation in the principal countries of interest, namely those that now have nuclear warheads.

A. U.S., Russia, U.K., France and China. The nuclear weapons programs in these five declared nuclear weapons states are mature. All have deployed a variety of nuclear designs, including modern two-stage thermonuclear weapons. All have extensive nuclear test archival data:

Country	Tests	
United States	1027	(24 with U.K.)
Russia	715	
France	204	
United Kingdom	45	(24 with U.S.)
China	39	

All have sophisticated design codes that have been normalized against their respective tests. These codes can be used to model accurately the performance of fission devices during the disassembly phase, which cannot be accessed empirically via hydronuclear testing. These codes may not adequately model the boost phase of new boosted designs or new thermonuclear secondaries, particularly if the designs differ radically from previously tested designs. Under a CTB regime where hydronuclear testing is permitted, hydronuclear tests would provide a highly confident basis for certifying the performance of a new generation of unboosted fission devices, including a new generation of compact, highly deliverable mini- and micro-nuke weapons with yields in the tens to hundreds of tons. The U.S. is currently prohibited from further development of this category of weapons by an act of Congress. Such a restriction may not last if the latitude to develop such weapons is afforded other nuclear weapon states under the terms of a CTB.

B. Israel. Israel has nuclear weapons and is presumed to have deployed fission weapons boosted with DT and/or lithium hydrides. Israel may have tested such a device at low yield on September 22, 1979 in the South Atlantic. There is conflicting evidence as to whether this event was a nuclear test. A White House panel concluded that the VELA sighting "contained sufficient internal consistency to cast doubt whether that signal originated

from a nuclear explosion or in fact from any light sources in the proximity of the VELA satellite." Israel may have conducted numerous secret hydronuclear tests. This is well within its capability, and these could have easily gone undetected. Israel may have obtained through espionage or other means the designs of U.S. and/or French nuclear weapons and/or calibrated warhead design codes. It is widely believed that Israeli scientists were present at French nuclear tests in the Sahara during the late-1950s, and the two countries may have shared nuclear weapons design and test data. Israeli scientists have had close professional contact with scientists at U.S. nuclear weapon laboratories in the field of nuclear technology and related sciences.

Hydronuclear tests could be expected to provide Israel with the same benefits that these tests provide the declared nuclear powers.

C. India and Pakistan. India has exploded a nuclear device, which it termed a "Peaceful Nuclear Explosion," in 1974. Both India and Pakistan are believed to have nuclear weapons, or components that can be quickly assembled into workable weapons. There is no public evidence to suggest that either country has developed a thermonuclear capability at this time. Director of Intelligence William Webster, however, told a Senate Committee in May 1989 that there were indications that India was building a hydrogen bomb. Hydronuclear tests would permit India and Pakistan to improve their fission weapon designs by incorporating levitated pit and hollow core technologies. Given the high degree of tension between India and Pakistan there are ample incentives for both to improve their respective nuclear weapons capabilities, including the warhead designs to permit deployment of intermediate range ballistic missiles. Hydronuclear testing would be especially useful if either country, or both countries, decided to pursue the development of compact low-yield nuclear weapons.

VI. The U.S. Executive Branch is Already Barred from Conducting Hydronuclear Tests by the Terms of the 1992 "Hatfield-Exon-Mitchell" Amendment.

Whether or not a future CTBT bans hydronuclear tests, such tests would violate Sec. 507 (the "Hatfield-Exon-Mitchell Amendment") of the Energy and Water Development Appropriation Act of 1992, P.L. 102-377, 106 Stat. 1343 (1992).

According to this statute:

> "[Sec. 507 (f)] **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." (emphasis added)

> Sec. 507(b) provides that "**no underground test of a nuclear weapon** may be conducted by the United States after September 30, 1992, and before July 1, 1993," and Sec. 507(c) permits "**an underground test of a nuclear weapon**" only if, among other conditions, the President has submitted an annual report specifically identifying the permitted purpose of such test. (emphasis added)

The statute prohibits underground tests of **nuclear weapons** at any yield. There is little if any room for argument that, irrespective of whether their purpose is weapons safety or weapon development, hydronuclear tests are tests of **nuclear weapons.** If fissionable or fusion materials are removed from a nuclear weapon to lower its yield, the test of such a device is still a **nuclear weapons test** that must meet the limitations imposed by Limited Test Ban Treaty, the Threshold Test Ban Treaty, and the Peaceful Nuclear Explosions Treaty. By the same token, if additional fissile material is removed, or if the chemical high explosive is detonated asymmetrically, it is still a test of a **nuclear weapon** even if is given the more descriptive name, "hydronuclear weapons test." Since the Limited Test Ban Treaty was signed on 5 August 1963, there has been only one test categorized by DOE as a safety test, and it was tested **underground** in compliance with the Limited Test Ban Treaty. Thus hydronuclear tests appear to be prohibited by the plain language of the statue.

The Hatfield-Exon-Mitchell Amendment uses the terms "nuclear weapon" and "nuclear explosive device " interchangeably. Sec. 507(a) of the statute makes funds 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." Sec. 507(e)(1)(A) likewise establishes the overall domain of tests covered by the statute by imposing a general standard that "only those **nuclear explosive devices** in which modern safety features have been installed...may be tested." Thus tests of both nuclear "nuclear explosive devices" and "weapons" are covered by the statute.

Section 507(d)(1)(B) required the President to submit a report to Congress containing a "plan for achieving a multilateral **comprehensive ban on the testing of nuclear weapons** on or before September 30, 1996." President Clinton has already gone on record that, in the view of the Executive Branch, this report requires "a plan...leading to a **total cessation of tests in 1996.**"[22] Likewise, in its budget submission for FY 1994, the Department of Energy stated, "**the law requires that all nuclear testing end on September 30, 1996.**"[23] Thus, Section 507(f) prohibits all U.S. underground testing, including hydronuclear tests, after September 30, 1996 and provides only a single exception: the detonation of a nuclear test by another country after that date. However, some may argue that there is another implicit exception. If the U.S. negotiates a "comprehensive" test ban treaty that does not

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[22] (emphasis added) *Cong. Record* (Senate) Feb. 16, 1993, p. S1513.

[23] Department of Energy FY 1994 Congressional Budget Request, Assistant Secretary for Defense Programs, Key Activity Summary, Weapons Testing, p. 77.

explicitly ban--and thus implicitly permits--hydronuclear tests, then the Hatfield-Exon-Mitchell prohibition on these tests is somehow nullified.

It is well established that a subsequently ratified treaty can supersede an inconsistent United States statute.[24] However, to do so, the treaty must actually be inconsistent with the statute. Thus, if a CTB Treaty **required** U.S. hydronuclear testing after 1996, and this Treaty were ratified, then the conduct of such tests would be permissible and Hatfield-Exon-Mitchell would in effect be amended to the degree that its provisions were inconsistent with the terms of the subsequent. However, it is inconceivable that a multilateral CTB Treaty will contain a **requirement** for hydronuclear testing. For 35 years, the nations of the world have called for a ban on all tests, not for their continuation.

If a test ban treaty **permitted**, but did not require, U.S. hydronuclear testing after 1996, it would **not** be inconsistent with Section 507(f). In comparable situations of apparent conflict between a statute and a treaty, U.S. courts have always strained to construe the two instruments in a mutually consistent way and give effect to both of them. If the statute is subsequent, the court will not invalidate the prior treaty unless Congress "clearly and unequivocally" exercises the intent to do so.[25] By the same logic, a subsequent treaty will not invalidate a prior statute **unless the parties clearly intend it to do so.**

The Hatfield-Exon-Mitchell Amendment would be consistent with a CTB Treaty permitting but not requiring hydronuclear tests for after 1996; the United States would act in accordance with both instruments by refraining from hydronuclear tests while other nations also refrained, and by testing only if another nation tested. **Therefore Section 507(f) would continue to ban such tests unless a foreign nation tested first.**

However, just as it is impossible to imagine that a test ban treaty will require hydronuclear testing, it is also inconceivable that a multilateral agreement will explicitly permit such tests. If the U.S. and other nuclear weapon states pressed for the flexibility to conduct such tests under the treaty and had their way in multinational negotiations, the treaty might not expressly forbid hydronuclear tests, but many countries would not want to give their **imprimatur** to any nuclear tests. Therefore, like other test ban treaties, the treaty would be phrased as a set of potentially ambiguous or less than fully comprehensive prohibitions, rather than as explicit permission for the nations of the world to continue very low-yield testing of nuclear weapons.

For all of the above reasons, the likely terms of a CTB Treaty would not conflict with Sec. 507(f), and the latter would continue to ban U.S. hydronuclear tests after 1996 unless another nation tests a nuclear weapon after September 30, 1996, or the statute is amended.

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[24] Chae Chan Ping v. United States, 130 U.S. 581 (1889).

[25] United States v. P.L.O., 695 F. Supp. 1456 (S.D.N.Y. 1988); Diggs v. Schultz, 470 F.2d 461 (D.C. Cir. 1972).

VII. Modifying the Draft CTBT Text.

Sweden on 6 December 1993, and Australia on 30 March 1994, have tabled draft CTB Treaties at the Conference on Disarmament (CD) negotiations in Geneva. The "Basic Obligations" of the parties, as set forth in Article I, are quite similar in the two texts, and read as follows--where there are differences the Swedish text is in **Bold** and the Australian text in *italics*:

Article 1

Basic Obligations.

1. Each State Party undertakes **to prohibit, to prevent, and** not to carry out, **in any environment,** any nuclear weapon test explosion, or any other nuclear explosion **at any place under its jurisdiction or control**,*and to prohibit and prevent such explosions at any place under its jurisdiction or control.*

2. Each State Party undertakes, furthermore, to refrain from causing, encouraging, assisting, **preparing,** permitting or in any way participating in the carrying out anywhere of any nuclear **explosion referred to in paragraph 1 of this Article.** *weapon test explosion or any other nuclear explosion.*

In both cases the text does not explicitly exclude hydronuclear testing. To do so we propose that first paragraph be amended to read, "any nuclear weapon test explosion, or any nuclear explosion, or the release of any nuclear fission energy caused by the assembly or compression of fissile material by chemical high explosive means," The second paragraph of the Australian text would have to be similarly amended.

This amendment would not prohibit any conceivable commercial activity not otherwise prohibited by the treaty.

VIII. Conclusion.

The principal nuclear weapon design concepts are generally known. The basic physical principles related to nuclear chain reaction, efficient implosion techniques by high explosive means, fission boosting, radiation coupling, and thermonuclear burn are widely available in the open literature. The basic physics parameters, such as nuclear cross sections, and equations of state, as well as computer codes for high explosive detonics, nuclear chain reactions, radiation transport, and thermonuclear burn, are freely available in the open literature.

Early, low-technology fission and thermonuclear warheads were designed without the benefit of high speed computers. Computer aided design and manufacture greatly facilitates optimizing weapon designs of all types, and predicting the yields. Most of the warheads in

the U.S. stockpile were designed using computers roughly equivalent to today's personal computers. The desktop computers of the next decade are likely to approach the speed and storage capacity of today's mainframe supercomputers. A few unclassified fission weapon design codes have been written by researchers outside of the nuclear weapons laboratories, but these codes have not been calibrated against archival nuclear test data.

High-yield nuclear testing is highly desirable for all but the lowest technology designs to provide confidence in the computer calculations, to predict yields, and in order to optimize the designs with respect to yield-to-weight and yield-to volume. If high yield testing is prohibited, hydronuclear tests can serve a useful role in the development of the full spectrum of unboosted fission weapons, including first generation nuclear weapons of the implosion type with yields in the 10 to 30 kiloton range, more sophisticated designs with yields up to about a megaton, and advanced micro-nuclear weapons with yields of 5 to 500 tons. Since hydronuclear tests do not generate sufficient yield to create the conditions for fusion of deuterium and tritium in the core, such tests do not provide a reliable means of extrapolating the performance of new boosted fission weapons, boosted thermonuclear primaries, or advanced thermonuclear secondaries.

In negotiating the CTBT the current strategy of the U.S. Government is not to define in the treaty what constitutes a nuclear test. If this strategy is successful and the treaty is ratified, the U.S. Government will interpret the CTBT to permit hydronuclear testing if such a test is conducted by any other country. A program of hydronuclear testing by any of the weapon states will encourage the others to conduct similar tests. The declared and undeclared nuclear weapons states then will be free under the CTBT, to design **and test** a wide variety of new modern fission weapons, thereby undermining the purpose of the treaty.

Nuclear test sites of declared nuclear powers may be maintained, in part, to facilitate the conduct of hydronuclear tests. In the United States these tests would be conducted at Los Alamos National Laboratory or the Nevada Test Site. If hydronuclear tests are conducted at the respective nuclear test sites, which may be necessary for safety reasons, such tests will make verification of the CTBT increasingly difficult. Since the marginal value of hydronuclear tests to insure the safety and reliability of existing stockpiled weapons is very small, they should be explicitly banned under the CTBT. To do so we propose that the "Basic Obligations" of the parties under Article I of the Swedish or Australian draft CTB Treaty be amended to ban any nuclear weapon test explosion, or any nuclear explosion, **or the release of any nuclear fission energy caused by the assembly or compression of fissile material by chemical high explosive means.**

Table 1. Energy Released From a Nuclear Fission Explosion.

Assumptions: alpha = 1 per shake Mass = 10.000 kg
tau = 1.00 shake

Time (shakes)	alpha*t	N Gen.	N (fissions)	Power (j/shake)	Yield (joules)	Yield (other units)		Energy Density (j/g)
0	0.00	0.0	1.00E+00	2.88E-11	2.88E-11	6.25E-18	kg TNT	2.88E-15
1	1.00	1.0	2.72E+00	7.84E-11	7.84E-11	1.70E-17	kg TNT	7.84E-15
2	2.00	2.0	7.39E+00	2.13E-10	2.13E-10	4.62E-17	kg TNT	2.13E-14
3	3.00	3.0	2.01E+01	5.79E-10	5.79E-10	1.26E-16	kg TNT	5.79E-14
4	4.00	4.0	5.46E+01	1.57E-09	1.57E-09	3.41E-16	kg TNT	1.57E-13
5	5.00	5.0	1.48E+02	4.28E-09	4.28E-09	9.27E-16	kg TNT	4.28E-13
6	6.00	6.0	4.03E+02	1.16E-08	1.16E-08	2.52E-15	kg TNT	1.16E-12
7	7.00	7.0	1.10E+03	3.16E-08	3.16E-08	6.85E-15	kg TNT	3.16E-12
8	8.00	8.0	2.98E+03	8.60E-08	8.60E-08	1.86E-14	kg TNT	8.60E-12
9	9.00	9.0	8.10E+03	2.34E-07	2.34E-07	5.06E-14	kg TNT	2.34E-11
10	10.00	10.0	2.20E+04	6.35E-07	6.35E-07	1.38E-13	kg TNT	6.35E-11
11	11.00	11.0	5.99E+04	1.73E-06	1.73E-06	3.74E-13	kg TNT	1.73E-10
12	12.00	12.0	1.63E+05	4.69E-06	4.69E-06	1.02E-12	kg TNT	4.69E-10
13	13.00	13.0	4.42E+05	1.28E-05	1.28E-05	2.76E-12	kg TNT	1.28E-09
14	14.00	14.0	1.20E+06	3.47E-05	3.47E-05	7.51E-12	kg TNT	3.47E-09
15	15.00	15.0	3.27E+06	9.43E-05	9.43E-05	2.04E-11	kg TNT	9.43E-09
16	16.00	16.0	8.89E+06	2.56E-04	2.56E-04	5.55E-11	kg TNT	2.56E-08
17	17.00	17.0	2.42E+07	6.97E-04	6.97E-04	1.51E-10	kg TNT	6.97E-08
18	18.00	18.0	6.57E+07	1.89E-03	1.89E-03	4.10E-10	kg TNT	1.89E-07
19	19.00	19.0	1.78E+08	5.15E-03	5.15E-03	1.12E-09	kg TNT	5.15E-07
20	20.00	20.0	4.85E+08	1.40E-02	1.40E-02	3.03E-09	kg TNT	1.40E-06
21	21.00	21.0	1.32E+09	3.80E-02	3.80E-02	8.24E-09	kg TNT	3.80E-06
22	22.00	22.0	3.58E+09	1.03E-01	1.03E-01	2.24E-08	kg TNT	1.03E-05
23	23.00	23.0	9.74E+09	2.81E-01	2.81E-01	6.09E-08	kg TNT	2.81E-05
24	24.00	24.0	2.65E+10	7.64E-01	7.64E-01	1.66E-07	kg TNT	7.64E-05
25	25.00	25.0	7.20E+10	2.08E+00	2.08E+00	4.50E-07	kg TNT	2.08E-04
26	26.00	26.0	1.96E+11	5.64E+00	5.64E+00	1.22E-06	kg TNT	5.64E-04
27	27.00	27.0	5.32E+11	1.53E+01	1.53E+01	3.32E-06	kg TNT	1.53E-03
28	28.00	28.0	1.45E+12	4.17E+01	4.17E+01	9.04E-06	kg TNT	4.17E-03
29	29.00	29.0	3.93E+12	1.13E+02	1.13E+02	2.46E-05	kg TNT	1.13E-02
30	30.00	30.0	1.07E+13	3.08E+02	3.08E+02	6.68E-05	kg TNT	3.08E-02
31	31.00	31.0	2.90E+13	8.38E+02	8.38E+02	1.82E-04	kg TNT	8.38E-02
32	32.00	32.0	7.90E+13	2.28E+03	2.28E+03	4.93E-04	kg TNT	2.28E-01
33	33.00	33.0	2.15E+14	6.19E+03	6.19E+03	1.34E-03	kg TNT	6.19E-01
34	34.00	34.0	5.83E+14	1.68E+04	1.68E+04	3.65E-03	kg TNT	1.68E+00
35	35.00	35.0	1.59E+15	4.57E+04	4.57E+04	9.91E-03	kg TNT	4.57E+00
36	36.00	36.0	4.31E+15	1.24E+05	1.24E+05	2.69E-02	kg TNT	1.24E+01
37	37.00	37.0	1.17E+16	3.38E+05	3.38E+05	7.32E-02	kg TNT	3.38E+01
38	38.00	38.0	3.19E+16	9.19E+05	9.19E+05	1.99E-01	kg TNT	9.19E+01
39	39.00	39.0	8.66E+16	2.50E+06	2.50E+06	5.41E-01	kg TNT	2.50E+02
40	40.00	40.0	2.35E+17	6.79E+06	6.79E+06	1.47E+00	kg TNT	6.79E+02
41	41.00	41.0	6.40E+17	1.85E+07	1.85E+07	4.00E+00	kg TNT	1.85E+03
42	42.00	42.0	1.74E+18	5.02E+07	5.02E+07	1.09E+01	kg TNT	5.02E+03
43	43.00	43.0	4.73E+18	1.36E+08	1.36E+08	2.95E+01	kg TNT	1.36E+04
44	44.00	44.0	1.29E+19	3.71E+08	3.71E+08	8.03E+01	kg TNT	3.71E+04
45	45.00	45.0	3.49E+19	1.01E+09	1.01E+09	2.18E+02	kg TNT	1.01E+05
46	46.00	46.0	9.50E+19	2.74E+09	2.74E+09	6.54E-01	tons	2.74E+05
47	47.00	47.0	2.58E+20	7.44E+09	7.44E+09	1.78E+00	tons	7.44E+05
48	48.00	48.0	7.02E+20	2.02E+10	2.02E+10	4.83E+00	tons	2.02E+06
49	49.00	49.0	1.91E+21	5.50E+10	5.50E+10	1.31E+01	tons	5.50E+06
50	50.00	50.0	5.18E+21	1.50E+11	1.50E+11	3.57E+01	tons	1.50E+07
51	51.00	51.0	1.41E+22	4.06E+11	4.06E+11	9.71E+01	tons	4.06E+07
52	52.00	52.0	3.83E+22	1.10E+12	1.10E+12	2.64E+02	tons	1.10E+08
53	53.00	53.0	1.04E+23	3.00E+12	3.00E+12	7.17E-01	kt	3.00E+08
54	54.00	54.0	2.83E+23	8.16E+12	8.16E+12	1.95E+00	kt	8.16E+08
55	55.00	55.0	7.69E+23	2.22E+13	2.22E+13	5.30E+00	kt	2.22E+09
56	56.00	56.0	2.09E+24	6.03E+13	6.03E+13	1.44E+01	kt	6.03E+09
57	57.00	57.0	5.69E+24	1.64E+14	1.64E+14	3.92E+01	kt	1.64E+10
58	58.00	58.0	1.55E+25	4.46E+14	4.46E+14	1.06E+02	kt	4.46E+10
59	59.00	59.0	4.20E+25	1.21E+15	1.21E+15	2.89E+02	kt	1.21E+11

Table 2. Energy Released From a Nuclear Fission Explosion.

Assumptions: tau = 1.00 shake Yield = 35.5 kilotons
Mass = 24 kg Eff. = 0.09

Time (shakes)	alpha (/shake)	alpha*dt	N Gen.	N	Power (j/shake)	Yield (joules)	Yield (kt)	Energy Density (j/g)
0	0.500		0	1.63E+05	4.69E-06	4.69E-06	1.12E-18	1.96E-10
10	0.500	5.000	10	2.42E+07	6.97E-04	1.39E-03	3.33E-16	5.81E-08
20	0.500	5.000	20	3.58E+09	1.03E-01	2.07E-01	4.94E-14	8.62E-06
30	0.500	5.000	30	5.32E+11	1.53E+01	3.07E+01	7.33E-12	1.28E-03
40	0.500	5.000	40	7.90E+13	2.28E+03	4.55E+03	1.09E-09	1.90E-01
50	0.500	5.000	50	1.17E+16	3.38E+05	6.76E+05	1.61E-07	2.82E+01
60	0.500	5.000	60	1.74E+18	5.02E+07	1.00E+08	2.40E-05	4.18E+03
70	0.500	5.000	70	2.58E+20	7.44E+09	1.49E+10	3.56E-03	6.20E+05
80	0.500	5.000	80	3.83E+22	1.10E+12	2.21E+12	5.28E-01	9.21E+07
81	0.450	0.475	81	6.16E+22	1.78E+12	3.62E+12	8.66E-01	1.51E+08
82	0.400	0.425	82	9.42E+22	2.72E+12	5.84E+12	1.39E+00	2.43E+08
83	0.350	0.375	83	1.37E+23	3.95E+12	9.13E+12	2.18E+00	3.81E+08
84	0.300	0.325	84	1.90E+23	5.47E+12	1.38E+13	3.30E+00	5.75E+08
85	0.250	0.275	85	2.50E+23	7.20E+12	2.01E+13	4.80E+00	8.38E+08
86	0.200	0.225	86	3.13E+23	9.02E+12	2.82E+13	6.73E+00	1.17E+09
87	0.150	0.175	87	3.73E+23	1.07E+13	3.80E+13	9.09E+00	1.59E+09
88	0.100	0.125	88	4.22E+23	1.22E+13	4.95E+13	1.18E+01	2.06E+09
89	0.050	0.075	89	4.55E+23	1.31E+13	6.21E+13	1.48E+01	2.59E+09
90	0.000	0.025	90	4.67E+23	1.35E+13	7.54E+13	1.80E+01	3.14E+09
91	-0.050	-0.025	91	4.55E+23	1.31E+13	8.87E+13	2.12E+01	3.70E+09
92	-0.100	-0.075	92	4.22E+23	1.22E+13	1.01E+14	2.42E+01	4.22E+09
93	-0.150	-0.125	93	3.73E+23	1.07E+13	1.13E+14	2.69E+01	4.70E+09
94	-0.200	-0.175	94	3.13E+23	9.02E+12	1.23E+14	2.93E+01	5.11E+09
95	-0.250	-0.225	95	2.50E+23	7.20E+12	1.31E+14	3.12E+01	5.45E+09
96	-0.300	-0.275	96	1.90E+23	5.47E+12	1.37E+14	3.27E+01	5.71E+09
97	-0.350	-0.325	97	1.37E+23	3.95E+12	1.42E+14	3.39E+01	5.91E+09
98	-0.400	-0.375	98	9.42E+22	2.72E+12	1.45E+14	3.46E+01	6.04E+09
99	-0.450	-0.425	99	6.16E+22	1.78E+12	1.47E+14	3.52E+01	6.14E+09
100	-0.500	-0.475	100	3.83E+22	1.10E+12	1.49E+14	3.55E+01	6.19E+09

Table 3. Energy Released From a Hydronuclear Test.

Assumptions: tau = 1.00 shake Yield = 3.70 lb TNT
Mass = 6.000 kg Eff. = 1.78E-08

Time (shakes)	alpha (/shake)	alpha*dt	N Gen.	N	Power (j/shake)	Yield (joules)	Yield (lb TNT)	Energy Density (j/g)
0	0.020		0	1.63E+05	4.69E-06	4.69E-06	2.24E-12	7.82E-10
100	0.020	2.000	100	1.20E+06	3.47E-05	1.73E-03	8.28E-10	2.89E-07
200	0.020	2.000	200	8.89E+06	2.56E-04	1.28E-02	6.12E-09	2.14E-06
300	0.020	2.000	300	6.57E+07	1.89E-03	9.47E-02	4.52E-08	1.58E-05
400	0.020	2.000	400	4.85E+08	1.40E-02	7.00E-01	3.34E-07	1.17E-04
500	0.020	2.000	500	3.58E+09	1.03E-01	5.17E+00	2.47E-06	8.62E-04
600	0.020	2.000	600	2.65E+10	7.64E-01	3.82E+01	1.82E-05	6.37E-03
700	0.020	2.000	700	1.96E+11	5.64E+00	2.82E+02	1.35E-04	4.70E-02
800	0.020	2.000	800	1.45E+12	4.17E+01	2.09E+03	9.96E-04	3.48E-01
900	0.020	2.000	900	1.07E+13	3.08E+02	1.54E+04	7.36E-03	2.57E+00
1000	0.020	2.000	1000	7.90E+13	2.28E+03	1.14E+05	5.44E-02	1.90E+01
1025	0.018	0.475	1025	1.27E+14	3.66E+03	1.87E+05	8.92E-02	3.11E+01
1050	0.016	0.425	1050	1.94E+14	5.60E+03	3.01E+05	1.44E-01	5.01E+01
1075	0.014	0.375	1075	2.83E+14	8.15E+03	4.71E+05	2.25E-01	7.85E+01
1100	0.012	0.325	1100	3.91E+14	1.13E+04	7.11E+05	3.40E-01	1.19E+02
1125	0.010	0.275	1125	5.15E+14	1.48E+04	1.04E+06	4.95E-01	1.73E+02
1150	0.008	0.225	1150	6.45E+14	1.86E+04	1.45E+06	6.94E-01	2.42E+02
1175	0.006	0.175	1175	7.68E+14	2.22E+04	1.96E+06	9.36E-01	3.27E+02
1200	0.004	0.125	1200	8.70E+14	2.51E+04	2.55E+06	1.22E+00	4.25E+02
1225	0.002	0.075	1225	9.38E+14	2.71E+04	3.20E+06	1.53E+00	5.34E+02
1250	0.000	0.025	1250	9.62E+14	2.77E+04	3.89E+06	1.86E+00	6.48E+02
1275	-0.002	-0.025	1275	9.38E+14	2.71E+04	4.57E+06	2.18E+00	7.62E+02
1300	-0.004	-0.075	1300	8.70E+14	2.51E+04	5.22E+06	2.50E+00	8.71E+02
1325	-0.006	-0.125	1325	7.68E+14	2.22E+04	5.81E+06	2.78E+00	9.69E+02
1350	-0.008	-0.175	1350	6.45E+14	1.86E+04	6.32E+06	3.02E+00	1.05E+03
1375	-0.010	-0.225	1375	5.15E+14	1.48E+04	6.74E+06	3.22E+00	1.12E+03
1400	-0.012	-0.275	1400	3.91E+14	1.13E+04	7.06E+06	3.37E+00	1.18E+03
1425	-0.014	-0.325	1425	2.83E+14	8.15E+03	7.30E+06	3.49E+00	1.22E+03
1450	-0.016	-0.375	1450	1.94E+14	5.60E+03	7.47E+06	3.57E+00	1.25E+03
1475	-0.018	-0.425	1475	1.27E+14	3.66E+03	7.59E+06	3.62E+00	1.26E+03
1500	-0.020	-0.475	1500	7.90E+13	2.28E+03	7.66E+06	3.66E+00	1.28E+03
1525	-0.022	-0.525	1525	4.67E+13	1.35E+03	7.70E+06	3.68E+00	1.28E+03
1550	-0.024	-0.575	1550	2.63E+13	7.58E+02	7.73E+06	3.69E+00	1.29E+03
1575	-0.026	-0.625	1575	1.41E+13	4.06E+02	7.74E+06	3.70E+00	1.29E+03
1600	-0.028	-0.675	1600	7.16E+12	2.07E+02	7.75E+06	3.70E+00	1.29E+03

Table 4. U.S. Announced Nuclear Tests for Safety Purposes

Year	Location	Type	Number	Yield (tons)
1955	NTS	Surface	3	zero
1956	NTS	Surface	1	very slight
1957	Bombing Range	Surface	1	zero
	NTS	Surface	3	zero/300/500
		Tunnel	1	zero
		Shaft	3	slight/slight/?
1958	Enewetak	Barge	1	zero
	NTS	Balloon	1	77
		Tower	5	zero/0.2/0.6/0.7/21
		Surface	3	zero/1.7/24
		Tunnel	3	<1/<1/115
		Shaft	6	zero/1.5/2/5.5/15/38
1988	NTS	Shaft	1	?
		TOTAL	34	

Figure 1. Nuclear Fission Explosion.

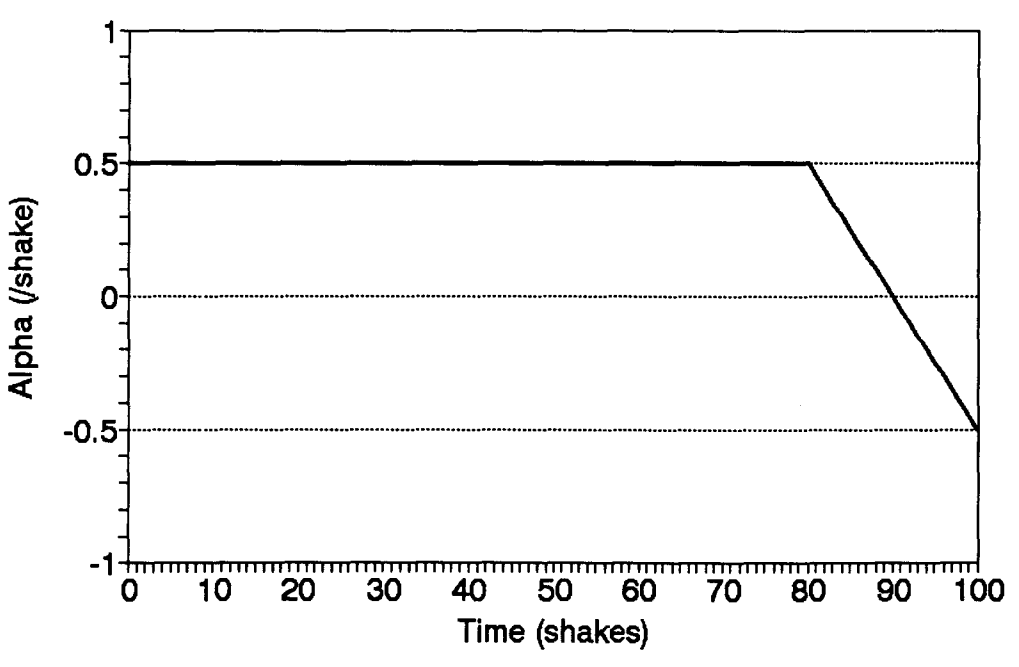


Figure 2. Nuclear Fission Explosion.

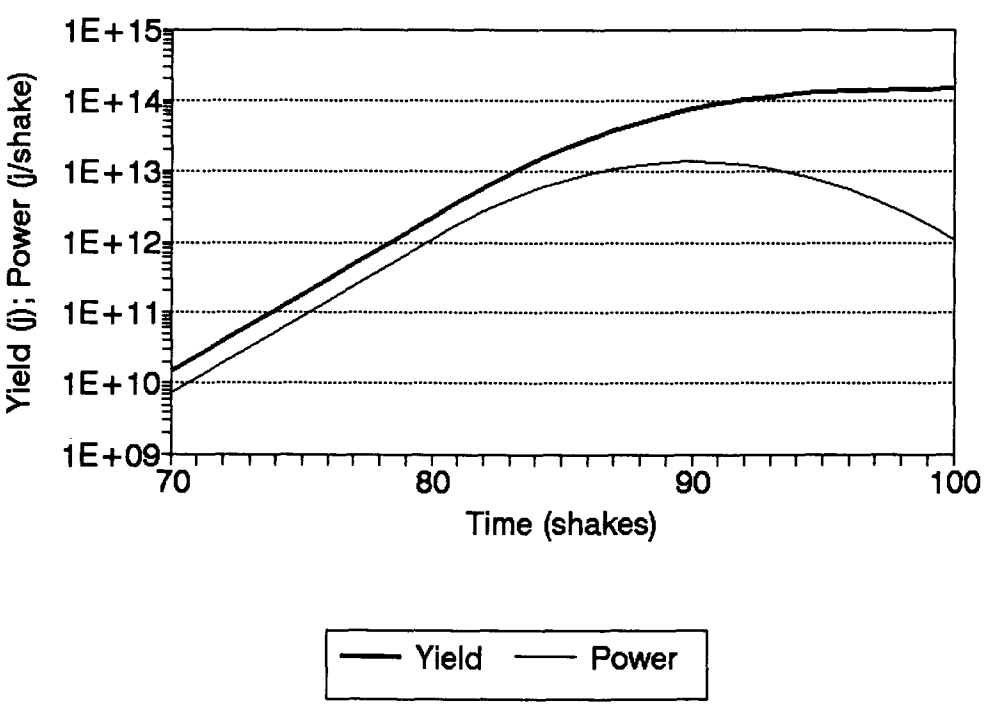


Figure 3. Hydronuclear Test.

Alpha -- Low Technology Weapon

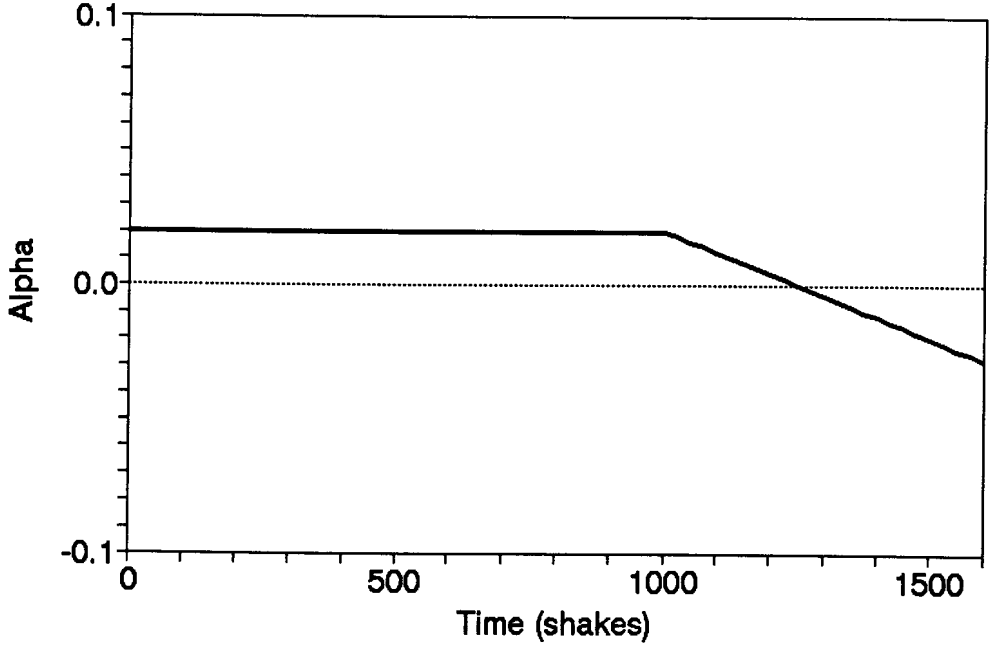
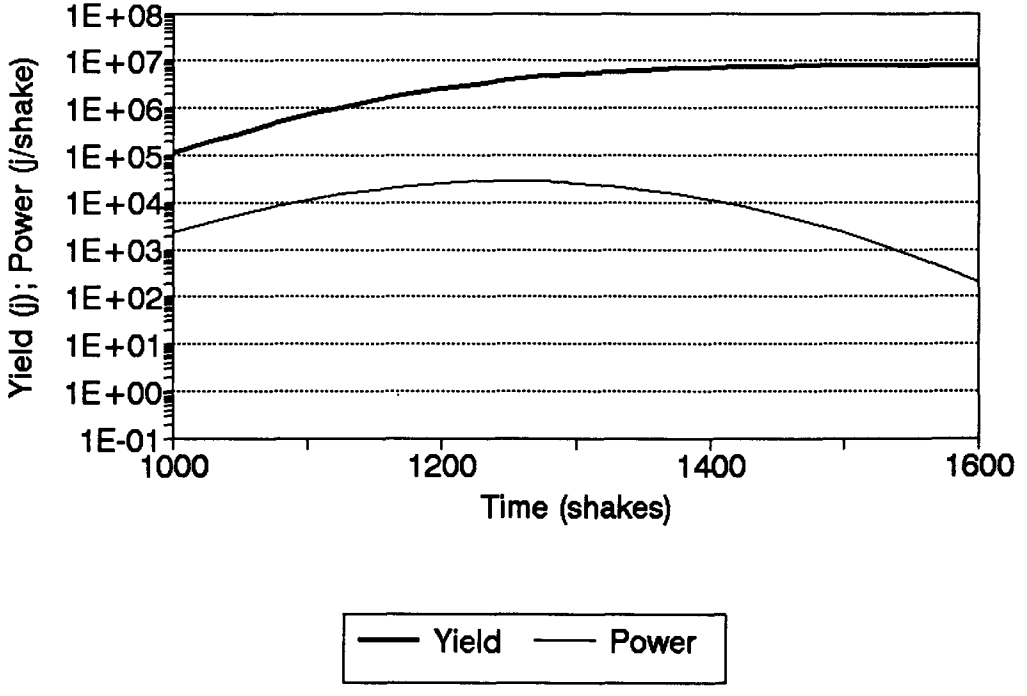


Figure 4. Hydronuclear Test.

Power and Yield--Low Technology Weapon



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