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The Question of Pure Fusion Explosions Under the CTBT

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Fusion research involving implosions of deuterium-tritium targets driven by laser or particle beams appears to be widely accepted as not prohibited under the Comprehensive Test Ban Treaty (CTBT). Research on fusion involving implosions driven by other means is underway in civilian and military laboratories in the US and other countries and could result in small (up to perhaps a few tons TNT equivalent) explosive fusion energy releases. However, the status of such experiments under the CTBT has not been clearly defined. Until the potential for this research to lead to the development of pure fusion weapons has been openly reviewed and an appropriate policy governing its conduct is established in the context of the CTBT, such experiments should be subject to two interim limits: (1) a maximum of $\sim 10^{14}$ neutrons produced; and (2) a ban on the use of tritium.

INTRODUCTION

The Comprehensive Test Ban Treaty (CTBT) bans "any nuclear weapon test explosion or any other nuclear explosion." However, neither the Treaty text nor the public negotiating record provide a technically precise understanding of the boundary between prohibited nuclear explosions and not-prohibited activities. There are gray areas that states will need to address in the context of ratification deliberations and for internal planning purposes.

In the case of fission explosions, the United States has imposed criticality as its own dividing line between a "nuclear explosion" and something less than that.[1] A policy regarding permitted fusion experiments is also needed. Were it possible to create compact, pure-fusion nuclear explosives, their detonation would obviously be prohibited by the Treaty. Explosives based on fusion alone could have as much potential as weapons as the fission or fission-fusion explo-

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sives in the nuclear arsenals today. Furthermore, if compact pure fusion explosives were developed, IAEA safeguards on the use of fissile materials—the method by which nuclear-weapons nonproliferation is verified—would be bypassed.[2]

Some types of research and development that could result in small—up to perhaps a few tons TNT equivalent—explosive energy releases from deuterium-tritium (DT) fusion are being pursued in both civilian and military research in a number of countries. At the 1975 NPT Review Conference, the U.S. asserted that research on certain methods of igniting small fusion explosions should not be prohibited under the NPT. The methods specified were the implosion and heating of fusion materials by converging beams of laser light or by energetic beams of charged particles produced by accelerators.[3] The implicit assumption was that neither high-power lasers nor particle-accelerators and their beam transport systems and energy sources could be miniaturized to the point where they could fit on a missile or in an aircraft bomb-bay. There appears to have been little objection by other governments to this view. Today laser- and particle-driven inertial-confinement fusion techniques are being pursued openly in a number of non-weapons states including Germany, which, when it signed the CTBT, stated its understanding that this research is not banned by the CTBT.[4]

"SIMILAR EXPERIMENTS"

In its official "interpretation" of the CTBT submitted to the Senate to set the stage for the ratification process, the Clinton Administration indicated its understanding that "activities not affected by the Treaty" will include "inertial confinement fusion and similar experiments."[5] The issue of further guidance with regard to the limits on "similar experiments" was debated within the Administration during the development of this interpretation, but no more specific unclassified guidance was provided. Such experiments—in which high explosives or magnetic fields are used instead of lasers or particle beams to drive the implosion—are currently an area of considerable interest in the U.S. weapons laboratories, in part because they provide an alternative arena in which weapons physicists can deepen their understanding of dense, high-temperature plasmas in the absence of nuclear-weapons tests. These experiments are also seen by some as potentially much less costly routes to inertial confinement fusion energy than laser and particle-beam approaches. Because they are also potential routes to the development of pure fusion weapons, a policy guiding this research is needed.

One approach, "magnetized target fusion," (see Appendix A) is currently the subject of joint unclassified research by Los Alamos National Laboratory and its Russian counterpart, the All-Russian Institute of Experimental Physics at Sarov (formerly Arzamas-16). Magnetized target fusion (MTF) involves creation of a "warm" (~100 eV) magnetized plasma for subsequent implosion by a liner compressed by a magnetic field. A full liner-on-plasma experiment has not taken place to date, but a DT plasma that produced 10^{13} neutrons without implosion has been created.[6,7] Another approach, under investigation at Sandia National Laboratory, generates soft x-rays by passing a huge pulse of current through a cylindrical array of fine wires, creating a plasma that is then imploded by the surrounding magnetic field to a density that traps the x-rays (see Appendix D). These x-rays would then be used to implode a small fusion target.[8]

Both of these approaches do away with the intermediary of lasers and particle accelerators, using instead very large electric current pulses generated by pulsed power sources to implode a fusion target. The current pulses may be generated by large capacitor banks or by the compression of magnetic fields with high explosives (Appendix A), a technique pioneered by Andrei Sakharov at Arzamas-16.[9]

The advent of the CTBT has probably also renewed interest at the weapons labs in attempting to ignite DT fusion *directly* using high-explosive implosion systems, if only because this will be one of the remaining experimental challenges that the designers of nuclear weapon implosion systems can use to hone their skills. Although U.S. progress in this area is classified, in early 1992 the Russian weapon laboratories reported neutron yields of 10^{13}–10^{14} neutrons, corresponding to the fusion of 10^{-10} to 10^{-9} grams of DT gas.[10] The production of 10^{14} neutrons would be accompanied by the release of an amount of fusion energy equivalent to roughly 60 mg of TNT.[11] The associated radiation dose at one meter would be about 0.2 Gy (20 rads)—significant but not great enough to cause death in the short term.[12]

Hans Bethe, who headed of the Los Alamos Theory Division during World War II, has expressed skepticism that such activities might lead to pure fusion weapons. However, he wrote a letter to President Clinton in April 1997 stating that "the time has come for our Nation to declare that it is not working, in any way, to develop further weapons of mass destruction of any kind. In particular, this means not financing work looking toward the possibility of new designs for nuclear weapons such as pure fusion weapons."[13] If such a policy were announced, there would need to be more specific guidance with regard to permissible activities. The purpose of this paper is to begin laying a technical basis for such guidance.

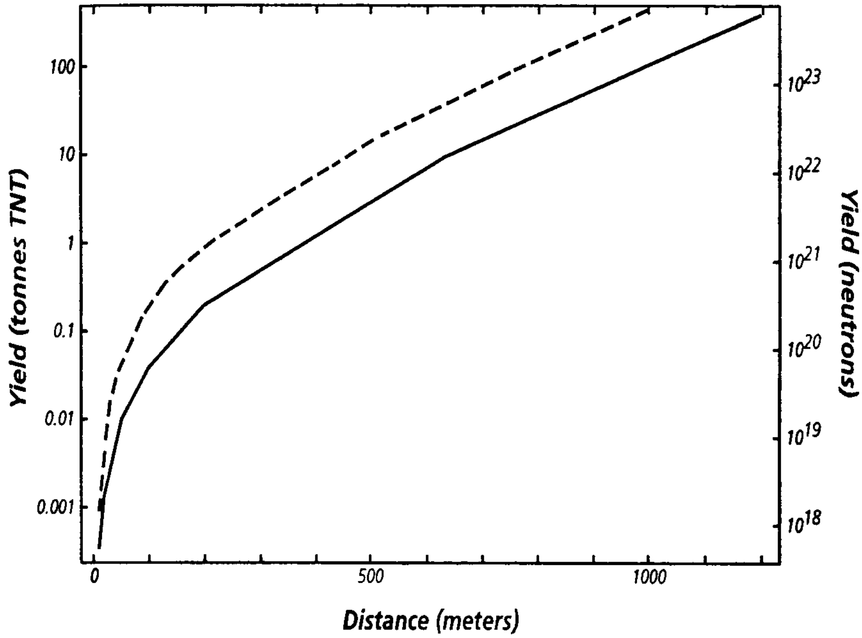

Figure 1: The solid line depicts the distance within which a person would receive a lethal radiation dose (4.5 Gy or more) from the high-energy neutrons produced by a fusion explosion detonated in open air. The dashed line shows the distance, accounting for the estimated shielding from concrete buildings in a city (see endnote 34).

POTENTIAL WEAPONS APPLICATIONS

Two potential weapons applications of fusion explosives would be: i) warheads with yield-to-weight ratios higher than achievable with conventional high explosives (HE), and ii) mini-neutron bombs. Figure 1 shows the lethal radius that would result from neutron radiation as a function of neutron yield. For example, the curves indicate that a weapon with a fusion yield equivalent to 1 ton of high explosive would deliver a lethal neutron dose out to 200–400 meters.

We have examined the fusion-weapon potential in a preliminary manner for the case of magnetized target fusion (Appendix B). We chose MTF not because it is of particular concern, but because it is the furthest developed pure fusion system powered by high explosives that is unclassified. We conclude that, while it appears to have little advantage over conventional high explosive for creating blast effects, it may have some potential as a mini-neutron bomb.

POTENTIAL BENEFITS

The non-weapons benefits claimed for the development of controlled fusion using pulsed-power techniques overlap several of those claimed for laser-driven inertial-confinement fusion: i) the discovery of a potential route to the economical release of fusion energy on a small scale; ii) an intense pulsed source of neutrons for scientific research applications and for simulating nuclear-weapons effects; iii) the study of an unexplored plasma density regime and an improved knowledge of plasma physics in general; and iv) a means by which to "exercise nearly all the theoretical and experimental skills necessary for preservation of nuclear weapon's design and testing capabilities."[14] These justifications should be subject to open review and debate outside.

Efforts to justify these experiments as energy research face a particularly high credibility barrier because energy systems based on pulsed-power techniques would not be economic unless the cost per pulse could be made very low.[15] It appears that this criterion may be difficult to meet. For instance, even if pulsed-power fusion progressed to the point where a single shot delivered 1 gigajoule (GJ), the total cost per shot would have to be less than fifteen dollars to compete with today's fission energy prices (Appendix C).

As for the final justification, assuring continued nuclear weapons expertise by developing and testing devices that are themselves potential nuclear weapons, could be seen as circumvention of the CTBT. Ray Kidder, a retired senior weapons expert at Livermore National Laboratory, has said of direct HE-driven fusion research: "This is a really good way to keep your troops up to speed and keep them interested...[but] if you're going to be true to the intent of the treaty, you don't do these things."[16]

INTERIM LIMITS

Signatories to the CTBT will have to address the fact that some nuclear-weapons labs are already openly conducting pulsed-power-driven fusion experiments and are probably interested in continuing to conduct chemical-implosion-driven fusion experiments in secret. Those conducting such experiments will have to deal with the fact that they may be asked about the permissibility of their work under the CTBT.

Given this situation, some interim limits may be called for. Richard Garwin, in a presentation to Chinese weapons experts in February 1996, suggested one possible interim limit on direct, chemical-implosion-driven fusion:

> "While the prospects of fusion energy nuclear explosions of damaging magnitude do not look promising with high-explosive assembly, I believe such capabilities should be regarded as banned by the Treaty. Nevertheless, both

> scientific curiosity and some practical purposes might be served by high-explosive systems that provoke a tiny amount of fusion. To set the scale, one gram of high explosive [HE] equivalent energy release corresponds to 1.6×10^{15} fusions. So one might set a limit (for HE-induced fusion only) at 0.1 gram of HE, corresponding to 1.6×10^{14} fusions."[17]

As noted earlier, this limit is approximately equal to the number of fusions reported by Russian experimentalists using direct high explosive assembly. High-explosive-driven pulsed-power fusion should be subject to the same limit until there has been a review of its potential dangers and benefits. In the case of MTF, given that 10^{13} DT neutrons have already been achieved by research conducted thus far (DT plasma formation, but no implosion), this limit would postpone the full liner-on-plasma test until a review has been conducted.

Ray Kidder has suggested an alternative (or perhaps complementary) approach: a ban on the use of tritium in fusion implosion systems not driven by lasers or particle beams.[18] He points out that, in the absence of tritium, a deuterium plasma will produce neutrons sufficient for diagnostic purposes, but is unlikely to ignite or burn. Because the use of tritium requires onerous arrangements to minimize the risk of exposure to the radioactive gas, fusion researchers usually work with deuterium plasmas initially, postponing the use of tritium as long as possible. Therefore, an interim tritium ban might be accepted.

AN OPEN REVIEW PROCESS

The weapon states should not attempt to interpret, unilaterally or in secret, how the CTBT constrains such activities. This would, in effect, leave the interpretation of the CTBT to the weapons labs in each country which, given their 40 years of opposition to the CTBT, would not be credible either domestically or internationally. Any domestic review should be as open as possible, but informed as necessary by reviews by independent experts of potential classified applications. There are a number of precedents for such arrangements.[19]

The proper international forum in which to offer any proposal for additional permissible activities involving fusion explosions should also be an open one. This might be an NPT Review Conference, as was done for laser- and beam-driven fusion. Or, if a country felt that it needed to pursue pulsed-power or chemical-implosion driven fusion in its Stockpile Stewardship Program, it could make that known at a CTBT Review Conference—just as the U.S. took pains to make clear its position on the permissibility of sub-critical experiments during the negotiation of the CTBT. Until this question is addressed in an international forum and a consensus is reached on the status of such experiments under the CTBT, we urge countries engaged in such research to publicly adopt interim limits such as those proposed here.

APPENDIX A: MAGNETIZED TARGET FUSION

In order for fusion energy to be released, two light nuclei must come sufficiently close together so that they have a reasonable probability of tunnelling through their Coulomb barrier. Historically, experimental study of controlled nuclear fusion has focused predominantly on two techniques to achieve this: i) magnetic confinement fusion, in which a deuterium-tritium (DT) plasma is heated while being confined by a strong magnetic field; and ii) inertial confinement fusion (ICF) in which a capsule containing DT is imploded by highly energetic laser or particle beams. The National Ignition Facility (NIF) under construction at Livermore National Laboratory will conduct research on laser-driven ICF. Magnetized target fusion is a third approach in which a wall-confined DT plasma is created in a magnetic field and then compressed.

The minimum conditions for DT "ignition" are that the plasma reach a temperature of at least 4 keV and satisfy the Lawson criterion, which requires the product of the plasma density and the plasma confinement time to be at least 10^{14} sec-cm^{-3}.

The standard "Tokomak" approach to magnetic confinement fusion contains the plasma within a toroidal vessel with a magnetic field. The Lawson criterion would be achieved by confining a relatively low particle density DT plasma (~10^{14} cm^{-3}) for a relatively long time (at least a second). The plasma is heated using techniques such as microwave heating and neutral atomic beam bombardment.

In laser-driven ICF, a plasma of much higher final particle density (~10^{24} cm^{-3}) created by the implosion of a millimeter-sized capsule must react within a expansion time constant (~10^{-10} seconds) determined by the inertia of the compressed capsule and fuel. A radial convergence ratio of about 30 is believed to be necessary for ICF ignition. The implosion velocity must also be very high (greater than 30 cm/microsecond) to achieve the required temperature.[20]

Magnetized target fusion is frequently described as an intermediate approach between magnetic confinement fusion and ICF that eliminates some of the difficulties of both while being limited to lower achievable energy gains. MTF falls between magnetic confinement fusion and ICF in its confinement time (~10^{-6} seconds) and density regime (~10^{20} cm^{-3}) (Table 1). In the MTF approach, a "warm" (~100 eV) magnetized plasma is imploded. The initial magnetic field (~10–100 kilogauss) confines the charged particles in the plasma to spiral orbits, thereby suppressing heat transport from the interior of the plasma to the chamber walls. This reduction of thermal losses lowers the implosion velocity requirements for adiabatic heating to ~1 cm/microsec-

Table 1: DT plasma densities and confinement times for tokomak-based magnetic confinement fusion (MCF), Magnetized Target Fusion (MTF) and Inertial Confinement Fusion (ICF). In order for the energy released by a fusion "burn" to repay the initial heating of the plasma, the product of final plasma density and plasma confinement time must be greater than or equal to $\sim 10^{14}$ s-cm^{-3} (the Lawson Criterion).

	MCF	MTF	ICF
Starting density (cm^{-3})	10^{14}	$\sim 10^{17}$	10^{21}
Compressed density (cm^{-3})	-	$\sim 10^{20}$	$\sim 10^{24}$
Confinement time (seconds)	~1	$\sim 10^{-6}$	$\sim 10^{-10}$

ond. The higher starting temperature of MTF fuel also reduces to about 10 the radial compression ratio required to complete the heating process.[21] The Los Alamos/Arzamas-16 collaboration plans to use magnetically driven liners as the implosion mechanism for MTF.

The Russian-designed "MAGO" scheme[22,23] for forming the warm, magnetized target plasma is described in Figure 2. If the MTF scheme is carried through, this preheated plasma will be imploded by a yet-to-be-developed liner that would replace the thick outer walls of the chamber.

A target plasma has already been formed using the MAGO chamber and its temperature proved sufficient to generate a burst of 10^{13} neutrons.[24] A liner has not yet been mated to the target plasma, but liner implosion tests have been conducted separately. The first implosion test with a DT plasma is planned to occur in the year 2000 if funding is made available. Explosive-driven flux-compression generators are expected to provide the required pulses of power to the MAGO chamber and the imploding liner. [25,26]

Explosive-Driven Flux-Compression Generators

Most US research on pulsed-power applications has used high-energy capacitor bank facilities. The prohibitive costs of large capacitor facilities led Soviet scientists to develop advanced explosive-driven flux-compression generators as an alternative means to create extremely high-energy pulses. These generators exploit the fact that the magnetic flux trapped by a conducting loop or coil stays constant, even when the area of the loop or the number of turns in the coil is varied. To maintain the flux under these conditions, Ampere's Law requires that the current in the loop or coil increase. High explosives are used to compress a current loop or to remove turns from a coil containing a magnetic field, thereby inducing an increase in current and magnetic field.

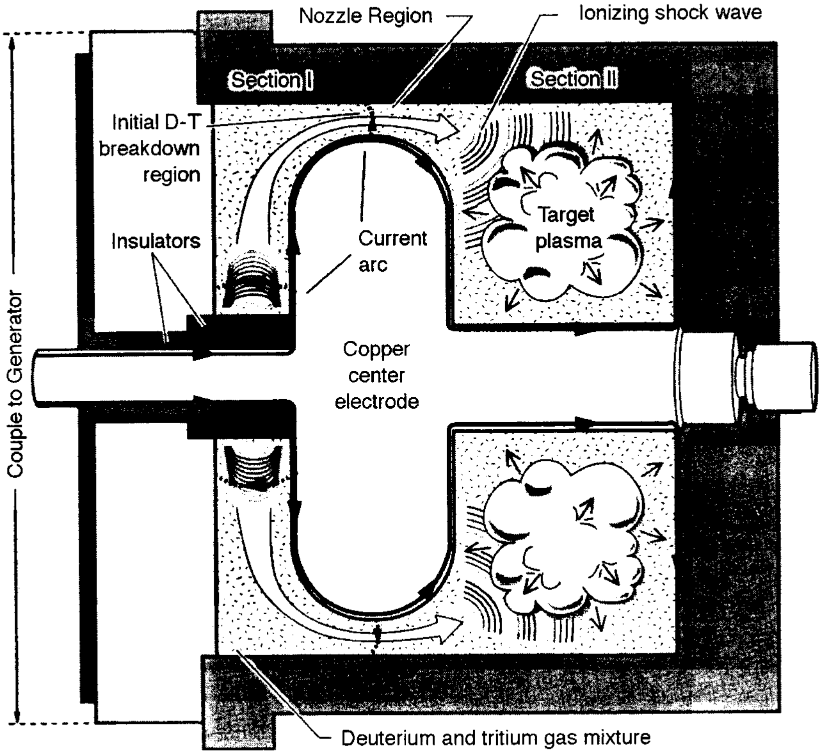

Figure 2: Cross section of the MAGO target plasma formation chamber. A current pulse of about 2 megamperes (MA) is passed through the electrode generating a magnetic field throughout the DT-gas-filled chamber. A stronger current pulse (6-8 MA) is then sent through the electrode, causing electrical breakdown of the gas in Section I and the nozzle region. The plasma is propelled by the Lorentz force into Section II, colliding with the gas there and creating ionizing shockwaves that convert it to a plasma. The proposal is to implode the plasma by a liner that would surround Section II in hopes of igniting fusion. (Figure courtesy of *Los Alamos Science*, Los Alamos National Laboratory.)

A helical flux-compression generator (HFCG) configured to deliver a large current, is shown in Figure 3. Such devices have amplified currents from capacitor banks by factors of several hundred to deliver output currents on the order of 10 megamperes (MA). Helical generators coupled to more sophisticated "disk explosive magnetic generators" (DEMGs), which were developed in Russia, have succeeded in generating currents of hundreds of megamperes.

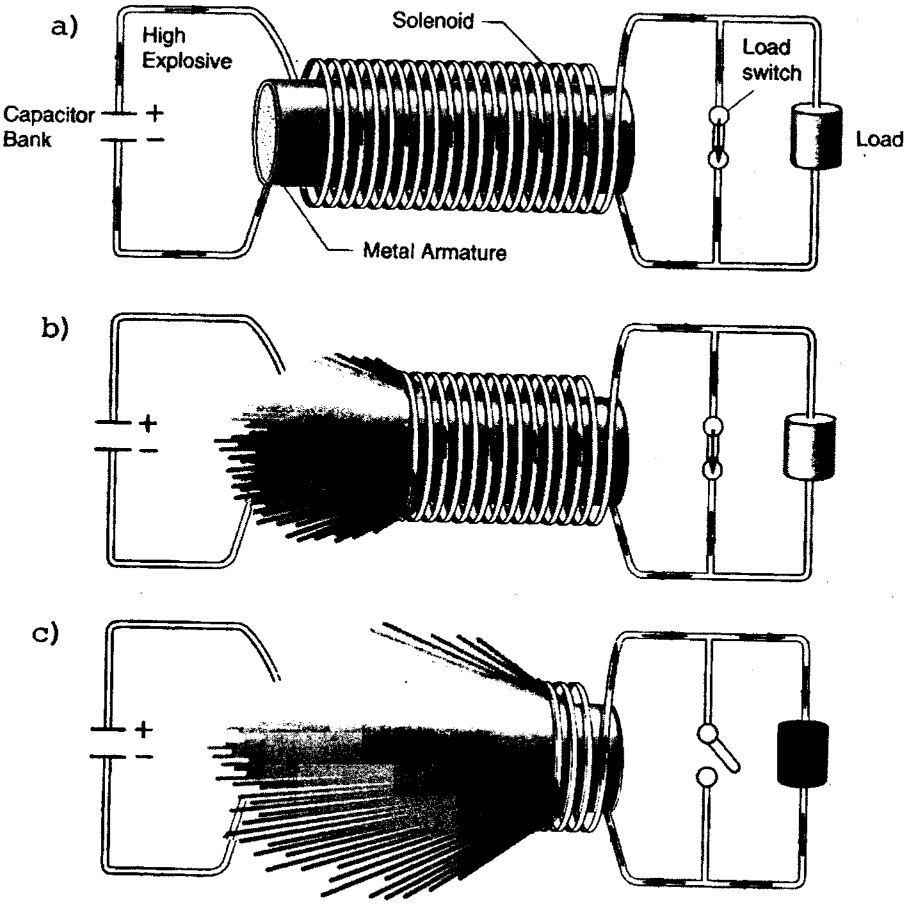

Figure 3: Helical generator. a) A high-explosive-packed cylindrical conducting armature sits inside a solenoid with which it forms a circuit. A current is passed through the circuit, setting up a magnetic field between the armature and the solenoid. The load switch is initially closed. b) When the high explosive is detonated at one end, the armature expands. As loops are removed from the coil by being short-circuited, a larger current must be induced in those remaining to preserve the flux. c) When the peak current is reached, the switch bypassing the load is opened. (Figure courtesy of *Los Alamos Science*, Los Alamos National Laboratory.)

The magnetic fields that can be generated using the large currents from flux-compression generators can implode a metal cylinder, or "liner," as shown in Figure 4. When the output current from the generator passes down the walls of the liner, a strong magnetic field is produced outside the conducting cylinder while the field inside remains zero, leading to magnetic pressure on the cylinder walls directed radially inward.

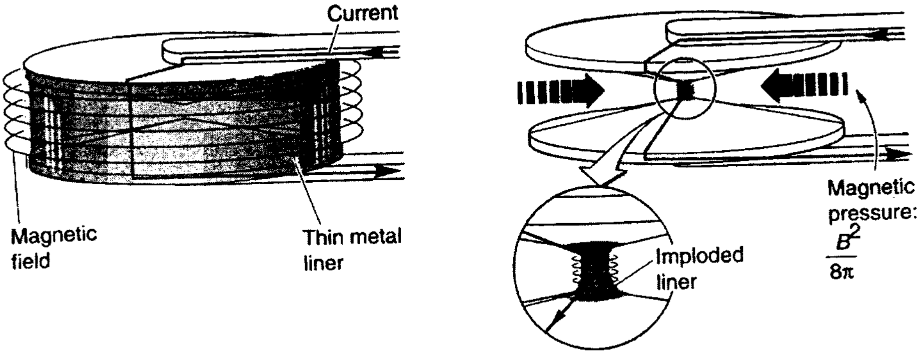

Figure 4: Liner implosion. When a strong current pulse is passed down the walls of a hollow conducting cylinder, or "liner," a large magnetic field is created outside its surface, while the magnetic field inside the cylinder remains zero. The unbalanced pressure of the magnetic field outside the walls of the liner then generates a radial force inward. (Figure courtesy of *Los Alamos Science*, Los Alamos National Laboratory.)

APPENDIX B: MTF AS A WEAPON

As currently planned, the first liner-on-plasma test of MTF will not rely on large capacitor banks, but high-explosive-powered flux-compression generators. In principle, such an MTF device could therefore be made portable—or, in weapons parlance, "deliverable." However, the weapons potential of MTF depends upon the area over which it can generate lethal effects for a given weight. We have estimated the weight of an MTF device based on published descriptions of flux-compression generators and the MAGO chamber, and on private communication with the MTF experimentalists. These masses could possibly be reduced by efforts at weaponization.

The building blocks of the pulse power system driving such a weapon would be helical and disk magnetic flux-compression generators (see Appendix A). An HFCG system in which the initial current is provided by a battery has been demonstrated to be able to deliver a peak current of ~1 MA current for longer than 10 microseconds,[27] suggesting that a system sufficient to provide the ~2 MA necessary to set up the initial bias magnetic field in the MAGO chamber is within reach. Such an HFCG could provide the initial current for a larger HFCG which then could generate the second current pulse of about 6 MA necessary to form the plasma.[28] The Los Alamos/Arzamas-16 team plans to use an HFCG coupled to a DEMG to deliver the requisite 50–100 MJ to the MTF liner.[29] An HFCG system could also be used to provide the seed current to this combination. A schematic of the system is shown in Figure 5. Table 2 provides estimates of the total mass and the high-explosive mass of each component. The total mass of the system is estimated at 3 metric tons, with about a tenth of that mass accounted for by high explosive.

The MTF literature indicates that MTF might be able to achieve fusion of 3–30 mg of DT fuel per shot for an energy release in the range 1–10 gigajoules (GJ), roughly equivalent to the detonation of 0.2–2 metric tons (t) of high explosive.[30,31] The total yield, including that from the 320 kg of actual high explosive, would be 0.5–2.5 t HE equivalent. A three-ton device of this yield would have no advantage over conventional high explosives in terms of blast effects. Indeed, only one-fifth of the energy would cause blast effects since eighty percent would be carried by neutrons.[32]

One way to increase the yield would be to surround the device with natural uranium. Uranium-238, the non-chain-reacting isotope which makes up 99.3 percent of natural uranium, can be fissioned by the fast neutrons produced by DT fusion. A layer of natural uranium a few centimeters thick could double or triple the explosive yield (Figure 6). Even so, the yield-to-weight advantage of such a device for creating blast effects compared to a conventional high explosive appears marginal (see Table 3).

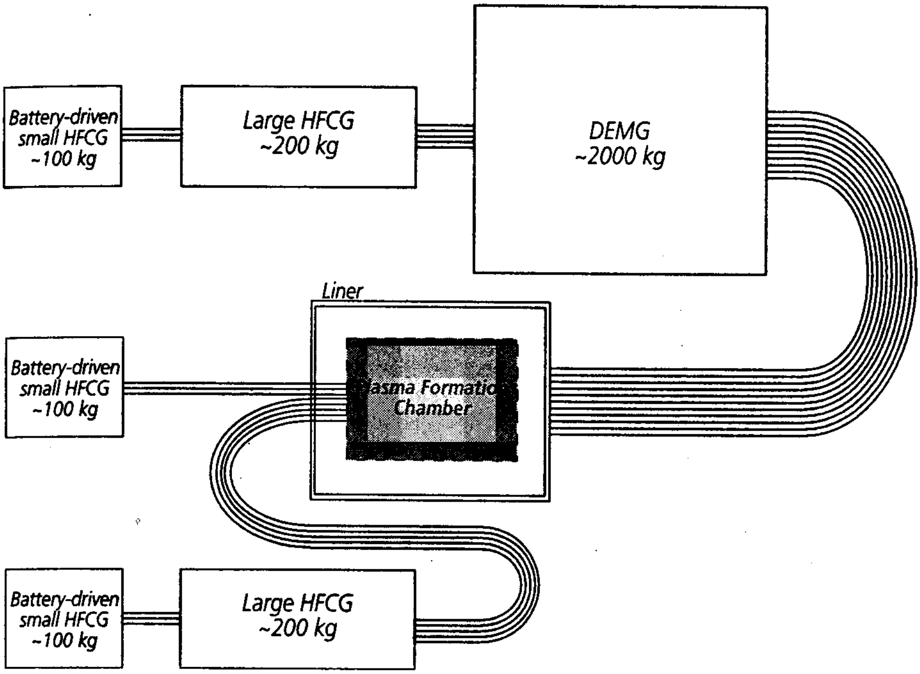

Figure 5: Schematic (not to scale) showing components of a hypothetical high-explosive-driven MTF device.

The release of 1–10 GJ of fusion-energy would also produce roughly $3.5\times10^{20-21}$ fast neutrons. This many neutrons would deliver a lethal radiation dose of 4.5 Grays (450 rads) in open space out to a radius of about 200–500 meters.[33] This radius would be reduced to about 100–300 meters by the presence of concrete walls (Figure 1).[34] The lethal blast radius from such a weapon, determined by the fusion yield plus the high explosive yield (about a ton HE equivalent), would be 10–20 meters in a built-up area.[35] The lethal radius for 300 kg of sarin nerve gas in a 1-ton Scud missile on an overcast day or night with moderate wind against an unprotected population would be about 250 meters.[36] Table 3 gives these lethalities in terms of area. A pure fusion weapon in the assumed yield range would therefore have a lethality in populated areas larger than a conventional weapon and perhaps comparable to a chemical warhead of similar weight.

The weapon potential would be greater if, instead of heating the entire plasma directly, fusion were achieved by creating a localized "spark" capable of heating a surrounding "cold" fuel volume to fusion conditions, an approach

Table 2: Approximate mass and high explosive (HE) content of basic components required for a high-explosive-driven MTF system. The plasma formation chamber was assumed to be similar to the MAGO chamber described in the text. "Cables" refers to electrical connections from one flux-compression generator to another and to the plasma chamber and liner (Figure 5).

Component	**Mass (kg)**	**Mass HE (kg)**
Plasma formation		
Small HFCG (1st pulse)[a]	110	10
Small HFCG (2nd pulse)	110	10
Large HFCG (2nd pulse)[b]	220	20
Plasma chamber [b]	50	-
Cables[c]	25	-
Liner implosion		
Small HFCG	110	10
Large HFCG	220	20
DEMG[b]	2000	250
Cables[c]	550	-
Liner[c]	5	-
Total	**3,400 kg**	**320 kg**

[a] See endnote 27.

[b] Based on values provided by I. Lindemuth, Los Alamos National Laboratory (LANL), private communication, February 15, 1998. The actual mass of conductor required is about ten times larger than the minimum amount that would be required to carry the current pulse (see footnote c below) due to the need to stabilize the chamber and generators against magnetic forces. This requirement accounts, for example, for more than half of the total DEMG mass (B. Reinovsky, LANL, private communication, February 15, 1998).

[c] The length of copper cables required to power the plasma chamber was assumed to be 5 meters. The total cross sectional area was determined by requiring that the electrical action from an average current of 10 MA carried for 10 microseconds did not exceed one tenth of the "action-to-burst" for copper (see J. Parker, p. 10-12). This gave a cross-sectional are of 2.5 cm^2 and mass of: (500 cm)(2.5 cm^2)(10g/cc) = 12.5 kg. Multiplying by two to account for dielectric and jacket mass we have 25 kg total. The masses of the liner and associated cables were estimated the same way except that the liner was taken to be aluminum. An assumed average current of 100 MA for 50 microseconds, with the same constraint on the electrical action as before, gave a liner cross sectional area of 90 cm^2 and total cross section area of the cables equal to 55 cm^2. The liner length was taken as 20 cm, and the length of cables 5 m. The mass of the liner was then: (20 cm)(90 cm^2)(3 g/cc) = 5 kg, and the mass of the cables (500 cm)(55 cm^2)(10 g/cc)(2) = 550 kg.

used in ICF research. There is apparently some hope of achieving high gain by using MTF as the spark to ignite a larger fuel mass,[37] which would make considerably higher yields possible.

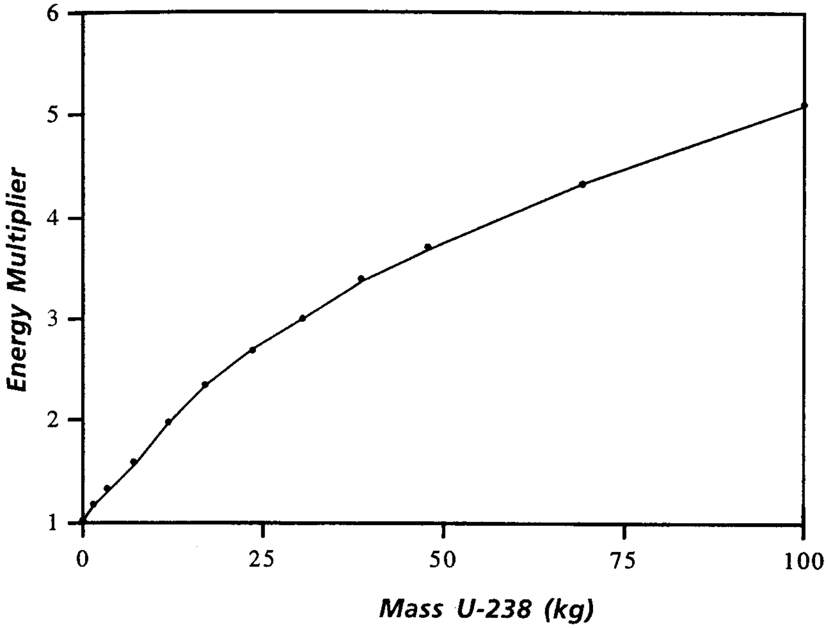

Figure 6: The factor by which the energy yield of a fusion explosive would be enhanced if it were surrounded by a layer of uranium-238. The data were generated using MCNP ("A General Monte Carlo Code for Neutron and Photon Transport," Version 4A, Los Alamos National Laboratory, 1994). The fusion explosive was modeled as a point source of 14 MeV neutrons at the center of a spherical shell of U-238 of inner radius 5 cm and density 19 g/cc.

Table 3: Comparison of lethality of MTF devices with conventional high explosive and chemical weapon of comparable mass. Lethality is due to blast effects except where noted.

Weapon	Yield (metric tons HE)	Lethal area (km^2)
1-ton high explosive	1.0	~10^{-3}
MTF device (0.5–2.5 t)[a]	~1	~10^{-3} (blast) 0.03–0.8 (neutrons)[b]
300 kg Sarin warhead on Scud	-	0.22
Hiroshima-type bomb	~15,000	~7[c]

a. Fusion yield (0.2–2.2t) plus yield from high explosive (0.3t) = 0.5–2.5t.

b. 4.5 Gray dose.

c. The area given is that of a circle centered at ground zero for which, for uniform population density, the number of people surviving within would be equal to the number killed outside.

APPENDIX C: MTF AS AN ENERGY SOURCE

MTF proponents argue that if MTF reaches its goal of fusion yields in the 1–10 GJ range, the technology might be integrated into a reactor design able to deliver economically competitive electric power. Part of the basis for this hope appears to be the high efficiency and low projected capital costs of magnetohydrodynamic (MHD) generators which could efficiently convert the kinetic energy stored in a hot (~20,000 K) plasma directly into electric power. However, several remaining economic issues call MTF's promise as a commercial energy source into question.

A primary source cited in support of MTF's energy potential is a 1993 paper by Grant Logan of Livermore National Laboratory who assumed that the pulse of fusion energy would be used to vaporize a blanket of working material to a temperature suitable for efficient MHD conversion.[38] Lithium hydride is the suggested blanket material for fusion explosions in the 1–10 GJ energy range. A small fraction of the lithium would be converted by neutron absorption to tritium for recovery and use in subsequent DT targets. The remaining lithium would be recycled. The electric power to drive the implosions would come from a reusable capacitor bank facility instead of high-explosive drivers.

Assuming a net energy yield per pulse of 1–10 GJ, a conversion efficiency of 50 percent, an electricity cost at the "bus bar" equal to $0.10/kWh (approximately twice the cost of electricity from a "successful" fission power plant today and perhaps what large-scale fission power might cost in a long term future when low-cost uranium resources have been depleted) the total allowed cost-per-shot works out to $14–140.[39] For a reactor that generated 1–10 GJ pulses, Logan estimates that the "target" costs would have to total about $0.5–5.0 per target in order for the reactor to be economic.[40] It is difficult to believe that the target costs could be made this low.[41] They include remanufacture of a DT-filled plasma chamber and surrounding metal liner as well as recasting several tens of kilograms of recycled lithium hydride into a new blanket.

Energy Gain

A liner kinetic energy of about 65 MJ is believed to be necessary for MTF to work.[42] For a capacitor bank to liner kinetic energy conversion efficiency of ~25 percent,[43] a 260 MJ capacitor bank would be required (existing capacitor banks deliver tens of MJ). Multiplying by a liner-kinetic-energy to plasma-energy conversion efficiency of 40 percent[44] gives an overall efficiency for converting capacitor-bank energy to plasma energy of 10 percent. Fusion yields of 1–10 GJ would therefore correspond to an overall energy gain between 4 and 40.

This gain is consistent with the upper limit that can be obtained assuming that the plasma must be uniformly heated to a temperature of 10 keV (a kinetic energy of 15 keV for each nucleus and electron in the plasma) and that all the reacting DT fuel is converted to $He^4 + n$ with the full 18 MeV recovered for every fusion. In this case, the maximum overall energy gain is given by:

$$\begin{aligned} G &= \frac{\text{Fusion energy}}{\text{Plasma energy}} \times \text{Efficiency} \\ &= \frac{18\ \text{MeV/fusion}}{(0.015\ \text{MeV/particle})\ (4\ \text{particles/fusion})} \times (0.1) \\ &= 30 \end{aligned}$$

This calculation would not apply if, instead of external energy being required to heat the entire plasma directly, fusion were achieved by creating a localized "spark" capable of heating the surrounding plasma to fusion conditions. In this case, higher yields and hence higher gains would be possible, improving the energy economics, but also increasing concerns about potential weapons applications.

APPENDIX D: WIRE-ARRAY Z-PINCH FUSION

Physicists have attempted for decades to use z-pinches to ignite fusion. A linear z-pinch involves passing a large current through a narrow plasma column. The plasma is heated by the current and confined by the associated magnetic field, which exerts a radial force inward on the plasma ions and electrons. In principle, a plasma could be maintained this way at high density and temperature long enough produce a fusion reaction, but this magnetic confinement approach has invariably been frustrated by instabilities that disrupt the pinch and as a result, has been largely abandoned.

An extension of this idea is to use a "fast" z-pinch to produce x-rays that could heat a hohlraum containing a DD- or DT-filled target, or could directly compress a fiber containing DD or DT. Z-pinch x-rays have been generated by sending a large (~10 MA) current pulse down a cylindrical array of fine wires. The wires vaporize and implode on axis, forming an optically thick plasma that traps radiation produced during thermalization and stagnation.[45] Plasmas emitting ~2 MJ of x-ray energy at a rate of about 200 terawatts (TW) have been created in experiments at the PBFA-Z pulsed power facility at Sandia National Laboratory.[46]

While a hohlraum-radiation temperature of ~250 eV is believed to be necessary to drive a hohlraum containing a fusion target to fusion conditions, the radiation temperatures that have been achieved (~140 eV) are believed to be adequate to begin diagnostic experiments with DD. Computational models predict DD yields of 10^{12} neutrons using an exploding pusher target, the first type of target planned to be tested on PBFA-Z later this year.[47] It is expected that roughly a hundred times more neutrons would be produced if DT were used.

Very high x-ray power can be achieved only if current is delivered to the load at high power (hence the name, "fast" z-pinch). In the experiment that produced 200 TW of x-ray power, an 11.7 MJ capacitor bank delivered 3 MJ to the load at a rate of 50 TW,[48] amounting to a four-fold power increase at an electrical-to-x-ray-energy conversion efficiency of more than 15 percent.[49] The current rise time was about one hundred nanoseconds. In contrast, today's most advanced flux-compression generators deliver hundreds of MJ to the load in about a hundred microseconds (~1 TW), and therefore appear to be too slow to drive a fast z-pinch.

NOTES AND REFERENCES

1. Fission reactors can go fast supercritical for brief periods. Pulsed-power fission reactors are designed to do so. The duration of the pulses is limited by negative feedback due to heating of the fuel. Safety experiments have also been conducted in which a liquid-moderated thermal-neutron reactor has been driven supercritical by the fast withdrawal of control rods and shuts itself down by heating or ejecting its moderator. None of these types of experiments appears to be close enough to a nuclear-weapons explosion to trouble those concerned about potential erosion of the CTBT.

2. If significant quantities of tritium were essential for such weapons, then the control effort might shift to tritium which, like plutonium, is made in reactors. For a discussion of other reasons for a tritium-control regime and some of the technical issues, see Kalinowski, M., "International Control of Tritium to Prevent Horizontal Proliferation and to Foster Nuclear Disarmament," *Science and Global Security,* Vol. 5:2, (August, 1995), pp. 131–203.

3. The United States submitted the following statement: "Certain questions have been raised by the delegation of Switzerland related to the development of a potential source of energy, and its relation to the NPT. As we understand it, the question is related to research which has been reported, involving nuclear reactions initiated in millimeter-sized pellets of fissionable and/or fusionable material by lasers or by energetic beams of particles, in which energy releases, while extremely rapid, are designed to be, and will be non-destructively contained within a suitable vessel. On the basis of our present understanding of this type of energy source, which is still at an early stage of research, we have concluded that it does not constitute a nuclear explosive device within the meaning of the NPT or undertakings in IAEA safeguards agreements against diversion to any nuclear explosive device." Quoted in, *The National Ignition Facility (NIF) and the Issue of Nonproliferation: Final Study,* (United States Department of Energy, Office of Arms Control and Nonproliferation, December 19, 1995), p. 35.

4. Germany made the statement: "It is the understanding of the German Government that nothing in this Treaty shall ever be interpreted or applied in such a way as to prejudice or prevent research into and development of controlled thermonuclear fusion and its economic use" [*UN Official Records,* XXVL4: 1996 Comprehensive Nuclear-Test-Ban Treaty, p. 911.]

5. "Comprehensive Nuclear Test Ban Treaty," Senate Treaty Doc. 105–28, (U.S. Government Printing Office, Washington, 1997), p. 4.

6. Younger, S. *et al.*, "Lab-to-Lab: Scientific Collaborations Between Los Alamos and Arzamas-16 Using Explosive-Driven Flux Compression Generators," *Los Alamos Science: Russian-American Collaborations to Reduce the Nuclear Danger,* (Los Alamos National Laboratory, 1996), pp. 49–71.

7. Energy and neutrons are produced via the fusion reaction, $D + T \rightarrow He^4$ + neutron + 17.6 MeV.

8. See e.g., Nash, T.J. *et al.*, "Dynamic Hohlraum Experiments on SATURN," *Dense Z-Pinches: Fourth International Conference,* N.R. Pereira, *et al.*, eds., (American Institute of Physics, 1997), pp. 175–182.

9. Sakharov, A., *Memoirs* (New York: Alfred A. Knopf, 1990), pp. 149–155; "Magnetic Cumulation" by A.I. Pavlovski in *Sakharov Remembered,* Sidney Drell and Sergei Kapitsa, eds., (New York: American Institute of Physics, 1991), pp. 185–202.

10. Anisimov, A.N. *et al.*, "About the Status and Future of Gas-Dynamic ICF," *Third Zababakhin Scientific Readings* (English abstracts of talks given at the Research Institute of Technical Physics, Chelyabinsk-70, January 14–17, 1992), p. 24.

11. $(10^{14})(18\text{ MeV})(1.6\times10^{-13}\text{ J/MeV})/(4.6\times10^{3}\text{ J/gTNT}) = 0.06\text{ g TNT}$.

12. $(10^{14})(14\text{ Mev})(1.6\times10^{-13}\text{J/MeV})/[4\pi(1\text{m}^2)(90\text{ kg/m}^2)] = 0.2\text{ Gy}$. (The neutron mean-free path in water is 90 kg/m^2.)

13. Broad, W.J., "Fusion research prompts fears of future bombs," *New York Times*, (May 27, 1997), and Colin Macilwain, "Research 'could still result in nuclear arms,' warn experts," *Nature*, Vol. 387, (May 29, 1997).

14. "Magnetized Target Fusion Experiments at LANL", http://wsx.lanl.gov/mtf.html, (January 8, 1988).

15. In the 1970s, Los Alamos proposed the development of power plants (Project Pacer) in which an average of one 50-kiloton thermonuclear explosive would be set off per day in an underground cavity to generate steam at an average rate approximately equal to that from a standard 1000-Megawatt power reactor $[50\text{ kt/day})(4.2\times10^{12}\text{J/kt})/(8.6\times10^{4}\text{sec/day}) = 2\times10^{9}\text{ W}]$. An analysis for the Arms Control and Disarmament Agency found that, even with the economies of scale inherent in the use of such powerful explosives, the project would still not be economic [F.A. Long, L.E. Elkins, R.L. Garwin, T. Greenwood, C. Hocott, H. Jacoby, G.W. Johnson and R. Morse, *An Analysis of the Economic Feasibility, Technical Significance, and Time Scale for Application of Peaceful Nuclear Explosions in the U.S., with Special Reference to the GURC Report Thereon* (April, 1975)].

16. Quoted in, W.J. Broad, "Fusion research prompts fears of future bombs."

17. Garwin, R.L., "Monitoring and Verification of a CTBT," Talking paper for a meeting between members of the Committee on International Security and Arms Control of the National Academy of Sciences and Chinese counterparts, Beijing, (February 7–8, 1996).

18. Kidder, R., private communication, (February, 1998).

19. For example: the Jason group reviews of the need for hydronuclear testing (*Nuclear Testing*, JSR-95-320, Mitre Corp, August 3, 1995) and arrangements for subcritical testing (*Sub-critical Experiments*, JSR-97-300, March, 1997); and the external review process of the DoE study, *The National Ignition Facility and the Issue of Nonproliferation*, (December 19, 1995).

20. See e.g., J.D. Lindl *et al.*, "Progress Toward Ignition and Burn Propagation in Inertial Confinement Fusion," *Physics Today*, (September, 1992), and T.H. Johnson, "Inertial Confinement Fusion: Review and Perspective," *Proceedings of the IEEE*, Vol. 72, no. 5, (May, 1984).

21. Lindemuth, I.R., "The Role of Z-pinches and Related Configurations in Magnetized Target Fusion," Los Alamos National Laboratory, LA-UR-97-2723, pp. 2–3.

22. Buyko, A.M. *et al.*, "Possibility of low-dense magnetized DT plasma ignition threshold achievement in a MAGO system," *Laser and Particle Beams*, Vol. 15, no. 1, pp. 127–132, (1997). "MAGO" is short for the Russian, *magnitnoye obzhatiye,* or "magnetic compression."

23. Lindemuth, I.R. *et al.*, "Target Plasma Formation for Magnetic Compression/ Magnetized Target Fusion," Physical Review Letters, Vol. 75, no. 10, (September, 1995).

24. Younger, S. *et al.*, p. 63.

25. Lindemuth, I.R., "The Role of Z-pinches and Related Configurations in Magnetized Target Fusion," pp. 4–5.

26. Lindemuth, I.R. *et al.*, "MAGO/MTF: A Marriage of Inertial and Magnetic Confinement," Los Alamos National Laboratory, LA-UR-96-3939, (November 4, 1996), p. 6.

27. Vorthman, J.E. *et al.*, "Battery-Powered Flux Compression Generator System," *Megagauss Fields and Pulsed Power Systems*, V.M. Titov and G.A. Shvetsov, eds., (New York: Nova Science Publishing, 1990). This device weighed 50 kg and contained 2 kg of high explosive.

28. Younger, S. *et al.*, p. 63.

29. *Ibid.*, pp. 56–57, 64.

30. (18Mev/fusion) $\times$ (1.6×10^{-13}J/MeV) $\times$ (6×10^{23} nucleii/mole)/[(2 nucleii/fusion) (2.5 g/mole)] = 3×10^{11}J/g.

31. Schoenberg, K.F. *et al.*, "Magnetized Target Fusion: A Low-Cost Development Path to Fusion Energy," Field Work Proposal for DOE Programs, (prepared May 9, 1997), p. 27.

32. The fusion reaction is $D + T \rightarrow n + He^4$ and the He^4 has approximately 4 times the mass of the neutron.

33. We have assumed a 4.5 Gy dose to be lethal, meaning that it would kill roughly half the population within 60 days ($LD_{50/60}$). A weapon that delivered a 4.5 Gy dose to a large number of people might be of interest to a terrorist, but this dose is too low to be useful on a battlefield: over 50 Gy are required to kill a person within hours or days (Samuel Glasstone and Philip J. Dolan, eds., *The Effects of Nuclear Weapons, 3rd edition* (U.S. Departments of Defense and Energy, 1977), p. 585.

34. The neutron doses were calculated using MCNP, "A General Monte Carlo Code for Neutron and Photon Transport," Version 4A, Los Alamos National Laboratory, (1994). For the calculation for unobstructed space, the ground was modeled as a layer of concrete 10 centimeters thick. The case including concrete buildings was modeled by placing a source of 14 MeV neutrons 2 meters above the concrete "ground" and 3 meters from a series of concrete walls, perpendicular to the ground and 7 centimeters thick, 6 meters apart. For computational convenience, the "walls" were actually half-disks of radius 10 meters. The dose was then calculated between the walls at a range of distances from the source.

35. Larger radius based on casualties from V-2 attacks (0.9 ton high-explosives per warhead) in London during World War II (average lethal radius, 21 meters). Lower radius based on casualties from the January 1991 Scud attacks on Tel Aviv, where modern apartment buildings are built with reinforced concrete columns, beams and floors. [Steve Fetter, George N. Lewis and Lisbeth Gronlund, "Why were Scud casualties so low?" *Nature,* Vol. 361, (January 28, 1993), p. 293.]

36. *Proliferation of Weapons of Mass Destruction,* (U.S. Congress, Office of Technology Assessment, 1993) p. 53.

37. Siemon, R., Los Alamos National Laboratory, "Magnetized Target Fusion," http://aries.ucsd.edu/SCICOM/AC-PANEL/REC-DOCS/W-PAPERS/mag-target.html (June 3, 1996).

38. Logan, B.G., "Inertial fusion reactors using Compact Fusion Advanced Rankine (CFARII) MHD conversion," *Fusion Engineering and Design*, Vol. 22, (1993), pp. 151–192.

39. $(10^9–10^{10}\text{ J})\times(0.5)\times\$0.1/\text{kWh})/(3.6\times10^6\text{ J/kWh}) = \$14–140$.

40. Logan, B.G., p. 169.

41. MTF enthusiasts are not unaware of this issue and refer to it as the "kopeck" problem: "Fairly large pulses of energy, when converted to electricity and sold at 5 cents per kWh, generate a small amount of revenue. The revenue could appropriately be measured in kopecks, and it takes a lot of kopecks to make a dollar..." K.F. Schoenberg *et al.*, p. 27.

42. Younger, S. *et al.*, p. 64.

43. Such efficiencies have been achieved with capacitor banks driving small liners. Efficiencies at least this good should be possible with larger liners. See J. Parker, A Primer on Liner Implosions with Particular Application to the Pegasus II Capacitor Bank," Los Alamos National Laboratory ATHENA Technical Report no. 1, (November, 1993), Ch. 9., and I.R. Lindemuth *et al.*, "MAGO/MTF: A Marriage of Inertial and Magnetic Confinement," p. 9, Table 1 (Note: the energy of the Atlas capacitor bank will be 36 MJ).

44. This efficiency was obtained using projected plasma energies and liner kinetic energies in K.F. Schoenberg *et al.*, Table 1, p. 7.

45. Deeney, C. *et al.*, "Power enhancement by increasing the initial array radius and wire number of tungsten Z pinches," Physical Review E, Vol. 56, no. 5, (1997).

46. Spielman, R.B. *et al.*, "PBFA Z: A 60-TW/MJ Z-Pinch Driver," *Dense Z-Pinches: Fourth International Conference*, N.R. Pereira *et al.*, eds., American Institute of Physics, (1997), pp. 101–118. "PBFA Z" has been recently renamed the "Z accelerator."

47. These computations were carried out by George Allshouse of Sandia. (J. Quintenz, Sandia National Laboratory, private communication, January 30, 1998).

48. Spielman, R.B. *et al.*

49. Quintenz, J., private communication, (February 27, 1998).