The Question of Pure-Fusion Explosions under the CTBT

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In September 1997, 34 years after President Kennedy and Premier Khruschev failed to include a ban on underground nuclear testing in the 1963 Limited Test Ban Treaty, President Clinton submitted the Comprehensive Test Ban Treaty to the US Senate for ratification. Intended to prevent future nuclear arms races, the CTBT would also reinforce the taboo created by 53 years of nonuse of nuclear weapons in war. (See the article in PHYSICS TODAY, March, page 24.)

One year later, no ratification hearings have been held, due to opposition led by Jesse Helms, chairman of the Senate Committee on Foreign Relations, which is responsible for conducting the hearings. Helms and other members of the Republican Senate leadership argue that the US cannot maintain its nuclear stockpile without testing.

The US nuclear weapons labs, by contrast, have accepted the CTBT in exchange for the $4.5 billion-a-year Science-Based Stockpile Stewardship and Management Program. But the lavishness of the program has also raised concerns both abroad and among some US arms control groups that the US may continue to develop new types of nuclear weapons through "virtual testing," using advanced computers and data provided by experimental facilities such as the billion-dollar laser-fusion National Ignition Facility (NIF), now under construction at Lawrence Livermore National Laboratory. Of particular concern is that the stockpile stewardship program could open up a route to pure-fusion weapons, in which thermonuclear explosions would be ignited by means other than fission explosions. Such designs would make it possible to bypass the techniques used today to verify nuclear nonproliferation (and, in the future, reductions)—namely, international controls on highly enriched uranium, plutonium and other artificial fissile materials.

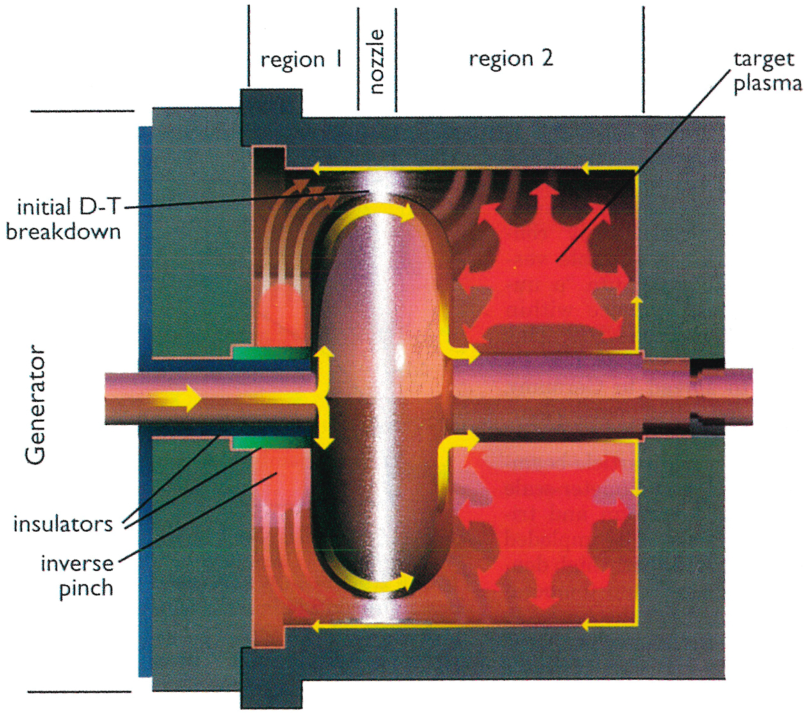

FIGURE 1. CROSS SECTION of the plasma formation chamber for the Los Alamos/Arzamas-16 magnetized target fusion experiment. A current pulse of about 2 MA generates a magnetic field throughout the chamber, which is filled with deuterium–tritium gas. A stronger pulse (6–8 MA) is then sent, causing electrical breakdown of the gas in region 1 and the nozzle. This plasma is propelled by the Lorentz force into region 2, colliding with the gas there and creating ionizing shockwaves that convert it to a "warm" plasma. The objective is to achieve fusion by imploding the plasma using a liner surrounding region 2. (Courtesy of Los Alamos National Laboratory.)

Hans Bethe, the head of the Los Alamos theory division during World War II, has expressed skepticism that the stockpile stewardship program might lead to pure-fusion weapons. Nevertheless, in April 1997, he wrote a letter to President Clinton 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."

'Similar experiments'

Although it remains to be seen whether pure-fusion explosives will surface as a major issue in the Senate's ratification process, a first round of debate on

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them has already occurred, during the White House's development of a 108-page "Article-by-Article Analysis" of the CTBT, which was sent to the Senate with the treaty. In this analysis, the Administration put forward its official view that "inertial confinement fusion (ICF) and similar experiments" are not banned by the treaty. But the analysis did not define "similar experiments," because of a stalemate over how far to expand the exemption for pure-fusion explosions beyond the one that now exists for ICF.

The exemption for ICF originated at the 1975 review conference on the Nuclear Non-Proliferation Treaty (NPT), at which the US declared that experiments "involving nuclear reactions initiated in millimeter-sized pellets of fissionable and/or fusionable material by lasers or by energetic beams of particles, in which the energy releases, while extremely rapid, are . . . non-destructively contained within a suitable vessel" do not constitute "a nuclear explosive device within the meaning of the NPT." This interpretation allowed ICF research to spread to Germany, Japan and other nonnuclear-weapon states.

In laser- and particle-beam-driven ICF, a millimeter-scale capsule of deuterium and tritium (D–T) would be imploded to create a sufficiently high density (~10^{25} cm^{-3}) and temperature (~10 keV) at the center to ignite the thermonuclear reaction $D + T \rightarrow He^4 + n + 17.6$ MeV. The fusion "burn" would then propagate through the surrounding fuel in the less than 10^{-10} seconds that the pellet remained compressed. An objective of NIF is that energy releases equivalent to the explosion of up to tens of kilograms of TNT will be achieved in this way. (See, for example, PHYSICS TODAY, September 1992, page 32.)

During the Clinton Administration's internal debate over the limits imposed by the CTBT, the three US nuclear weapons labs—Lawrence Livermore, Los Alamos and Sandia—argued that if small pure-fusion explosions driven by laser and particle-beam implosions are allowed, so should be explosions driven by other devices that might prove simpler and less costly. On the other side of the debate, arms controllers expressed concern that, unlike traditional ICF, some of the other approaches might have the potential to be developed into transportable weapons.

Magnetized target fusion

The attention of two of us (Jones and von Hippel) was attracted to this topic[1] by a 1996 special issue of *Los Alamos Science* that featured an article on magnetized target fusion (MTF) experiments being conducted jointly by Los Alamos National Laboratory and its Russian counterpart, the All-Russian Scientific-Research Institute of Experimental Physics, formerly known as Arzamas-16.[2]

MTF involves the creation of a "warm" (100–300 eV) magnetized D–T plasma with a volume on the order of a liter, which is then imploded to an intermediate density (10^{20} cm^{-3}) on a timescale of several microseconds by a metal liner driven inward by a magnetic field (see figure 1). The sizes, timescales and densities involved in MTF are intermediate between those of ICF and traditional magnetic confinement fusion.

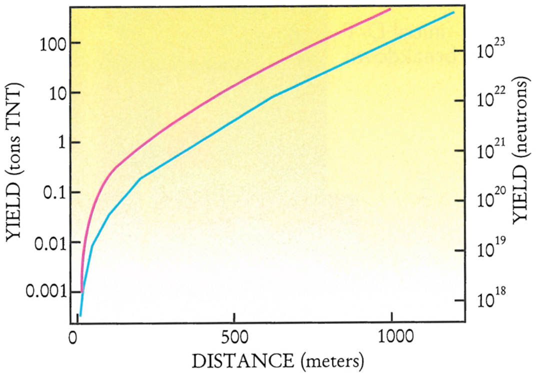

FIGURE 2. A FUSION EXPLOSION detonated in the open air would administer a lethal radiation dose (4.5 grays or more) to a person located within the distance depicted by the blue line. The red line shows the distance when the shielding effects of a city's concrete buildings are taken into account. (Adapted from ref. 1.)

A full liner-on-plasma MTF experiment has yet to take place, but the warm D–T plasma has been created and the first implosion experiments could begin in the year 2000. The hope is that MTF will eventually achieve fusion of about 3–30 mg of D–T fuel for an energy release in the range of 1–10 GJ, equivalent to the detonation of 0.2 to 2 metric tons of TNT—roughly one hundred times the fusion energy release expected from NIF.

In the US–Russian experiments, the large currents required for creating the magnetized plasma were produced by high-explosive-driven magnetic-flux-compression generators pioneered at Arzamas-16 by Andrei Sakharov.[3] Conceptual designs have been developed for systems in which the liner implosion would also be powered by such generators. This approach would do away with the massive intermediary apparatus of lasers or particle accelerators used in ICF, resulting in a system that could be transported. The total weight of the magnetized fusion apparatus, including the explosive current generators, would be only 3 tons.

Measured in terms of explosive yield, such a device would have no advantage as a weapon over a conventional explosive of the same weight. However, the release of 1–10 GJ (0.25–2.5 tons of TNT equivalent) from D–T fusion would also produce $3.5 \times (10^{20}-10^{21})$ fast neutrons. This many neutrons would deliver a lethal radiation dose (450 rads or 4.5 Sieverts) over an area with a radius of 200–500 m (see figure 2)—comparable to the lethal area of a missile warhead carrying nerve gas.

The US, with its huge arsenal of compact, powerful nuclear explosives, would not be interested in a low-yield pure-fusion weapon—except in special applications, where the device's "clean" nature (that is, the absence of radioactive fission products) and low yield would be seen as important features. Similarly, terrorists or countries seeking their first weapons of mass destruction would find it easier to produce nerve gas than to produce such a device.

Other approaches

This situation could be different, however, if one could achieve higher fusion yields with less input energy. For that to happen, a fusion device would have to be designed so that, as with ICF, the external energy source would drive only a small fraction of the fuel mass to ignition, which would then cause a much larger mass of fuel to burn.

One alternative to laser-driven ICF being pursued at Sandia National Laboratories is the so-called z-pinch, in which a dense, high-temperature plasma is created to provide an intense source of x rays (see PHYSICS TODAY, June 1998, page 56).[4] The plasma is formed by a rapid discharge of current from a massive capacitor bank through a cylindrical array of fine, parallel wires. The plasma is then imploded on axis by the pressure of the external magnetic field created by the current. The objective is to drive the implosion of a D–T pellet by means of two such x-ray sources coaxially and symmetrically located at opposite ends of the pellet within a common x-ray-containing enclosure.

Plasmas emitting about 2 MJ of x-ray energy in 10 ns—comparable to the pulses that NIF's lasers are designed to deliver—have already been created in experiments at Sandia's Z pulsed-power facility (previously known as PBFA-Z).[5] But it appears that a z-pinch could only be used for a portable pure-fusion weapon if the microsecond pulses produced by explosive flux-compression generators could be shortened by more than an order of magnitude while preserving adequate efficiency. That would be a formidable task, in view of the limited detonation velocity of chemical explosives and the limited conductivity of metals used in flux-compression generators.

The Russian weapons labs have also attempted to generate pure-fusion explosions with implosions driven directly by chemical explosives. These efforts became known in early 1992, when one of Russia's weapons labs hosted an international conference at which several papers were presented on the systematic efforts made in the Soviet Union since the early 1950s to ignite fusion through chemical implosions of D–T gas. In theory, it should be possible to create a shock pressure high enough to achieve ignition through the cumulation of multiple shockwaves in a spherical system consisting of alternating layers of dense and light materials. In practice, however, deviations from perfect symmetry and mixing between the D–T fuel and the liner compressing it were reported to have limited the temperatures achieved to an order of magnitude below the ignition threshold and neutron yields to less than 10^{14} neutrons.[6]

Clarifying US policy

We see no immediate danger of a militarily attractive new type of weapon being developed from the current unclassified research programs on pure-fusion explosions. However, it seems imprudent to leave the weapons labs with no guidance while they pursue a line of experimentation that conceivably could lead to pure-fusion weapons and that realistically appears to have no nonweapons use. ICF, MTF and z-pinch enthusiasts claim that their research might result in an economical source of power, but that seems extremely unlikely. There is no question that the cost of power from systems driven by conventional explosives would be completely prohibitive.

We therefore propose as an interim limit that pure-fusion systems driven either directly or indirectly by chemical explosives be restricted to the use of deuterium fuel only. In the absence of tritium, a deuterium plasma will produce neutrons sufficient for diagnostic purposes, but is extremely difficult to ignite. Since the use of tritium requires onerous arrangements to minimize the risk of radiation exposure, fusion researchers usually work with deuterium plasmas, postponing the use of tritium as long as possible. An interim tritium ban should therefore be both acceptable and enforceable.

A complementary limit suggested by Richard Garwin would limit experiments involving direct high-explosive-induced fusion to yields of 10^{14} neutrons, an energy release equivalent to exploding about 0.1 g of TNT. This neutron yield is also approximately the peak yield reported by Russian experimenters from direct high-explosive implosion of D–T and by the Los Alamos/Arzamas-16 group from magnetized target fusion during the D–T plasma formation stage.

The process of setting longer-term limits on this type of research should be as open as possible, and informed as necessary by independent experts who can assess potential classified applications. Likewise, the international forum for considering additional permissible experiments involving fusion explosions should also be an open one.

A clear line needs to be drawn between permitted and forbidden experiments with pure-fusion explosions. The Comprehensive Test Ban Treaty is silent on the matter, and the US government has found it too difficult to anticipate future technological developments to make its own definitive interpretation. We feel that some interim guidance is required to ensure that timely action is taken should technological developments begin to head in a potentially dangerous direction.

References

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