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Dangerous Thermonuclear Quest:

The Potential of Explosive Fusion Research for the Development of Pure Fusion Weapons

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Preface

Since the Indian and Pakistani nuclear tests of May 1998, there is renewed recognition in the world that nuclear dangers remain very high. Over the course of the 1990s, the hope that the end of Cold War antagonisms would enable complete nuclear disarmament have given way to a new set of nuclear dangers.

The high points for disarmament came early in the decade. In 1991, in the aftermath of the attempted coup in the Soviet Union, President Bush ordered most tactical nuclear weapons withdrawn from the US arsenal. It was the largest unilateral nuclear disarmament action in history. President Gorbachev reciprocated. In 1991 and 1992, the United States and the Soviet Union/Russia signed two strategic arms reductions treaties, START I and START II. The erosion of the momentum toward disarmament was already perceptible by 1993. Russia's conventional military weakness caused it to reverse the Soviet no-first-use nuclear policy that had been in effect since 1978. In 1994-95, the five nuclear weapons states parties to the Nuclear Non-Proliferation Treaty (NPT), led by a very determined United States, persuaded the majority of the world's countries to agree to an indefinite extension of the NPT. At the same time, the nuclear weapons states failed to make any explicit commitment to nuclear disarmament, other than a test ban treaty. The test ban treaty itself has been vitiated by "stockpile stewardship" programs which seek to preserve nuclear weapons stockpiles for the indefinite future.

The central problem is that nuclear weapons states have repeatedly shown by their actions, and all too often in explicit statements, that they have no intention of pursuing total nuclear disarmament as required under Article VI of the NPT. The United States and Russia still have huge arsenals on hair-trigger alert at a time when command and control systems in Russia are deteriorating. Commercial stocks of weapons-usable materials are rising even though plutonium has been shown to be an uneconomical fuel. Plans to put surplus plutonium into non-weapons-usable form are being used to resurrect dreams of a plutonium economy. Dangers of black markets in fissile materials have increased because of the economic distress in Russia, which is deepening as the Asian economic crisis spreads and affects other parts of the world. Even China, the only nuclear weapons state to repeatedly call for complete nuclear disarmament, is modernizing its nuclear arsenal.

The failure of the arms control and arms reduction process to create a direction for complete nuclear disarmament was underlined in May 1998, when India and Pakistan conducted nuclear tests and declared themselves to be nuclear weapons states. The five nuclear weapons states whose arsenals were temporarily legitimized by the NPT have been lecturing India and Pakistan to disarm. These lectures are unlikely to be effective in view of their failure to live up to their own treaty obligations under Article VI of the NPT. Furthermore, in many countries, US sanctions against Pakistan are being angrily contrasted with its support of Israel, the state which is estimated to have the largest nuclear arsenal of non-signatories to the NPT.

Adding to this political crisis, nuclear weapons states continue to develop new nuclear weapons designs under the rubric of "stewardship" of existing arsenals in spite of their treaty commitments to end the nuclear arms race and to pursue complete nuclear disarmament in good faith. In particular, the United States intends to retain huge teams of designers, and to give them research tools that will maintain a high level of challenging scientific projects related to nuclear weapons design. Following the United States and other nuclear weapons states, India announced its own plans for a "stockpile stewardship" program as part of its own plan for eventually renouncing nuclear testing.

The potential creation of nuclear weapons that do not use plutonium or highly-enriched uranium may be the most dangerous of all these developments. These weapons may take the form of pure fusion weapons -- that is, nuclear weapons that only have a thermonuclear component. Weapons that have a thermonuclear component that triggers a fission component made of relatively widely available uranium-238 may also be developed.

A large part of the military danger of pure fusion weapons would arise from the fact that they could be made in sizes from very small to very large and that they would not be accompanied by intense fall out. Further, by making it possible to reducing the blast damage area of the weapon, the potential for tactical use of such weapons could be expanded, perhaps with less fear of nuclear retaliation. These factors are likely to lower the threshold of nuclear weapons use. It is of course difficult to predict the results of pure fusion weapons development, other than to say that it would likely set off a new and costly arms race. But one thing is not in doubt. Such weapons should not be confused with conventional weapons. Even small pure fusion weapons would have a far greater lethal effect that corresponding conventional bombs because of the neutron radiation from fusion reactions. The neutron radiation from a one ton TNT equivalent explosion would have a lethal area roughly a hundred times larger than a conventional explosive with the same blast effect.

Pure fusion weapons will be very difficult to create. The scientific feasibility of fusion explosions has been demonstrated only in thermonuclear weapons, where the hot dense gases (called plasmas) are heated and compressed to high enough temperatures and pressures by a fission explosion. This scheme of confining plasmas by the inertia provided by the kinetic energy of the particles is called "inertial confinement fusion" or ICF. If ICF or other similar schemes could achieve fusion explosions without fission triggers, pure fusion weapons may become possible.

Only recently have devices been developed that could individually or jointly contribute to demonstrating the feasibility of pure fusion weapons. These include, the Magnetized Target Fusion (MTF) program (a joint US-Russian effort being undertaken at the Los Alamos National Laboratory in New Mexico), the National Ignition Facility (NIF), a huge laser fusion research device costing well over one billion dollars, being built at Lawrence Livermore National Laboratory in California, and the z-pinch facility at Sandia National Laboratory in New Mexico. Some of these devices rely on inertial confinement. Others rely on confinement by combining inertial and electromagnetic compression, which are two different potential ways of creating pure fusion explosions. The aim is to create a small thermonuclear explosion in a laboratory. It would, if their designers succeed, be the equivalent of hydronuclear fission experiments, which are laboratory fission explosions, of the same order of magnitude as some of the planned fusion experiments. We will designate all devices that could achieve pure fusion explosions by various confinement schemes by the term "explosive confinement fusion" (ECF).

A number of countries have ICF programs. France is building a device similar to the NIF called the Laser Mégajoule (LMJ) project. Equally noteworthy is that non-nuclear weapons states are also planning such devices, since they claim that they are for scientific research and for potential commercial energy applications. Much of the literature on pure fusion explosions is therefore automatically unclassified.

If pure fusion weapons are developed, the problems facing today's proliferation controls and safeguards regimes would be dwarfed by the new control issues. Currently, the acquisition of the necessary plutonium or highly enriched uranium is one of the main bars to proliferation of nuclear weapons. By contrast, fusion weapons would require only deuterium and tritium. Deuterium is a readily available material. While tritium production entails its own difficulties, tritium controls lag far behind those of fissile materials. Though there have been proposals for safeguarding of tritium, it is not currently under international safeguards. However, there is some level of national and international control on its sale.

This report covers the following topics:

- an overview of the nature of pure fusion weapons
- the state of research into ECF today
- the technical prospects for pure fusion weapons
- the relation of pure fusion and other non-fission-triggered nuclear weapons to the US Stockpile Stewardship program
- the proliferation risks that these weapons present and their consequences for nuclear disarmament.

There are several potential approaches to fusion weapons not presented here that are possible in theory but are at present quite speculative. For instance, we have not discussed pure fusion weapons based on lithium-6 deuteride as the only fuel. For such advanced approaches to work, the immense obstacles facing pure fusion weapons using deuterium and tritium as fuels (D-T fuel) must first be largely or wholly solved.

The development of pure fusion weapons could represent as great a departure from present-day military postures as the hydrogen bomb did from fission weapons. Yet, despite the huge stakes, there has been little public debate on the question. The topic is still largely confined to arms control and academic circles. One aim of our report is to broaden the debate so that it might correspond more closely to the importance of the subject. In this report, we will use the Comprehensive Test Ban Treaty, which has been signed by about 150 countries, including the United States, as the criterion for assessing the legality of actions related to nuclear explosions.

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Summary and Recommendations

A great qualitative change in the nature of nuclear weapons occurred four-and-a-half decades ago when nuclear fission and nuclear fusion were combined into thermonuclear weapons, popularly called "hydrogen bombs." Even so present-day generation nuclear weapons produce considerable levels of fallout in the form of highly radioactive fission and this has been one of the main factors limiting their military application.

Pure fusion weapons -- that is, weapons that would not need a fission trigger -- have long been thought of as desirable by the nuclear weapons establishment because they would not produce fission product fallout. Yet, the lethality of the weapons due to neutron radiation as well as explosive force would still be great. Moreover, thermonuclear reactions do not require a minimum critical mass to be assembled. Hence pure fusion weapons could range in size from a few kilograms to multi-megatons of TNT equivalent.

Pure fusion weapons have been unattainable so far because it is very difficult to create the conditions that enable a large enough number of nuclear fusion reactions to occur in a small enough space and short enough time. Fusion reactions involve the fusion of light nuclei, which results in a release of nuclear energy. (Fission, on the other hand, releases energy through the splitting of heavy nuclei.) Positively-charged nuclei exert repulsive (opposing) electrical forces on each other, which are very strong at close range. These forces must be overcome if the nuclei are to be brought close enough together so that the probability of fusion reactions may be high. This is done by heating the fuel to extremely high thermal temperatures (hence the term "*thermo*nuclear") -- comparable to or higher than temperatures in the interior of the sun. This allows the kinetic energy of the nuclei to be large enough to overcome the repulsive force. The even greater attractive force between nuclear particles, which operates to a significant degree only at very close range, is then able to overcome the repulsive electrical force and produce nuclear fusion.

Keeping together a dense enough mass of nuclear material for long enough to produce a large number of nuclear reactions, but short enough to produce an explosion, has proved possible by only one means. That has been to create the extremely high temperatures and pressures by a fission explosion. The barriers for producing pure fusion weapons -- that is, weapons that would not require this "primary" fission explosion (called the trigger of the thermonuclear warhead) -- have so far proved insuperable. However, work in the last decade or so has resulted in a great deal of technical progress, to the point that it is possible to conceive of pure fusion explosives that could be compact enough to be used as weapons. If such weapons were to be developed, it would represent a fundamental transformation in the potential employment of nuclear weapons as instruments of war and have a substantial adverse effect on non-proliferation and nuclear disarmament.

Summary of Findings

1. Pure fusion weapons can, in theory be made in varying sizes from small to huge. By reducing the sizes of possible nuclear explosions, pure fusion weapons could lower the threshold of nuclear weapons use. This would tend to erode the norm against use of these weapons of mass destruction that has been built up for over half a century.
2. The scientific feasibility of pure fusion weapons has not yet been established. Until recently, there were no devices that could establish such feasibility.
3. Major advances in the last decade in plasma physics and in various technologies to achieve fusion reactions at high rates in laboratory setting have opened up new possibilities for pure fusion weapons.
4. Three major technologies could contribute to the establishment of the scientific feasibility of pure fusion weapons, and other weapons that do not require fission triggers: (i) inertial confinement fusion programs designed to achieve ignition (such as the National Ignition Facility being built at Livermore), (ii) capacitor or high explosive driven electromagnetic devices such as the Magnetized Target Fusion program at Los Alamos and Arzamas-16, and (iii) other non-fission methods of generating intense x-rays, such as the wire-array z-pinch program at Sandia Lab. These programs reinforce each other in the development of fusion technology.
5. In some respects it will be less difficult to make pure fusion weapons than to generate commercial power from pure fusion, once thermonuclear ignition has been achieved in a laboratory setting.
6. One major roadblock to the development of pure fusion weapons is the achievement of ignition in the plasma. This requires sufficient compression and heating of the fuel pellet in a precise way. The second problem is to get large enough non-fission energy sources ("drivers") to perform the work of compression and heating of the fuel pellet to thermonuclear conditions within practical limits of size and weight.
7. Several technologies could help overcome the technical hurdles facing pure fusion weapons. They include development of advanced materials manufacturing technology, which could lead to reduced driver size and help make better ICF targets.
8. Once ignition has been demonstrated at a laboratory level, it will be difficult to contain the development of pure fusion weapons. Fusion weapon proliferation controls will be far more difficult than with fission weapons because the materials are not currently under the same level of international control and because more of the relevant literature is non-classified. In fact, pure fusion weapons would by-pass most

of the system of international non-proliferation safeguards. Political pressures to develop such weapons would also be likely to intensify.

9. The main mechanism to prevent a radically new and dangerous nuclear weapons situation from developing in the world is to ban the construction of machines that could achieve ignition of thermonuclear plasma without a fission trigger. Devices that use high explosives either directly or indirectly as part of the driver pose special dangers because they could be converted to practical weapons with less difficulty once feasibility is established. Other less restrictive mechanisms could include a ban on the use of tritium in devices involving the use of high explosives.

10. The NPT allows for a broad range of ICF research. But the CTBT is much more stringent. For instance, while the NPT allows peaceful nuclear explosions, but Article I of the CTBT bans nuclear explosions altogether. Unfortunately, it does no define them. However, there is no technical basis on which laboratory thermonuclear explosions can be excluded from this ban.

11. Our review of the CTBT indicates that experiments, and hence facilities, designed to achieve thermonuclear explosive ignition are illegal. This includes large laser facilities such as the NIF in the US and the Laser Mégajoule project in France, as well as the planned wire-array z-pinch facility called X-1. However, this question is still a matter of international debate and controversy because there is no official public negotiating record on this issue in the specific context of the CTBT negotiations that led up to Article I which bans all nuclear explosions.

12. There is as yet no official interpretation of the CTBT in regard to experimental fusion explosions and the facilities designed to achieve them. Hence, the US and other countries are proceeding as if their plans for facilities like NIF and LMJ are legal under the CTBT. An official opinion on this issue is urgently needed. In this context, it is important to note that our research shows that neither facility is essential to maintaining the safety of existing nuclear stockpiles or to their reliability for deterring nuclear attacks.

Recommendations

It is essential to prevent the development of pure fusion weapons. Such weapons would greatly complicate the already difficult task of achieving enduring non-proliferation and complete nuclear disarmament, as required by Article VI of the NPT. A set of policies that restrict explosive confinement research is needed to accomplish this goal:

1. Ignition of the fusion fuel should be used as the definition of a fusion nuclear explosion for purposes of CTBT compliance, by analogy with hydronuclear fission experiments. This would prohibit all explosive ignition experiments. Therefore construction of the National Ignition Facility at Livermore, California, the Laser

Mégajoule project in France and planning of all other explosive research facilities designed to achieve thermonuclear ignition should be stopped.

2. The combination of high explosive drivers and the use of tritium in fusion research should be banned.

3. The total fusion energy output in explosive fusion research should be limited to 10^{14} neutrons per shot. This would prevent attempts to gain useful information by increasing the energy of the driver and fusion energy output while staying below ignition. Explosive fusion research should be distinguished from other fusion research by defining explosions in this context as events occurring in less than one millisecond.

4. The next CTBT conference, which may be held as early as September 1999, should issue a formal opinion explicitly including laboratory thermonuclear explosions within the prohibition of nuclear explosions in Article I of the CTBT.

5. Magnetized Target Fusion experiments that would achieve ignition should be stopped.

6. ICF research and other research not designed to achieve ignition should be reevaluated for its potential to contribute to pure fusion weapons development and that of nuclear weapons that do not require a fission trigger. In the meantime it may be allowed to continue since it is not prohibited by any treaty.

7. Stockpile stewardship programs, under which ECF research is conducted, should reflect the spirit of the CTBT and exclude weapons design aspects.

8. The nuclear weapons states should declare formally that they are not going to design new nuclear weapons or upgrade old weapons. As part of this declaration, they should explicitly renounce the development of pure fusion weapons and all other weapons that do not require fission triggers.

9. A widespread public debate on the disarmament and non-proliferation consequences of pure fusion weapons is needed to forestall the emergence of serious new problems.

10. The CTBT should be ratified by all countries without conditions. In other words, ratification should not be conditional on projects such as NIF and LMJ.

Chapter 1: Varieties of Nuclear Weapons

A. Historical Background

The concept of the first nuclear weapons was based on the idea of splitting (or fissioning) nuclei of heavy materials that could sustain chain reactions. But even before the first fission bomb had been built or tested, Manhattan Project scientists were conceptualizing even more powerful bombs, based on *fusion* of light nuclei. These bombs would come to be popularly called hydrogen bombs, or more precisely, thermonuclear weapons. The term "hydrogen bomb" derives from the use of isotopes of hydrogen to make such weapons. The term "thermonuclear" derives from the fact that fusion nuclear reactions occur at extreme temperatures -- roughly as high as or higher than those in the interior of the sun. As will be discussed below, current thermonuclear weapons still need a fission component (called the primary). A pure fusion weapon would eliminate the fission component.

Pure fusion bombs are even more interesting than fission weapons to designers of nuclear weapons for several reasons:

1. They present more complex scientific and technical challenges.
2. They can, in theory, be made from commonly available non-radioactive materials, notably deuterium (which is a non-radioactive isotope of hydrogen and relatively easily extracted from seawater) and lithium.
3. Fusion reactions require no minimum critical mass. Therefore, in contrast to fission weapons, pure fusion weapons can, in principle, be made very small -- comparable in explosive power to common conventional weapons. At the same time, fusion explosions can be made very large (as large or larger than current thermonuclear weapons).
4. Weapons made with only a thermonuclear component would produce no fission products, eliminating by far the largest source of radioactivity in fallout from nuclear weapons explosions. This could make the weapons more politically feasible to use.

Attempts to design thermonuclear weapons showed early on that the enormous temperatures and pressures required could most easily be achieved by triggering the fusion reactions by means of a fission explosion. This trigger, or "primary" part of the weapon, would set off a thermonuclear explosion in the "secondary" part of the weapon. However, the use of fission triggers meant that two of the militarily most important advantages of thermonuclear weapons were lost. First, nuclear weapons would have a practical minimum size that was large, though that lower limit has tended to decline with time (see below). Second, the use of a fission component would mean a large amount of fallout.

Both the US and the Soviet Union succeeded in building thermonuclear weapons in the early to mid-1950s. They soon began to build up enormous arsenals of thermonuclear weapons. But the idea of pure fusion weapons persisted because of their advantages. In a 1960 article in *Foreign Affairs*, physicist Freeman Dyson noted that the flexibility in yield that could be achieved by pure fusion weapons was "theoretically a simple way to escape from the tyranny of critical mass." He further stated that pure fusion weapons "would provide, without gross inefficiency, an explosive power adapted to the needs of small-scale and local warfare." [1] Dyson's article was written in the context of the 1958-1961 U.S.-Soviet nuclear testing moratorium, which was largely the result of worldwide protests against the radioactive fallout from atmospheric testing of nuclear weapons. The above-ground tests had resulted in heavy fallout of fission products like cesium-137, iodine-131, and strontium-90.

But Edward Teller, the scientist who led the US hydrogen bomb effort, opposed the moratorium. Instead, he urged the development of "clean" bombs -- that is, nuclear weapons with a relatively low fission component, or even pure fusion weapons.[2]

Fallout also turned out to be a military liability. It contaminated large areas, the extent of which depended mainly on the height of the explosion, the explosive power of the fission component, and the weather. It created risks for the troops of the side using the weapons and made it more problematic to occupy the country in which the bombs were used. For instance, many United States armed forces personnel who occupied Hiroshima and Nagasaki in the immediate aftermath of World War II and who assisted in the atmospheric nuclear testing program complained of illnesses that they and others believed resulted from radiation exposure.[3]

Hence the development of "clean" bombs was much more than political expediency. It was the nuclear weapons establishment's response to people’s demands for an end to nuclear testing largely on account of fallout. "Clean bombs" were also potentially of considerable military value to the nuclear weapons powers in the context of

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[1] Dyson 1960.

[2] Findlay 1990, p. 7 and the accompanying footnote number 52 (printed on p. 14). Two types of "clean" bombs have been proposed. One type, pure fusion weapons, have never been made. The second type, "neutron bombs," contain a relatively small fission trigger and are designed mainly to generate neutron radiation to kill and maim while keeping blast and heat damage to property as low as possible. They were built in the 1980s and made a part of the US nuclear arsenal. (Critics have labeled neutron bombs "capitalist weapons” because they limit damage to property while maximizing damage to people.) It should be noted that the design objectives of neutron bombs and pure fusion explosions are partly different -- in the former immediate radiation damage is sought to be maximized relative to blast effects, which is not the case with pure fusion explosives. But both of them were, in part, motivated by the desire to avoid or at least minimize the controversies surrounding the fallout that necessarily accompanies a fission explosive – which can remain hazardous for long periods of time.

[3] Wasserman et al. 1982, Chapter 1.

their nuclear war planning because bombed areas that were almost free of long-lived radionuclides would be easier to occupy.

Early research indicated that pure fusion weapons would be very difficult to build. Many scientists believed that it would be impossible to achieve the conditions needed for thermonuclear reactions without a fission trigger. Much of the relevant research was subsequently declassified.

Research on a new fusion technology to aid nuclear weapons design began in 1960 with the invention of the laser.[4] The new research tool was laser fusion. In a manner similar to earlier research, laser fusion research has undergone extensive declassification. A part of the motivation for declassification has been the hope and claim that ICF research may be a useful approach to commercial power production using fusion.[5] However, some of the research remains classified in the United States (particularly research which enters energy density and temperatures regimes considered most relevant to thermonuclear weapons).

The immediate interest in laser fusion was not for pure fusion weapons but for studying thermonuclear reactions on a small scale in a laboratory environment. Unlike a warhead, the laser fusion apparatus would not be destroyed by the experiment. In laser fusion, a small total amount of energy would be deposited in a tiny pellet containing thermonuclear fuel. The transformation of light elements into electrically charged gases at high temperatures and pressures could be studied. If the temperatures and pressures could be made high enough, some fusion reactions could be initiated, without an explosion. Other approaches similar to laser fusion were also developed in which some non-fission source of energy (a "driver") would trigger nuclear fusion reactions. Such technologies go under the general rubric of "inertial confinement fusion," or ICF. The phrase "inertial confinement" refers to the fact that only the enormous forces of inertia generated by the implosion of a fuel pellet hold the fuel together long enough for fusion reactions to occur.[6]

While the importance of ICF technologies to the study of the physics of nuclear weapons and to their design was evident, the potential for containing such explosions also raised the possibility that they could be used to generate electrical energy. After all, as Edward Teller pointed out, a gasoline engine is powered by many small explosions

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[4] Lindl 1995, p. 13

[5] There was also a declassification of some fission research in the 1950s and after for the purpose of accelerating development of commercial nuclear fission reactors.

[6] There are other ways of confining electrically charged gases, notably in magnetic fields. See below.

contained in metal cylinders.[7] Similarly, it was thought that small, contained fusion explosions could also be used to generate energy. But the fusion explosions would be much larger than those gasoline engines (many kilograms of TNT equivalent).[8] The complications of extracting energy from such explosions in a near-total vacuum and the high energy neutrons generated by the fusion reactions would be far greater than those of an internal combustion engine.

This dual military and commercial potential of ICF is similar to the situation with fission power, in which the achievement of chain reactions in laboratory setting can be applied either to nuclear weapons or nuclear power production.[9] To understand the role of inertial confinement fusion, it is important to have a more detailed understanding of the conversion of mass to energy using fission and fusion reactions, as well as the basic workings of fission-triggered thermonuclear explosions.

B. Converting Matter into Energy

Einstein's discovery early in the twentieth century that energy and matter are equivalent opened up many theoretical possibilities for creating new weapons and new sources of energy.[10] The basic idea that intrigued physicists and writers of fiction alike was that very small amounts of matter were equivalent to huge amounts of energy. Hence it seemed possible to invent weapons that could wreak destruction on a scale had been considered to be the province of the gods. And in the age of the machine where everything from lights and laundry at home to gigantic factories were powered by electricity, made from huge amounts of coal or oil, the prospect that small amounts of matter could power whole towns was no less intriguing.

But first, ways had to be found to turn bits of matter into energy. Four routes seemed theoretically possible:

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[7] E. Teller, "A Future ICE (Thermonuclear, That Is!)," *IEEE Spectrum* 60 (January, 1973) as cited in Duderstadt and Moses 1982, p. 4. Teller and Stanislaw Ulam made the key discovery that allowed fusion explosions to be made compact enough to be made a part of deliverable nuclear warheads. See York 1976, pp. 78-79.

[8] One kilogram of TNT equivalent is equal to an energy release of about four-and-a-half million joules.

[9] A 1996 IEER report showed that the development of fission power was largely motivated by Cold War competition. At least in the US, the desire was to make propaganda to the effect that the US atom was peaceful in contrast to the militaristic Soviet atom. See Makhijani and Saleska 1996.

[10] This equivalence is expressed in the famous equation $E=mc^2$ where m stands for mass, c for the speed of light, and E for energy. One gram of matter (about one-thirtieth of an ounce) is equivalent to 90 trillion joules of energy – which is about equal to 700,000 gallons of gasoline.

1. The nuclei of atoms could be converted into energy in whole or in part by a matter-antimatter annihilation process.[11]
2. Heavy nuclei could be split into smaller fragments, thereby converting a small portion of the mass of the heavy nuclei into energy. Such nuclear reactions are called fission reactions.
3. Light nuclei could be fused together, thereby converting a small portion of the mass of nuclei into energy. Such nuclear reactions are called fusion reactions. These are the nuclear reactions that generate the energy in stars, including the sun.[12]
4. Combinations of the above three types of nuclear reactions could also be used.

Only one of these four approaches, fission, has been applied successfully in both military and commercial arenas. Fusion has found application only in nuclear weapons. Even in this one application, fusion reactions must be triggered by the use of a fission explosive. Hence, the possession of fissile materials, notably plutonium-239 and/or uranium-235, has been a prerequisite for making nuclear weapons of any kind. The need for a fission "trigger" to initiate fusion reactions that will yield a net energy output means that it has so far been impossible to apply fusion to commercial energy production.

C. Fission energy[13]

The nuclei of certain heavy atoms such as uranium or plutonium can be split with neutrons.[14] Fission reactions split the nucleus of the heavy atom into two smaller fragments, called fission products, while also liberating more neutrons. These fission products are of intermediate atomic weight. The combined mass of the liberated neutrons plus that of the fission products is slightly smaller than the original nucleus. The difference in mass between the initial and final products appears as energy.

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[11] Matter-anti-matter reactions do occur naturally and are researched for a variety of reasons. However, practical application of this research to weapons is highly speculative. A discussion of anti-matter based weapons is beyond the scope of this report.

[12] It should be noted that the Earth literally runs on fusion reactions. The sun's energy comes from fusion reactions, primarily the fusion of hydrogen (at this stage in the sun's evolution). However, unlike the rapid burn of fusion fuel in ICF, the sun's fusion is a slow burn, taking billions of years to exhaust its fuel. In general, stars generate energy from a variety of fusion reactions.

[13] For a discussion of the basics of nuclear physics see Makhijani and Saleska 1996. Appendix A of this report can also be found on IEER's website (www.ieer.org).

[14] Nuclear fission can also be induced by bombardment of the nucleus by electrically charged particles, such as protons. However, since the nucleus is positively charged and protons are also positively charged, and since positive charges repel each other, these types of fission reactions are more difficult to accomplish than reactions with neutrons. Fission can also be induced by bombarding the nucleus with energetic gamma rays (photons). This process is called photofission. Finally, some heavy nuclei also undergo "spontaneous fission" in which it is not necessary to add energy or particles.

If one neutron from each fission creates, on average, one more fission, then a self-sustaining chain reaction is achieved. Other things being equal, such a reaction will continue so long as there is sufficient material available for fission.[15] How much material is sufficient to sustain a chain reaction depends on the specific fissile material, the geometry in which the material is arranged, the medium in which the fissile material is immersed, and other factors. The minimum amount of fissile material needed to sustain a chain reaction is called a "critical mass."

There is only one radionuclide that occurs in nature in any significant quantity that can sustain a chain reaction. It is uranium-235, which constitutes about 0.7 percent of natural uranium; almost all the rest is another isotope, uranium-238, which can be fissioned when bombarded by fast neutrons, but which cannot sustain a chain reaction. But uranium-238 when bombarded with neutrons can also undergo another set of nuclear reactions that transmutes it into plutonium-239, which can sustain a chain reaction. All significant commercial and military applications of nuclear fission energy are based on the use of uranium-235 and/or plutonium-239.[16,17]

The nuclear reactions that constitute the fission of uranium-235 can be generically written as follows:

U-235 + n --> U-236

U-236 --> fission fragments + 2 to 4 neutrons + 200 MeV energy (approximately)[18]

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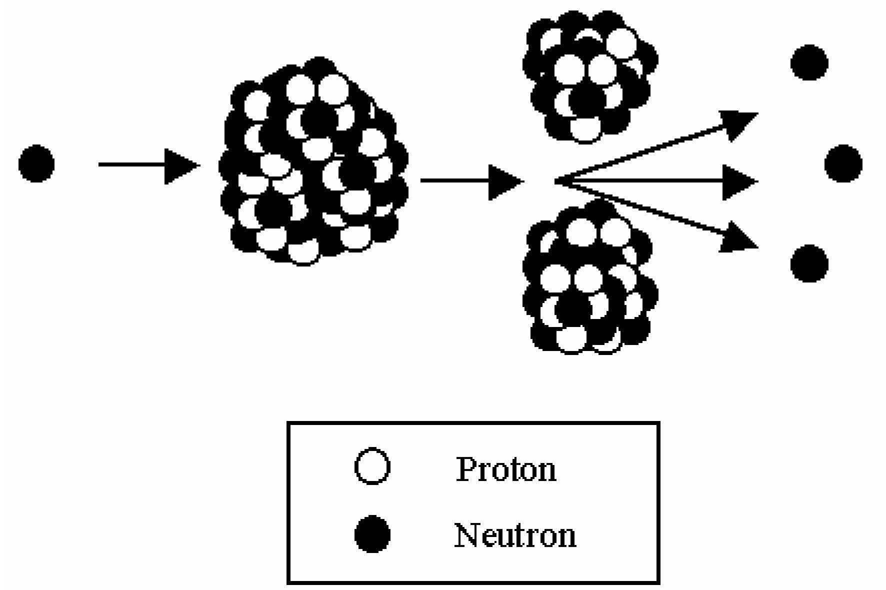
[15] Of course, in practice, matters are more complex. For instance, the build-up of fission products is a complicating factor.

[16] Uranium-233 is a fissile isotope of uranium that does not occur in nature, but it can be made from thorium-232, which does. The process is analogous to the transmutation of uranium-238 into plutonium-239. However, no schemes for using thorium-232 as an energy source have been commercialized, though several have been proposed. Nor has uranium-233 been used in operational nuclear weapons, so far as public information indicates. The DOE released information in January 1997 indicating that it possessed about half a metric ton of uranium-233 (Makhijani 1997). This has been used in experimental reactors, but may also have been used in experimental weapons designs. The DOE does not have plans to use this either in weapons or reactors, since it has essentially been declared a waste which awaits appropriate disposal, presumably in a geologic repository.

[17] Plutonium-241 is also created in nuclear reactors. It is a fissile isotope of plutonium. It is present in very small quantities in weapon-grade plutonium, but in substantial amounts in reactor-grade plutonium, which can also be used to make nuclear weapons.

[18] An electron-volt (eV) is the amount of energy acquired by an electron when it is subject to one volt of electrical potential difference. It is equal to $1.6*10^{-19}$ Joules. Although it is a tiny amount of energy in macroscopic terms, it is significant in atomic terms. A keV is a thousand electron-volts and an MeV is a million electron-volts.

Figure 1: The Fission Process



The reactions for fission of plutonium-239 are similar to those for uranium-235.

Thermonuclear weapons (or "hydrogen bombs") use fission triggers employing either plutonium-239, or highly enriched uranium (which consists of over 90 percent uranium-235), or both in a primary stage. This initial fission explosion is needed to create the extremely high temperature and pressure conditions needed to set off the secondary fusion reactions in which a substantial portion of a thermonuclear weapon's energy is generated. The first nuclear test was a plutonium-239 bomb (code-named Trinity and exploded on July 16, 1945). The second test, which was the first wartime use (the bomb dropped on Hiroshima), was a weapon made with highly enriched uranium (the bomb dropped on Nagasaki was a plutonium bomb similar to the Trinity test bomb).

To create an explosion it is necessary for most of the fission energy to be released in a very short time. In contrast to fission nuclear explosions which happen in an extremely short time -- typically less than 0.1 microsecond -- fission is also used to generate energy in a sustained fashion, over long periods of time in nuclear reactors. In commercial power production, the fission process is controlled and the power output can be varied smoothly, within the design capabilities of the reactor.

The principal difference between explosive release of nuclear energy and sustained operation of nuclear reactors is that in the former the chain reaction grows very rapidly while in the latter, the chain reaction is sustained at a level corresponding to the power output desired.

Explosions can be made compatible with energy generation if they are small enough to be contained in a vessel and if the energy can be transferred out of the vessel and converted into a useful form such as steam. This principle is behind proposals to use inertial confinement fusion as a source of power. As noted above, this idea is technically comparable to the release of energy in the form of explosions of mixtures of compressed gasoline and air in internal combustion engines that power automobiles. But gasoline explosions are small enough that the cylinders in which they occur can last for many years, though there are typically on the order of a thousand explosions a minute in each cylinder. Of course, the energy release from each explosion is small, which is why thousands of small explosions are needed each minute to run a car.

Whether commercial power can be created using small explosions from fusion reactions is one of the purposes of research into inertial confinement fusion. However, the main motivation for the large US and French projects now under construction, (called the National Ignition Facility and the Laser Mégajoule project respectively), is military. Potential energy applications have been claimed for them. However, energy devices should be justified on the merits of comparison with other approaches to solving energy problems, especially given the enormous expense of these devices and the very long time frame (several decades or more) in which research may lead to fruition (see Chapter 5 for CTBT-related objections).

D. Fusion energy

Fusion reactions release energy when two nuclei combine and yield nuclear reaction products that are, in sum, slightly lighter than the original nuclei. The underlying reason for such energy release is the same as that from fission -- that is, the mass difference shows up as energy.

The most common man-made fusion reaction, and the one responsible for most of the fusion energy release in thermonuclear explosions involves two isotopes of hydrogen, deuterium (D) and tritium (T). The former is a non-radioactive isotope, with one proton and one neutron in the nucleus. Tritium, which has one proton and two neutrons in its nucleus, is highly radioactive.[19] This thermonuclear fusion reaction produces an alpha particle, which is a helium nucleus and a neutron:

deuterium (D) + tritium (T) --> helium-4 (He-4) (3.5 MeV) + neutron (14.1 MeV)

The total energy released per D-T fusion reaction is 17.6 MeV, with most of it being the kinetic energy of the neutron. Even though the D-T reaction is the least difficult fusion reaction to create, it is still not an easy feat. It has been attained on a large scale only in the context of nuclear explosions. While not reaching the levels of thermonuclear bombs, laboratory ICF facilities have achieved a significant number of

[19] The specific activity of tritium is about 9,600 curies per gram. Its half-life is 12.3 years.

fusion reactions (10^{12}-10^{13} neutrons per shot).[20] Note that deuterium, or D, is also written as H-2, which is hydrogen with a nominal atomic mass of 2 units. Similarly, tritium, or T, is written as H-3.[21]

There are many other fusion reactions that yield energy. Some have been recreated in the laboratory and in weapons while others occur only in stars. Some examples of such reactions are given below ("He" stands for helium and "p" stands for a proton, which is the nucleus of an ordinary hydrogen atom):

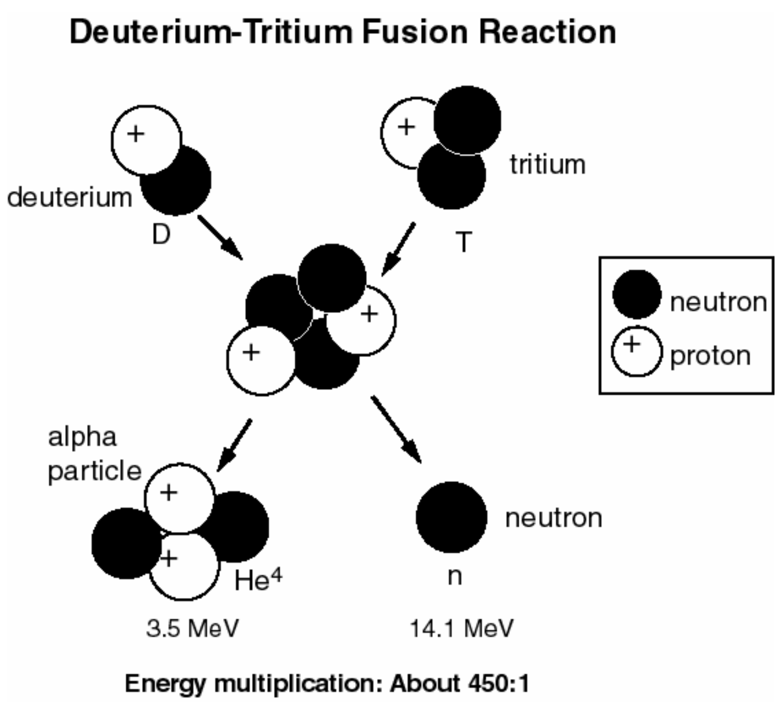
D + D → T + p (proton) + 4.04 MeV

D + He-3 → He-4 + p + 18.353 MeV

Li-6 + proton → He-3 + He-4 + 4.018 MeV

Li-6 + n → T + He-4 + 4.8 MeV

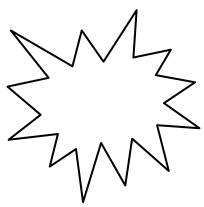
Figure 2: The Deuterium-Tritium Fusion Reaction



[20] Since each D-T fusion reaction releases one neutron, the number of neutrons released in one experimental shot indicates how many fusion reactions occurred and how much energy was released.

[21] Throughout this report, the chemical symbols for elements are used to represent their nuclei, since at the thermonuclear fusion temperatures, all atoms are converted into free electrons and nuclei -- that is, into plasmas -- see text.

The lithium-neutron reaction can be coupled to the D-T reaction to form what is known as the Jetter cycle, an important component of the physical process which occurs in current thermonuclear weapons. The Jetter cycle consumes only deuterium and lithium-6, both widely available non-radioactive materials and releases a large amount of energy, primarily through the D-T fusion reaction. The Jetter cycle needs a source of neutrons to initiate it. Theoretically, this could be an external initiator or neutrons from D-D fusion. The only products of the reaction-cycle that are not consumed within it are helium-4 and energy, plus whatever residuals there are from the neutron initiator. This ignores certain practical matters, such as radiative and neutron losses. For example, neutrons can escape instead of being captured by the lithium making this less than a perfect closed-loop process.



T + D → He-4 + n + 17.6 MeV

↑ ↓

4.8 MeV + T + He-4 ← Li-6 + n

Figure 3: The Jetter Cycle. The Jetter cycle consumes Li-6 and D while producing energy through the D-T and T-He fusion reactions.

High temperatures are needed for fusion reactions to give the atoms of the materials enough energy for their nuclei to come close enough together to interact and fuse. At normal temperatures, atoms of material collide at the atomic level and either bounce off each other or react chemically to create new compounds. Fusion reactions are distinct from fission reactions in this respect because the latter can and do occur even when the materials are cold.

One might ask why such high temperatures are required for fusion reactions but not for fission reactions. The reason is that most fission reactions are created by neutrons, which are electrically neutral and thus can pass relatively easily through the electrons that surround the nuclei of atoms and penetrate into the nucleus. Further, being neutral, neutrons are not repelled by the positively charged nuclei of atoms. A neutron can collide with the nucleus of an atom even when the neutron itself has very little energy. Theoretically even zero energy neutrons can be absorbed into the nucleus of an atom. Since certain materials will fission when their nuclei absorb a neutron with no energy whatsoever (they are called fissile materials), it is possible to have fission reactions at room temperatures (or even lower).[22]

Heating up materials to high temperatures converts them into gases. When the temperatures are high enough, electrons (the light, negatively charged particles circling around the nuclei of atoms) are stripped from the atoms. This process is called ionization; it creates free electrons (not bound to atoms) and positively charged ions (the rest of the atom after one or more electrons have been stripped). At the enormous temperatures characteristic of fusion reactions, all atoms are completely ionized, and all materials are in the gaseous state. The inter-particle interactions in such an electrically charged gas are dominated by electromagnetic forces even though the gas itself is, overall, electrically neutral. Such gases are called plasmas.[23] This is the normal form of matter in stars, where temperatures are very high. The Earth and other solar system planets are relatively cool and the normal form of matter consists of electrically neutral atoms. In other words, the temperatures of the solar system's planets are not high enough to ionize atoms.

The fact that atoms from which electrons have been stripped are not electrically neutral anymore, but rather are positively charged, creates difficulties for producing fusion reactions. In most collisions between positively charged nuclei, they "bounce" off each other before they come close enough to fuse together. This is because positive charges repel each other. However, if the plasma is hot enough -- that is the particles in it have a high enough kinetic energy -- some of the nuclei come very close to each other despite the electrical repulsion between them (much in the way that a ball rolling up an incline can go over the top if it has a high enough speed initially). If the nuclei get close enough to each other, the forces of nuclear attraction, which at close range are far stronger than repulsive electrical forces, cause the nuclei to fuse. Thus, high temperatures are essential to the production of these nuclear reactions because it is only

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[22] When fission reactions are triggered by positively charged particles, such as protons from an accelerator, these positively charged particles must have very high energies so as to overcome the repulsive electrical forces with the protons in the nuclei.

[23] This is an approximate definition of a plasma. A more exact definition is mathematically involved, including consideration of the number of charged particles per unit volume, the characteristic electromagnetic collision distances, and the relative length of the local inter-particle electromagnetic interactions compared to the overall dimensions of the gas. The term plasma is also used in a variety of other situations to describe materials in which the constituent particles are electrically charged and the inter-particle interactions are dominated by electromagnetic forces. The study of the behavior of electrically charged gases is an important branch of physics called plasma physics. Note that the kinds of plasmas we are discussing in this report are not related to the more familiar use of the same term to describe a component of blood.

when the plasma is hot enough that a large number of particles will be able to overcome electrical repulsive forces (called the "coulomb barrier") and fuse.[24]

In plasma physics, temperatures are usually measured in terms of the energy of charged particles, that is in electron-volts (eV) or kilo-electron-volts (keV). One electron-volt is the amount of energy acquired by an electron accelerating through a one-volt electric potential (an ordinary AA battery is rated at 1.5 volts). The amount of energy required to separate the electron bound to the hydrogen atom from its nucleus is 13.6 eV. By comparison a neutron at room temperature (20 degrees Celsius, or 293.16 degrees Kelvin) has an energy of only 0.0253 eV.[25] The minimum temperature needed to initiate sufficient D-T fusion reactions to be of interest to weapons designers and scientists is on the order of 10 million degrees Kelvin (which is about the same as 10 million degrees Celsius, or about 18 million degrees Fahrenheit). Practical devices require temperatures over 100 million degrees Kelvin. Efficient devices using the D-T reaction would require temperatures in the 200 to 400 million degrees Kelvin range -- that is about 20 to 40 keV. As points of reference, the temperature on the surface of the sun is about 6,000 degrees Kelvin and that in the interior of the sun is about 15 million degrees Kelvin.[26]

The high temperatures required to create fusion reactions and the possibility of fission reactions at a wide variety of temperatures is a central difference between these two classes of energy-producing nuclear reactions. It has been a principal obstacle to the development of commercial fusion power and of fusion weapons.

A number of approaches have been tried to overcome the technical obstacles confronting fusion power. The two principal approaches have been magnetic fusion and inertial confinement fusion:

1. **Magnetic fusion**. Very low densities of deuterium and tritium nuclei (thousands of times lower than atmospheric pressure) would be confined by magnetic fields at thermonuclear temperatures for periods of time on the order of one second or more. By keeping the particles confined in these magnetic "bottles," the hot gases would not come into contact with the relatively cold walls of the containment chamber and

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[24] A coulomb is the metric unit for measuring electrical charge. The magnitude of the charge of an electron or proton is $1.6*10^{-19}$ coulombs (the former is negative; the latter is positive).

[25] The temperature in degrees Kelvin is calibrated to the absolute zero of temperature being zero degrees Kelvin. This is the same as -273.16 degrees Celsius. One degree temperature difference on the Celsius scale is the same as a one degree temperature difference on the Kelvin scale. One degree Celsius temperature difference equals a 1.8 degree Fahrenheit temperature difference. At high temperatures, the temperatures in degrees Celsius and Kelvin are about equal. A temperature of one electron volt is equal to about 11,600 degrees Kelvin. Since all calculations relating to ICF are very approximate, temperature conversions may be made to one significant digit only – that is, 1 eV is about equal to 10,000 degrees Kelvin. We have used this approximation throughout this report.

[26] Norman 1994, pp. 813-814.

hence could be kept hot long enough for fusion reactions to occur. This process is also called Magnetic Confinement Fusion (MCF).

2. **Inertial confinement fusion (ICF)**: Small scale fusion explosions are created by compressing deuterium and tritium to very high pressures and temperatures for extremely short periods of time. The high speed at which the nuclei of deuterium and tritium are imploded, using lasers or other means, provides the particles with an inertia that keeps them moving towards each other even as the thermonuclear reaction causes the mass to explode -- hence the term "inertial confinement fusion" to describe the process. If the implosion is powerful enough, the mass will be contained long enough (on the order of one billionth of a second) for enough fusion reactions to occur to yield an energy output greater than that required to produce the implosion. Small pellets of deuterium and tritium would be imploded at a rate of one to a hundred times a second, each generating energy equivalent to several kilograms of high explosive.

Other approaches have included impact fusion (in which a projectile is fired at high velocities and its impact on a solid material creates x-rays), pulsed power (such as the z-pinch experiments in which a large electric current provides much or all of the initiating energy) and Magnetized Target Fusion (MTF, or MAGO in Russian),which is combination of inertial confinement fusion and magnetic fusion. In this program, ignition of a D-T plasma is sought by a combination of chemical explosives and compression of the plasma by high magnetic field or electric current.[27] This last idea was first conceived of by Andrei Sakharov in 1951. It has been part of US nuclear bomb research since about 1957. Both the US and Soviet laboratories have pursued MTF research as part of their weapons programs. Los Alamos National Laboratory and its Russian counterpart, Arzamas-16, are jointly pursuing unclassified MTF research.

The central aim of all approaches is to get a net output of fusion energy without the use of fission reactions as the "driver" for the fusion stage. In place of a fission trigger, a variety of energy sources are used to create the high temperatures needed to initiate fusion. A number of sources of energy have been considered for drivers:

- lasers
- light ion beams
- heavy ion beams
- chemical explosives
- electromagnetic energy sources (including electrical current and magnetic fields)
- combinations of the above

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[27] Younger et al. 1996, pp. 52-55.

While high temperatures are a requirement for fusion systems, the amount of time for which a plasma must be confined varies from one system to another. This is because the various fusion schemes operate in very different ranges of plasma densities. The total number of fusion reactions (and hence the total energy output) depends on the number of deuterium and tritium ions that come close enough to each other. For a given temperature, this in turn depends on plasma density and confinement time. The greater the density and the longer the confinement time, the higher the probability of fusion reactions, and the greater the energy output. Therefore, the central figure of merit for the performance of a fusion system is defined by the product of density and confinement time. A minimum requirement for establishing the scientific feasibility of a fusion system using D-T reactions is that product of plasma density (measured in nuclei per cubic centimeter) and confinement time (measured in seconds) be more than 10^{14} particle-seconds per cubic centimeter.[28] For instance, this criterion is satisfied if one confines, on average, one hundred trillion particles for one second in one cubic centimeter of space. It is also satisfied if the density is a million times higher and the confinement time is only one microsecond. This rule of thumb for measuring the performance of fusion systems is called the *Lawson criterion* and is written as $n\tau > 10^{14}$ particle-seconds per cc.[29] Practical systems -- that is, ones that yield a net output of energy -- must have a density-confinement time product at least ten to twenty times greater than the Lawson criterion value.

In magnetic fusion, the goal is to sustain high temperatures for relatively long periods (one second or longer). Considerable progress in creating fusion reactions in magnetically confined plasmas has been made over the past several decades of research. However, the goal of simultaneously maintaining temperatures, densities, and confinement times sufficient for net energy output has so far eluded researchers.

In inertial confinement fusion, containment time is kept short (a fraction of a nanosecond) but the density is very high.[30] At very high densities (far greater than that of normal solids) the particles in an ICF plasma are packed very close together. Under these conditions, a sufficient number of fusion reactions can be made to occur in a very short time, provided the temperature is high enough. The shorter the containment time, the higher the requirement for density.

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[28] Duderstadt and Moses 1982, p. 3.

[29] The usual symbol for particle density is n and that for confinement time is τ.

[30] It should be noted that there are two different time-scales in ICF experiments. The compression of the pellet occurs on the scale of a few nanoseconds (billionths of a second). The burn time (or confinement time), which is the interval for which plasma conditions suitable for thermonuclear reactions are maintained, is a small fraction of a nanosecond. The exact time intervals depend on the size of the target. The larger targets that are proposed for fusion energy facilities would have somewhat longer compression and confinement times.

It has so far proved impossible to create high enough temperatures and densities (or, equivalently, pressures) simultaneously to achieve ignition before the mass flies apart.[31] The fuel for an ICF system is in the form of a pellet chilled to cryogenic temperatures. In one arrangement to be used in the National Ignition Facility, a part of the deuterium-tritium mixture is a solid and a part is in gaseous form.[32] In this way, a relatively high starting density is achieved (compared to the gaseous state at room temperature).

By drastically reducing confinement time, ICF systems overcome one of the main problems with magnetic fusion. Achieving long confinement times poses severe problems because it is very difficult to contain a very hot plasma. Plasmas are prone to instabilities, and these are aggravated at very high temperatures. Moreover, gases tend to expand at high temperatures unless some countervailing force keeps them confined.[33] Hence, the long confinement times required of magnetic fusion systems pose very great practical problems. However, the advantages of short confinement time in ICF systems are offset by the requirement of a correspondingly high density.

Magnetized Target Fusion operates in a confinement time and density regime between that of magnetic fusion and ICF (see below). The plasma is initially confined in a magnetic field at relatively low temperatures in the 100 to 200 eV, range, roughly a hundred times too low for a significant number of fusion reactions to occur. Creating a plasma at this relatively low temperature reduces problems of plasma instability. To initiate thermonuclear fusion, the MTF plasma is then compressed by setting off a chemical explosive that generates high electric currents or, equivalently, very large magnetic fields. The main characteristics of the three fusion systems are shown in Table 1. As this table illustrates the necessary confinement time gets progressively shorter as the starting density (expressed in particles per cubic centimeter or cm^{-3}) increases.

[31] There is more than one way to define the term "ignition" as applied to thermonuclear plasmas. We will use the term "ignition" to mean a plasma producing thermonuclear energy output equal to the driver energy – that is, a break-even energy level. If ignition occurs simultaneously throughout the fuel pellet this is called "volume ignition." If ignition occurs initially in the central core of the fuel pellet and then spreads out to the rest of the pellet this is called "spark ignition" (see below).

[32] Lindl 1995, p. 53.

[33] In stars this force is provided by gravity.

Table 1: Characteristics of Three Fusion Systems for Deuterium-Tritium Plasma Ignition

Parameter	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 (s)	~1	$\sim 10^{-6}$	$\sim 10^{-10}$

Source: Jones and von Hippel 1998. Reprinted with permission.

The weapons design applications of ICF and other fusion weapons programs fall into several categories:

- pure fusion weapons that depend only on fusion reactions and do not involve fission reactions at all
- weapons that use fusion reactions to trigger a larger release of fission energy using relatively easily available uranium-238 from depleted uranium or natural uranium
- new designs for fission-fusion warheads
- new ways of using of fissile materials to trigger thermonuclear reactions such as the use of sub-critical primaries to design nuclear weapons
- the use of fusion reactions to breed plutonium-239 or uranium-233, both of which are weapons-usable, from readily available but non-weapons-usable uranium-238 and thorium-232 (respectively).

The last application has also been proposed for commercial power programs.[34] Weapons applications of these technologies are considered, overall, to be easier than commercial power applications.[35]

E. Fission-fusion weapons

The first fusion weapons, known as thermonuclear weapons were made in the early to mid-1950s in the United States and the Soviet Union. These weapons solved the immense engineering difficulties posed by large driver energy requirements and the

[34] Commercial power based upon breeding of Pu-239 or U-233 using neutrons from fusion reactions is different than what is generally meant by “breeder reactors.” The latter are fission reactors fueled with plutonium and uranium in which the fissile material created by the reactor is larger than the amount of initial fuel used by the reactor.

[35] For instance, the 1990 National Academy of Sciences review of the US ICF program stated that "Energy applications of ICF are more difficult than defense applications." (NAS-NRC 1990, p. 15) See also Maniscalco 1980. Both the NAS and Maniscalco made these statements in the context of a broad range of military applications such as studies of weapons effects as well as design of thermonuclear weapons with fission triggers. While they did not explicitly discuss pure fusion weapons, the general idea applies in this specific instance also.

transfer of the driver energy to the fusion fuel by using powerful fission bombs as "triggers" for the fusion portion of the warhead.

A typical nuclear warhead in the arsenals of the declared nuclear weapons states has both fission and fusion components. The "primary" stage of the warhead consists of a fissile core, called a "pit," surrounded by chemical high explosives. When the chemical explosive is detonated, it compresses the pit. At the same time, a neutron initiator injects neutrons into the process and a fission explosion results. The fission process is made more efficient by the addition of a few grams of D-T mixture into the pit at the time of the explosion.[36] Energy released from the fission of the primary raises the D-T mixture to thermonuclear temperatures. The neutrons released from fusion produce more fissions and enable more complete use of the fissile material in the primary. (The D-T component of the primary is called a "booster." It does not contribute significantly to the explosive power of the warhead and is not a "hydrogen bomb" as the term is usually used.) The small fusion component of the primary also makes the thermonuclear portion of the secondary more efficient and reliable (see below).[37]

The fission explosion in the primary of the weapon generates x-rays that compress the secondary. This secondary contains lithium-deuteride as well as fission components. The lithium is converted into tritium in the course of the explosion, which in turn fuses with deuterium nuclei to release energy in D-T reactions (see Figure 3 above). The secondary is therefore different from the primary since tritium gas is not used and does not need to be periodically replenished. The use of lithium instead of using tritium directly makes the secondary easier to manufacture and maintain. Typically, the secondary also contains uranium components, both highly enriched uranium and uranium-238, which undergo fission from the fast neutrons and release fission energy.[38]

Andre Gsponer of the Independent Scientific Research Institute has described in detail the workings of various types of thermonuclear weapons and the history of their design.[39] The initial designs were cumbersome and difficult or impossible to use as weapons. For instance, the first US thermonuclear explosion contained large amounts of liquid deuterium, which required cryogenic refrigeration equipment. The breakthrough

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[36] Tritium is a radioactive substance and decays with a half life of approximately 12.3 years. As a result the United States and other nuclear weapons states periodically replenish the tritium in their warheads. For a discussion of tritium requirements of the US nuclear arsenal under various arms reduction scenarios, see Zerriffi 1996.

[37] Gsponer and Hurni 1998, Sections 1.3 and 1.4.

[38] Most modern thermonuclear weapons get a large proportion of their energy from the fission of uranium-238 in the secondary.

[39] Gsponer and Hurni 1998, Chapter 1.

in thermonuclear weapons design came with the Teller-Ulam method (the Zel'dovich-Sakharov method in the Soviet Union).

It should be noted that while the adjective "thermonuclear" is used to describe such warheads, a great deal of the explosive energy actually comes from the fission components in the secondary. The first thermonuclear bomb based on the Teller-Ulam approach, exploded on March 1, 1954.[40] The Teller-Ulam method has made thermonuclear weapons design so reliable "that *all* first hydrogen bombs worked the *first time*."[41] In the Teller-Ulam approach, now standard on all thermonuclear weapons, the casing of the warheads, made out of uranium-238, plays a role similar to a *hohlraum* in an ICF device. A hohlraum is a chamber made of a material with a high atomic number that converts energy of incident particles or photons into x-rays that compress the fuel pellet. For example, the hohlraum can be made of gold. Gold atoms absorb laser energy and re-emit x-rays. ICF systems using hohlraums are called *indirectly driven systems* since the driver energy is not deposited directly into the pellet. This is similar to the way a fission-triggered thermonuclear weapon works.[42] This is one of the reasons that ICF programs at US weapons laboratories have focused their efforts since the mid-1970s on developing indirect drive ICF systems.

ICF research using indirect drivers is most clearly and immediately applicable to nuclear weapons research in two ways:

- It can be used to create new designs of fission-triggered thermonuclear warheads.
- It can be used to create pure-fusion weapons or other weapons that do not require a primary fission trigger. These weapons are called "fourth generation nuclear weapons."[43]

We will first discuss the potential of ICF and, to a lesser extent, other fusion technologies to contribute to the development of fourth generation nuclear weapons in general and of pure fusion weapons in particular (Chapters 2-4). Then we will explore the non-proliferation and disarmament consequences of these possibilities (Chapter 5).

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[40] The bomb was detonated at Bikini Atoll. Among other things, it deposited heavy fallout on Rongelap Atoll, some of which persists to this day, and on a Japanese fishing boat, the Lucky Dragon, that happened to be in the vicinity (around 100 miles away).

[41] Gsponer and Hurni 1998, p. 18. This is not to say that there have not been any tests which did not achieve their stated goals. It took two-and-a-half years after the Lawrence Livermore Laboratory was founded before it had a successful test. Some tests were duds or got yields far below anticipated levels. For instance, Shot Koon, which was part of the thermonuclear weapons program and of Operation Castle in 1954 was expected to yield 1.5 MT, but got 110 kt. (see NRDC 1988, p. 22).

[42] There is a difference. In the Teller-Ulam design, the casing of the warhead *contains* x-rays that are created in the fission primary whereas in ICF the hohlraum actually *converts* the driver energy into x-rays.

[43] Gsponer and Hurni 1998. The first three generations were fission, boosted fission, and fission-fusion thermonuclear weapons.

Chapter 2: Inertial Confinement Fusion Basics

No minimum requirement corresponding to a critical mass or chain reaction in fission exists for fusion reactions. Practically speaking there must be a sufficient number of nuclei to produce a large number of collisions between them, leading to fusion reactions. But this requirement does not pose a significant constraint on the lower limit of explosive power that can be achieved because there are a very large number of nuclei in a very small weight of mixture of any material. For instance, a sizable D-T fusion explosion can be created with as little as a milligram (one-millionth of a kilogram or about two millionths of a pound) of a deuterium-tritium mixture.[44]

All ICF schemes have two basic components -- the fuel pellet and the "driver." The fuel pellet contains the fuel, such as a deuterium-tritium mixture that will undergo fusion reactions, and other components. The driver provides the energy to the pellet to compress it to the high densities and temperatures needed to initiate the fusion reaction. For net energy production, the energy produced by the fusion reactions must be greater than the energy input into the driver. Such an achievement would prove the technical feasibility of the device. However, a lower and less difficult threshold, called scientific feasibility, is generally set as a first goal. Scientific feasibility is said to be demonstrated when the fusion energy output is greater than the driver energy output. ICF machines that have commercial power production as a goal must also have a third component – a system for extracting kinetic energy in the neutrons produced by the fusion reactions that will convert this energy into electricity or other useable forms.

The ratio between the fusion energy output and the driver energy output is called *gain*. A gain of one is required to prove the scientific feasibility of fusion schemes and corresponds to the definition of ignition used in this report. It has only been achieved in the context of thermonuclear explosions initiated by a fission trigger.

In practice a gain considerably greater than one is required for fusion schemes, whether they are for energy production or for explosive purposes. As noted above, a net energy output is achieved only when the fusion energy output exceeds the energy input to the driver. For instance, laser drivers currently have efficiencies on the order of one percent, but this can be increased to around 10 percent.[45] Ion beam drivers can have efficiencies up to about 20 percent.

The coupling between the energy in the driver and the fuel pellet is also not perfect. In a typical case, only about 10 percent of the energy of the driver may wind up

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[44] We will consider only deuterium-tritium fusion reactions in this report. The observations regarding the conditions for achieving fusion are qualitatively valid for all types of energy-producing fusion reactions. But the specific temperatures, pressures, and confinement times needed are different.

[45] Actually, the one percent efficiency of current lasers is based on electrical energy input. If we take into account average losses in electricity production, laser efficiency would be only one-third of one percent.

in heating and compressing the pellet.[46] Hence, a gain of 100 to 1,000 is required before the fusion energy output equals the energy input into the system, depending on driver efficiency and type.

An energy producing system faces even more severe constraints, since only a fraction of the energy output of the fusion pellet can be converted into a usable form, such as electricity.[47] Hence, practical energy schemes would require gains of several hundred before breaking even overall. Gain requirements can be reduced considerably by improving the efficiency of the driver and of the coupling between the driver and the fuel pellet.

Figure 4 shows a schematic diagram of an ICF system. The driver shown is a system of lasers, but other drivers could also be used. Figure 5 shows how this is analogous to the way an internal combustion engine operates, in terms of the general steps. Figure 6 represents the details of the delivery of energy to the fuel pellet, and its subsequent ignition and explosion. The steps in this process are:

- Deposition of driver energy into the outer layer of the fuel pellet
- Fuel pellet compression
- Fuel pellet ignition (not yet achieved in the laboratory)
- Fuel pellet explosive burn (not yet achieved in the laboratory).

Ignition and explosive burn are achieved simultaneously if the entire volume of the plasma is heated to thermonuclear temperatures by the driver, and sequentially if the driver ignites only the inner core of the plasma.

[46] Lindl 1995, p. 3.

[47] A thermal-electric fusion power plant efficiency would likely be of the same order of magnitude as a fission power plant efficiency, which currently is about 33 percent.

Figure 4: Schematic Diagram of an ICF System

Source: Livermore 1994, page 15

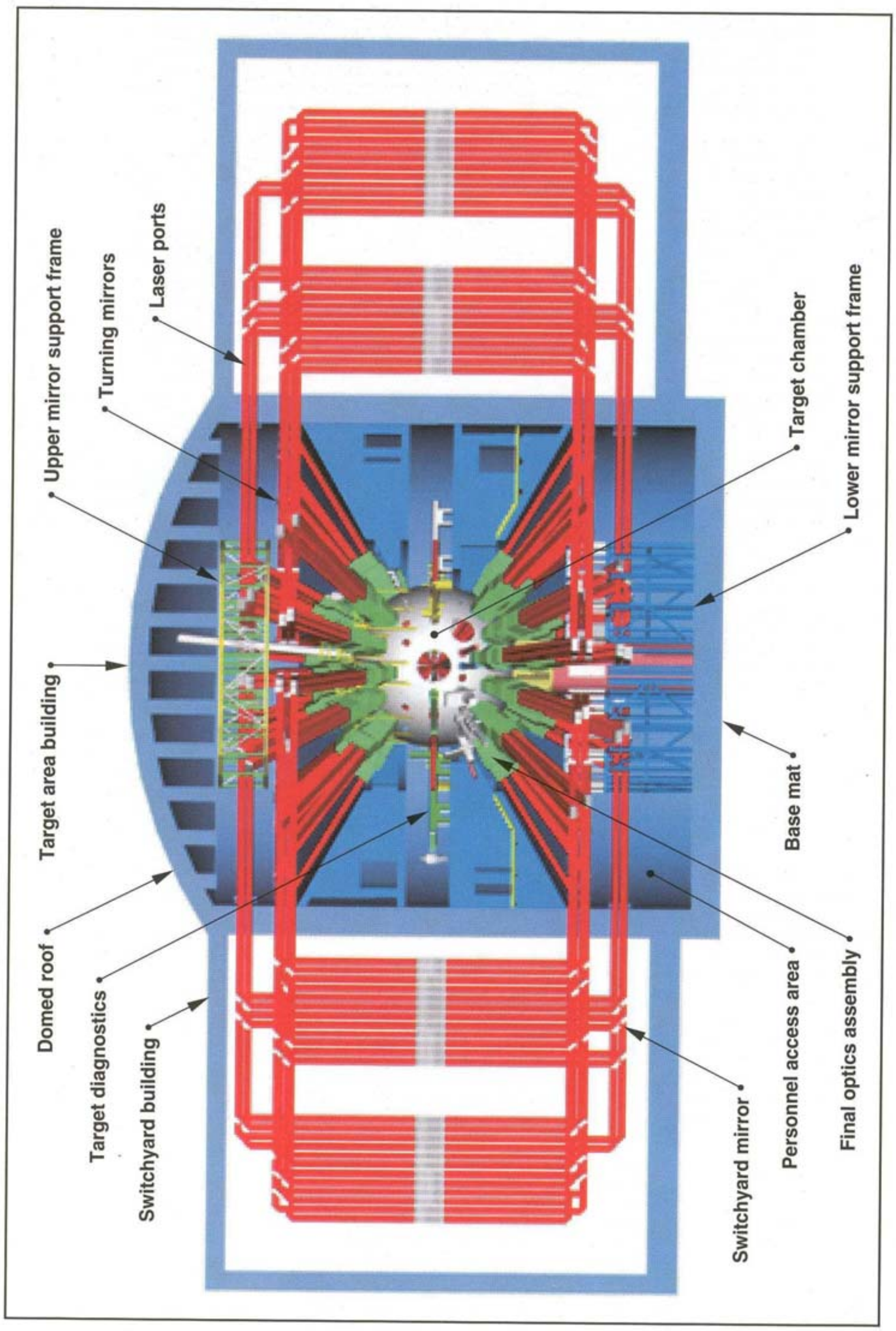


Figure 5: Analogy of ICF to an Internal Combustion Engine

Source: Duderstadt and Moses 1982, Figure 1.2, p. 5.

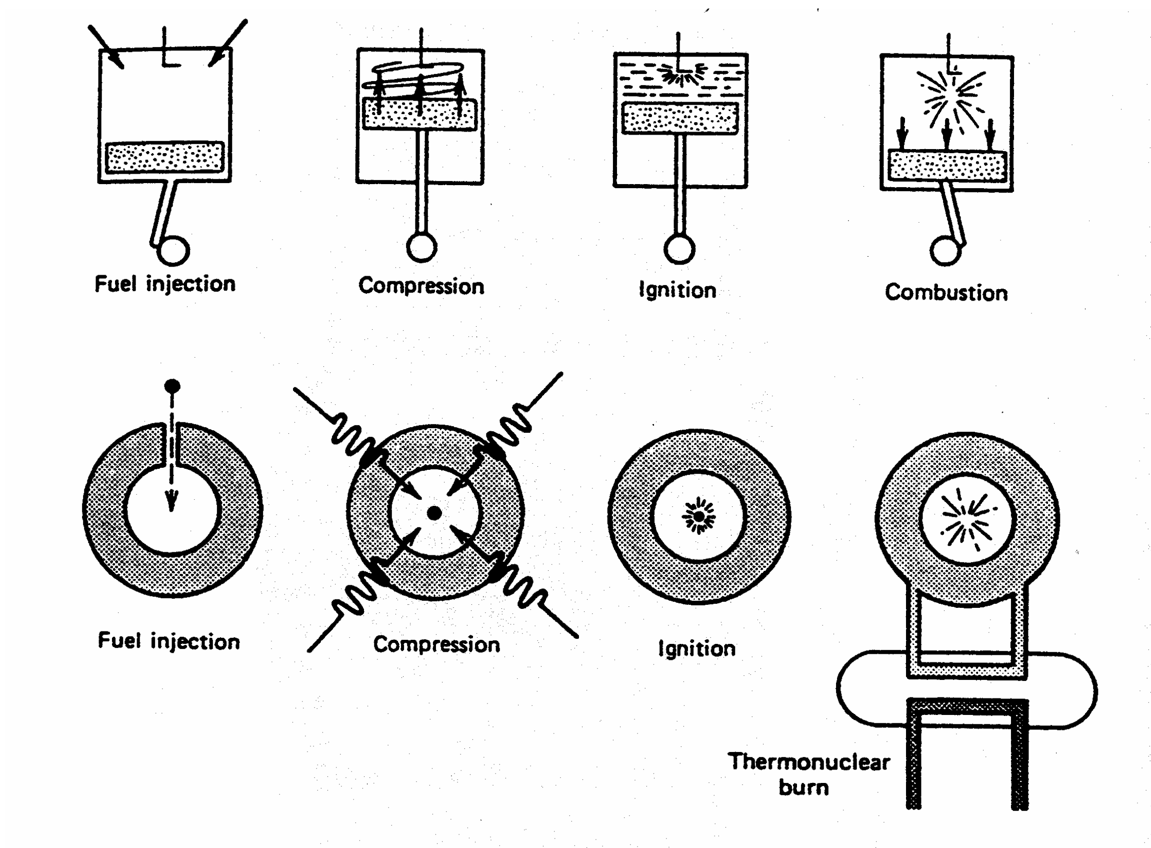
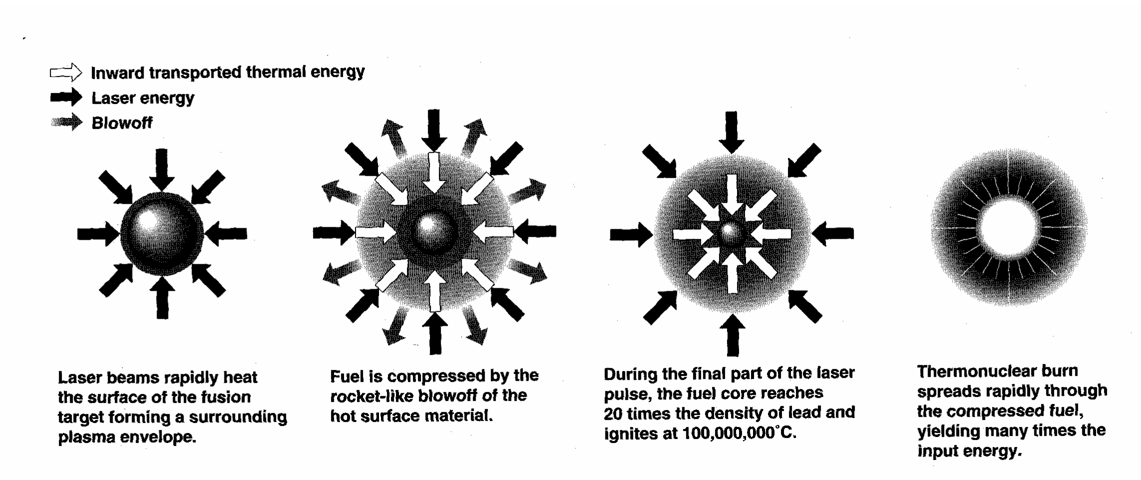


Figure 6: Steps in fuel pellet ignition and burning

Source: Livermore 1994a, page 4



A. Deposition of driver energy

ICF driver energy must be transferred to the fuel pellet rapidly and in an appropriate form. The driver energy serves both to compress the fuel pellet and to raise it to the temperatures necessary for a large number of fusion reactions to occur (at least a few keV for practical devices).[48]

The coupling of the energy in the driver can be accomplished by two different methods. The first method is to directly couple the driver with the fuel pellet. In this direct drive approach, the driver (such as a laser or ion beam) is focused directly onto the surface layer of the fuel pellet. In the indirect-drive approach, the driver is focused onto the inner surface of a chamber made of heavy material, such as gold.[49] The gold (or other material) absorbs the driver energy and re-radiates it as X-rays. The X-rays generated in the chamber, which is called a hohlraum, can be more symmetrically deposited into the target than the energy directly from driver.

Aside from the problem of generating a sufficient amount of energy in the right form, there is still the question of how this energy is actually to be transferred to the fuel pellet. This is a crucial task, since the functioning of the device depends on the efficiency and speed of this energy transfer.

One way the driver energy can be made to produce a very rapid compression of the fuel pellet is to deposit it in a surface layer of the fuel pellet that would rapidly evaporate and shoot outward. This creates an effect similar to millions of tiny "rockets" taking off simultaneously from the surface of the fuel pellet. The "thrust" of these "rockets" pushes the pellet inwards from all directions and creates an implosion.[50] This process is called ablation

If ablation occurs fast enough, it creates a shock wave implosion of the fuel pellet. These shock waves travel rapidly inward. In order for the pellet to ignite and use the fuel efficiently, the compression of the fuel pellet must be highly symmetrical. In most designs, the compression must be spherically symmetrical. Symmetry imposes the following requirements on the coupling between the driver and the fuel pellet:

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[48] The probability of D-T fusion reactions is very low at temperatures well below 1 keV, and increases very rapidly with increasing temperature up to about 10 keV. It has a rather broad peak between about 20 keV and roughly 1,000 keV. Lindl 1995, p. 4, Figure 2. Also, it should be noted that creating temperatures of a few keV in the pellet will result in burn temperatures of 20 to 30 keV.

[49] Strictly speaking, the material must have a high atomic number, for which the usual symbol is Z. Such materials are often referred to as "high-Z" materials.

[50] Newton's third law, which states that action and reaction are equal and opposite, is the physical principle underlying pellet compression. The forces that propel the surface layer outward as it evaporates create an equal but opposite inward force that compresses the pellet.

- The deposition of the driver energy on the surface layer must be highly uniform and the pellet must be spherical to within very small manufacturing tolerances.
- The surface layer must be highly uniform so that the compression is uniform.
- The evaporation of the surface layer must be rapid and uniform.

The requirement of a highly symmetrical implosion means that the pellet itself must be spherical to within a very small tolerance. This is very difficult to achieve for the small explosion needed in ICF, since the pellet itself is very small -- its radius in ICF is typically on the order of only about one millimeter. Emerging advanced materials manufacturing technologies could make the manufacture of very symmetrical pellets both efficient and inexpensive.

Another requirement is that the ablation process occur very rapidly (on the order of nanoseconds if inertially confined explosions are desired) and initiate the shock wave implosion of the rest of the pellet. The ablation process itself must be highly uniform, since the implosion shock waves must be set off essentially simultaneously over the whole surface of the pellet. The spherical symmetry requirement also means that the irregularities on the surface of the fuel pellet must be so small that they do not distort the ablation and compression processes. The internal construction of the pellet must also be spherically uniform, otherwise the speed of the shock wave in different parts of the pellet will vary as it implodes.

In direct drive systems, the driver energy must be symmetrically deposited on the ablator to achieve symmetrical compression. In the case of indirect drive systems, the driver symmetry requirements can be relaxed, but the driver must be configured so that the energy output of the hohlraum is symmetrical.

B. Driver requirements

A central problem in ICF is generating the energy that is to be transferred to the fuel pellet. As we have discussed, the pressures and temperatures needed are extremely high. In fact, the temperatures must be higher than those in the interior of the sun. This poses considerable constraints on driver design. Several different considerations must be taken into account in regard to the choice of the driver:

- **Total Driver Energy:** Does the driver have enough energy output to produce the compression and high temperatures needed to start thermonuclear fusion reactions?
- **Driver Efficiency:** What is the efficiency with which the driver converts input energy into a form that can be transferred quickly into a pellet? For instance, if lasers are used to compress the pellet, how much electricity (and hence fuel) is needed to produce the light energy that is beamed on to the fuel pellet?
- **Driver-Fuel Pellet Coupling:** How much of the energy output of the driver is actually delivered to the pellet?

- **Driver Pulse Time:** Can the driver deliver the energy in a short enough pulse to compress the pellet quickly? In other words will the driver deliver sufficient pulsed power to the fuel pellet to cause it to ignite?

How much energy the driver must transfer to the fuel pellet depends on the amount of the D-T mixture that is to be ignited and the mode of ignition. In the volume ignition mode, on the order of one megajoule of energy needs to be dumped into the plasma in order to heat a one-milligram D-T pellet at normal liquid density to a 10 keV temperature. (The driver energy output would be an order of magnitude higher based on current target technology, or about 10 MJ.) This is really quite a small amount of energy -- about the electricity consumption of a 100-watt bulb for just under three hours. But it must be delivered to a very small pellet in an extremely short time -- on the order of one-billionth of a second. This means that the power of the driver, that is the rate at which the energy is delivered, has to be enormous. For a fuel pellet compression time of one nanosecond, and just one megajoule of driver energy output, the power must be 1,000 trillion watts.[51] This is about 1,500 times the entire installed electrical capacity in the United States. Evidently, the heating of a pellet cannot be accomplished by simply plugging the driver to the electrical grid even though the total amount of energy needed is quite small.

The second challenge is to impart one megajoule of energy to a small target, say one milligram. This means that the energy delivered per unit mass is very high. This requirement arises from the need to heat up the small mass to very high temperatures.

Current drivers have a number of problems. Driver efficiencies tend to be very low, ranging from below one percent to twenty-five percent at best. As we have discussed, low driver efficiencies mean that the fusion reaction must have a correspondingly large energy gain to compensate for the energy loss in the driver.

Low driver efficiencies place a very great premium on the efficiency of transfer of energy between the driver and the fuel pellet. Every unit of driver energy output that is lost means that many times more energy was lost at the driver input. Creating an efficient coupling between the driver and pellet is a difficult task because at the high temperatures involved, the pellet quickly becomes a plasma. Such plasmas are notoriously unstable. Plasma instabilities destroy the implosion symmetry, causing the plasma to distort and dissipate. Radiative energy losses from plasmas are another major problem.

Driver considerations for weapons applications are somewhat different than those for commercial power applications of ICF. In the latter, the premium is on driver and

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[51] Duderstadt and Moses 1982, p. 6. Power is the rate of energy output. It is measured in a number of different units, but watts is the most common. One watt is equal to one joule per second. Hence, a one megajoule output in one nanosecond amounts to $10^6/10^{-9} = 10^{15}$ watts. This can also be written as one thousand terawatts (1,000 TW).

coupling efficiencies, since the net power output must be as large as possible and since the fuel utilization must be high. Unlike weapons, the size of the driver is not a central consideration for fixed, central station power plants. In weapons, efficiency and fuel utilization are also crucial considerations. But cost constraints can be relaxed compared to commercial applications.[52] Further, the recovery of the energy from the neutrons is not an objective.

C. Fuel pellet compression

Why is fuel pellet compression necessary at all for inertial confinement fusion, when fusion can be achieved at much lower pressures in magnetic fusion? As we have discussed, in magnetic fusion, the energy output is achieved at very low pressures (or densities) by making the confinement time very long -- one second or more. In the case of explosions, the confinement time is short, so the density must be correspondingly high. The time in which fusion reactions occur is called the "burn time," and the time it takes for the fuel assembly to fly apart is called the "disassembly time." The ratio of burn time to disassembly time is a measure of the efficiency of the explosive process. The larger the ratio, the greater the consumption of reacting material in fusion reactions.

This race between burn time and disassembly time can be expressed in simple mathematical terms by requiring the product of the density of imploding material and its radius to be greater than a certain minimum number. A high density means that there will be a sufficient number of atoms of material close to each other for fusion reactions to occur, and a large radius means that the disassembly time will be long enough to allow a sufficient number of reactions to occur. The disassembly time corresponds approximately to the concept of confinement time of the plasma. It is the time interval after which fusion reactions will stop because the pellet has disintegrated. As a result, the product of the density and radius of the compressed pellet is a useful figure by which to assess ICF systems. It corresponds approximately to the Lawson criterion discussed earlier.

The product of density (in grams per cubic centimeter) and radius (in centimeters) must be about 3 grams per square centimeter (g/cm^2) for achieving a net energy output from ICF.[53] In this case, approximately one-third of the deuterium and tritium would

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[52] Nuclear weapons have been very expensive. The cumulative cost of the US nuclear weapons program to date is estimated to be greater than 5.4 trillion dollars, excluding future clean-up liabilities. Schwartz, ed. 1998.

[53] This corresponds to an nt product of about $2*10^{15}$ particle-seconds per cc. The Lawson criterion is nt $\approx 10^{14}$ (IAEA 1995, p. 25). The density-radius product that corresponds to the Lawson criterion is about 0.15 grams per square centimeter for a temperature of about 20 keV. The burn fraction is about 2 percent. The burn fraction increases to about 3 percent at 40 keV. Calculated from Lindl 1995, equation 9, p. 5.

produce fusion reactions.[54] This generalization is valid for temperatures in the 20 to 40 keV range. The rest would be recovered and reused, if the application were commercial power production. However, in weapons applications it would be dispersed in the environment (though, of course, the radioactivity of the dispersed tritium would be very small in comparison to the fallout from fission explosions and this is one of the "advantages" of pure fusion weapons).

Gaseous deuterium and tritium at room temperature have very low densities (a fraction of one milligram per cubic centimeter). Using deuterium and tritium gas at room temperature would mean an impossibly huge "fuel pellet" and a correspondingly huge amount of driver energy to compress it. However, a gaseous D-T mixture could be confined at room temperature at high pressure to alleviate this problem, because compressing the gas would reduce its volume and the required driver energy.

The usual starting point for an ICF experiment is therefore a liquid or solid D-T mixture, which requires cooling a D-T gas mixture to cryogenic temperatures -- 23.5 degrees Kelvin. This increases the starting density of the fuel and hence reduces the driver energy required for compression. The NIF baseline target uses a combination of gaseous D-T (at 0.3 mg/cc) surrounded by denser solid D-T and then an ablation layer.

For experiments that must be contained in a laboratory, it is necessary to keep the total mass of the reactants small, to a few milligrams or less, meaning that the pellet will have a small radius. The pellet must be compressed to high pressures in order to increase the density of the fuel and achieve a suitable product of density and radius.[55] Hence, the fuel pellet is first compressed to much higher densities (at least one hundred times greater than the density of D-T liquid) in order to achieve an efficient burn of the fuel and still keep the overall explosion to a size that can be contained in a laboratory.

Thermonuclear reactions in the core of the sun are produced under conditions of high density and temperature. The containment of hot gases in the sun (and other stars) is provided by the immense gravitational force that comes from the great mass of the sun itself. The pressure in the sun's interior is equivalent to 100 billion times the Earth's atmospheric pressure and its temperature is 1 to 2 keV. The sun retains its coherence as a star despite such huge pressures and temperatures because of the high gravitational force that it exerts on masses in, on, or near it.[56] In other words, its gravity prevents the mass of the sun from flying apart like a giant hydrogen bomb.

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[54] Lindl 1995, p. 5. The burn fraction is given by the expression $f \approx \rho R/(6 + \rho R)$ for temperatures in the 20 to 40 keV range where ρ is the density of the plasma and R is the radius. In this expression, density is in grams/cc and radius is in centimeters.

[55] Since the density, ρ, increases as the inverse cube of the radius, R, the product of radius and density increases as the inverse square of the radius. Mathematically: $\rho \propto 1/R^3$, so that $\rho R \propto 1/R^2$. Hence, if the radius is reduced by a factor of 10, the ρR product increases by a factor of 100.

[56] Duderstadt and Moses 1982, p. 44.

D. Thermonuclear ignition

Plasmas can be heated up to ignition temperatures in several modes. In the volume ignition mode, the entire plasma is heated by the driver. This mode requires the greatest driver energy. In the "spark" ignition mode, only about two percent of the mass of the pellet at the center of the fuel pellet is heated up to thermonuclear temperatures. This considerably reduces the driver energy requirements. The energy in the alpha particles created by the fusion energy reaction in the ignited core then heats up the layer next to the core and ignites it. This in turn releases sufficient alpha particle energy to ignite the next outer layer, and so on. This process is an outwardly propagating fusion burn wave in which the high energy alpha particles moving outward heat up the particles of deuterium and tritium that are still moving inward due to the kinetic energy imparted to them by the compression of the fuel pellet.

Although spark ignition is desirable from the point of view of driver requirements, it also faces significant obstacles. It is no longer enough for the temperature of the plasma to be several keV (such that there is a high probability of D-T reactions). In addition, the compression must be high enough to create a very dense plasma. This is because the alpha particles released from the fusion reactions in the pellet core must collide with the relatively cool plasma in the next outer layer with high probability, thereby heating it up. If the plasma is not dense enough and not enough alpha particle energy is deposited in the cooler outer layers a propagating burn wave will not be created.

The neutrons from the explosion escape and deposit most their energy outside of the pellet, whereas the alpha particles (fast helium nuclei) generated by the fusion reactions mainly heat the plasma itself.[57] The deposition of alpha particle energy in the plasma also compensates for radiative energy losses. At very high compressions a part of the neutron energy also helps to heat the plasma.

Another approach to improving the efficiency of ICF devices has recently been suggested. This approach, called "fast ignition," would compress the pellet so that the density of the plasma stays constant, instead of a compression that maintains the symmetry in pressure conditions in the plasma. Fast ignition also relies on an asymmetrical laser pulse that would ignite one side of the pellet after symmetrical compression has been initiated by the driver. The burn wave would them propagate through the plasma asymmetrically (see Figure 7). One advantage of fast ignition is that a higher gain can be achieved for a given driver energy since a second energy source is providing the "spark" for ignition rather than compression of the fuel pellet. In other words, the driver does not need to compress the fuel pellet to as high a density. This in turn would reduce driver efficiency requirements.[58]

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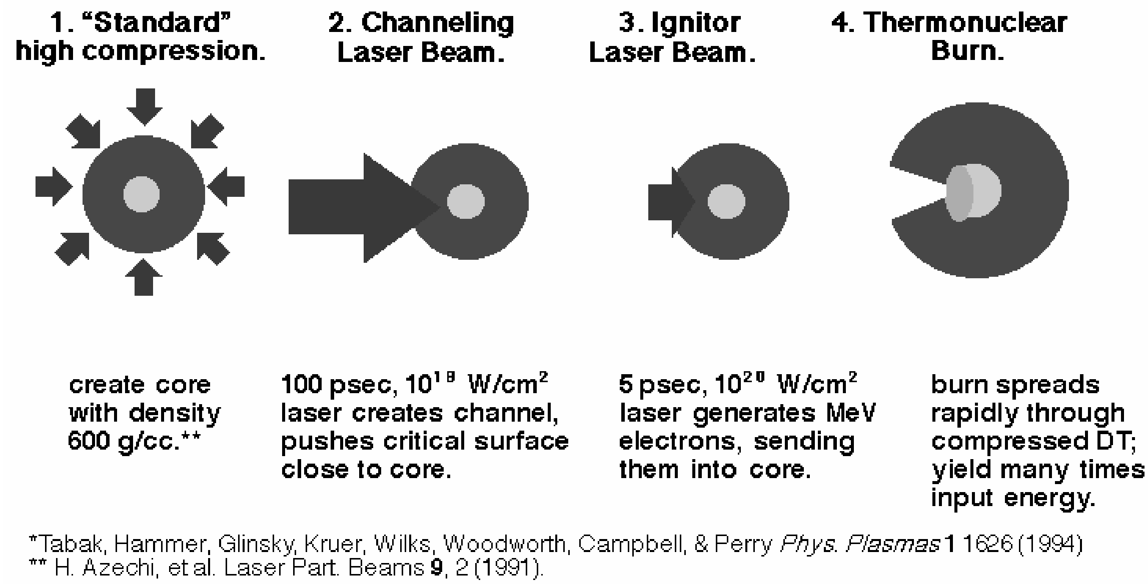
[57] Lindl 1995, p. 7.

[58] Key et al. 1998, p. 1.

Figure 7: The Fast Ignition Concept



Chapter 3: Various ECF Schemes

The details of fuel pellet compression and ignition are very similar in different ICF schemes. The main differences arise in how the energy needed to compress the fuel pellet is generated and delivered to it. Thus, various ICF schemes can be classified according to the nature of the drivers.

Fusion-scale lasers and ion-beam accelerators are large and immobile and therefore ill-suited as driver candidates for fusion weapons. However, they contribute to the development of both current generation thermonuclear weapons and pure fusion weapons in several ways, such as by demonstrating the scientific feasibility of ICF, by enabling design of fuel pellets for other schemes, and by allowing more precise computer modeling of other schemes more suited to weapons. Moreover, the various schemes complement each other to some extent. For example, the Heavy Ion Fusion Group at Lawrence Berkeley Laboratory appears to have an ongoing collaborative relationship with Lawrence Livermore's fusion group.[59]

Table 2 lists the major ICF driver facilities that are either operating or are planned worldwide. The energies and pulse times are provided and where possible supplementary information such as neutron production information is provided. The table does not list all of the facilities which are in early planning stages as well as many smaller operating facilities.

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[59] An interesting component of this is the separation of weapons and non-weapons work at the national laboratories. Lawrence Berkeley Laboratory (LBL) is a laboratory which does not conduct research and design of nuclear weapons. In 1997 and early 1998, there was some controversy at the laboratory when some of its scientists realized that their work was being used by Los Alamos for the Dual Axis Radiographic Hydrodynamic Test (DARHT) facility (see Locke 1998 for an example of news coverage of this and other issues related to LBL and nuclear weapons). Similarly, scientists at Berkeley may want to review the weapons implications of the work of the heavy ion fusion group for the National Ignition Facility and other fusion projects with potential military applications.

Table 2: List of Major ICF Driver Facilities and Their Operating Parameters (Table Includes both Operating and Planned Facilities)

Location	Driver	Operating Parameters	Neutron Production per Shot
Sandia National Laboratory (USA)	PBFA-II (light ion beam)	36 Beams 100 TW (design) 10 TW (1988 actual)	Unknown
Sandia National Laboratory (USA)	Z-pinch	2 megajoules 290 TW 140 eV temperature	D-T target not used yet.
Sandia National Laboratory (USA)	X-1 (successor to z-pinch) (Conceptual Design)	16 megajoules 1000 TW	Projection Unknown
Europe	Heavy Ion Design for Ignition Facility (HIDIF) (Conceptual Design)	48 Beams 1 megajoule 27 TW	Projection Unknown
Lawrence Livermore National Laboratory (USA)	NOVA laser	10 Beams ~40-70 kilojoules ~100 TW	10^{8}-$3.6x10^{13}$
Lawrence Livermore National Laboratory (USA)	National Ignition Facility (NIF)	192 Beams 1.8 megajoules ~360 TW	10^{19} (projected under maximum 20 MJ yield scenario)
Osaka (Japan)	GEKKO-XII	12 Beams 15-30 kilojoules 0.1-10 nanoseconds	10^{13}
Osaka (Japan)	Kongoh (Under Design)	92 Beams 300 kilojoules 100 TW	?
Bordeaux (France)	Laser Mégajoule	1.8 megajoules 120 TW	Same range as NIF
VNIIEP (Russia)	Iskra-5	12 Beams 15 kilojoules 0.25 nanoseconds	?

Sources: Schirmann and Tobin 1996; Gsponer and Hurni 1998; Velarde 1993; Livermore 1996b; Singer 1998.

A. Laser Drivers

Laser drivers work by first creating a pulse of laser light in the laser medium.[60] A variety of lasing media are possible, each with their own advantages and disadvantages. However, the basic principles are the same. The case of NIF provides a good example of a laser-based ICF facility.

[60] For a description of how lasers work see Krane 1983, section 8.8.

NIF's laser system is based upon a neodymium-doped glass laser, the primary type of laser system for ICF research. Each of NIF's 192 beams starts as a pulse in what is called a "master oscillator." These extremely low energy pulses are then boosted to an energy of about 10 joules before going through the main amplification stage. Each pulse passes through the amplifiers four times. The optical system is complex; the laser pulses pass through a variety of lenses, filters, and amplifiers before being focused onto the target. This optical system not only amplifies the pulses but is designed to optimize the frequency of the light and counter negative optical effects which could affect the pulse. The result is that the 192 original pulses are amplified from a few nanojoules each to a total energy of 1.8 megajoules and focused onto the target.[61]

NIF's peak power is expected to be around 500 trillion watts (also called terawatts and abbreviated as TW). Assuming ignition is achieved, the neutron production of NIF will be in the range of 10^{19} neutrons/shot (assuming a 20 MJ energy output).[62] In comparison, NOVA, a ten beam laser facility at Lawrence Livermore National Laboratory, has a peak power around 120 TW and produces approximately 10^{13} neutrons/shot.[63]

Lasers provide some significant advantages for research into Inertial Confinement Fusion. Laser pulses can be made very short and with high energy, and can be shaped fairly easily.[64] This gives laser fusion facilities considerable flexibility as research tools. However, lasers also have their disadvantages. For facilities such as NIF, design problems include minimizing damage to optical components, creating light of the correct wavelength, minimizing instabilities which affect the symmetry of the compression, and other challenges. The main disadvantages of laser fusion relate to practical applications. For inertial fusion energy one large problem (in addition to those which NIF will have to overcome) is the repetition rate. NIF will only be able to deliver one shot approximately every eight to fourteen hours.[65] By contrast, a large commercial power plant using ICF will require around five shots per second. Laser drivers also have low efficiencies,

[61] DOE 1996a pp. I-17 – I-19, NAS-NRC 1997, pp. 26-27, Livermore 1994, p. 8-9. Each pulse is amplified about to about a trillion times its initial energy.

[62] The anticipated energy output if ignition is achieved is called an "yield scenario" Livermore 1996, p. 61

[63] There has been considerable debate as to whether or not NIF will be able to achieve its goals, including ignition. A number of technical issues related to the laser system and to capsule design and production (among others) remain to be worked out. It is beyond the scope of this report to analyze these issues. We have, therefore, conducted our analysis with the assumption that all facilities discussed will perform as intended by their designers. For one discussion regarding the potential obstacles to NIF achieving its goals see NRDC 1997.

[64] Pulses from lasers (and other energy sources) can be shaped so that the energy is delivered to the target in particular ways. For example, a pulse can be shaped to have a relatively long period of time in which a little energy is deposited on the target followed by a very short period of time in which a lot of energy is deposited.

[65] Schirmann and Tobin 1996 state that NIF will have 600-1200 shots per year.

currently around 1% for solid-state lasers such as those to be used in NIF. Theoretically, this class of lasers can exceed 10% efficiency. However, this would still be lower than the 20% efficiency that ion beam drivers can achieve now.[66]

B. Ion Beam Drivers

Ions are atoms that are no longer electrically neutral. They have either gained or lost an electron. In the following discussion we will consider positive ions only (atoms that have been stripped of one or more electrons) since they are the ones relevant to ICF schemes. Since the atoms are no longer neutral they are subject to manipulation by electromagnetic forces and can be accelerated to extremely high velocities. There are a variety of electromagnetic acceleration techniques which are described below.

In general, the advantages of ion beam approaches are in their high pulse rates and high efficiencies (in comparison with laser systems). Depending on the system, pulse rates are currently approaching or even exceeding the requirements of inertial fusion energy designs. In the case of induction heavy ion accelerators, the pulse rate is high enough that one accelerator may be able to feed multiple beam lines or even reactor chambers.[67] As discussed above, driver efficiency plays a large role in determining the viability of ICF based energy systems. Low efficiencies mean a greater amount of energy is needed to yield a specified driver output. Ion beams have driver efficiencies ranging from 10 to 25 percent, in comparison with around one percent for current laser systems such as those to be used in NIF.[68]

Ion beams also have their disadvantages. One problem is that they are difficult to focus. For ion beams to work for fusion, the ion-containing pulses must be extremely short in duration. In other words, the ions must be packed together very closely. However, the positive charges of the ions result in a repulsive force between them. This not only causes the ions to separate and spread out (called "beam divergence"), but can also result in ions reacting with their surroundings during their passage through the accelerator.[69] Achieving high power levels (large energy levels in short periods of time) in an accelerator also poses major difficulties, but specifics depend on the type of accelerator being used.

The current requirements for heavy ion beams, consisting of elements such as lead or bismuth, are far lower than those for light ion beams. Heavy ion beam accelerators must be driven at higher energies (1 to 10 giga-electron-volts) in order for

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[66] Soures 1993, p. 352.

[67] Kessler et al. 1993, p. 685.

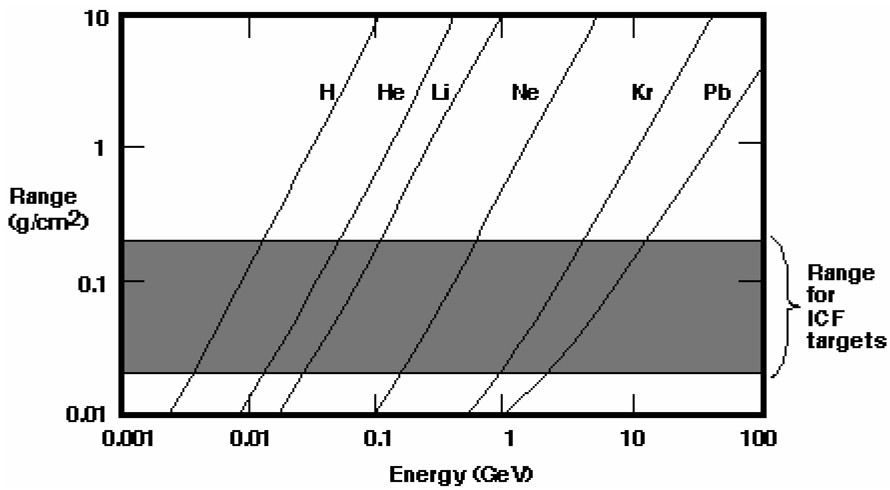
[68] Muller 1993, p. 439 and Soures 1993, p. 352. According to Bangerter and Bock 1995, p. 111, heavy ion accelerator efficiencies as high as 40% are achievable.

[69] Muller 1993, p. 438-9.

the beam to penetrate the target at the proper depth and generate x-rays. This means that the current requirement for a power level of 1,000 terawatts is in the 100 to 1,000 kiloampere range.[70]

Light ion beams, consisting of protons or other light ions such as lithium, operate at voltages that are about 100 times lower; the current requirements for a given power level are proportionately greater.[71]

Figure 8: Energy-Range Relationship for Light and Heavy Ion Beams



Source: LBL HIF Website

1. Heavy Ion Beams

Heavy ions[72] can be accelerated using two different types of machines: Induction and Radio-Frequency (RF) accelerators (see below). In either case, an ion source is necessary. A generic ion source would consist of a gas of the desired element being ionized by an electric discharge (such as from a filament). The ions are extracted from the discharge tube by placing a negative electrode outside the ion source to which the positive ions are attracted.[73]

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[70] The power level is simply the product of the voltage and current. Hence, for a given power level, determined by the constraints of the fusion scheme, the lower the voltage, the higher the current needed.

[71] Bangerter and Bock 1995, p. 112-113.

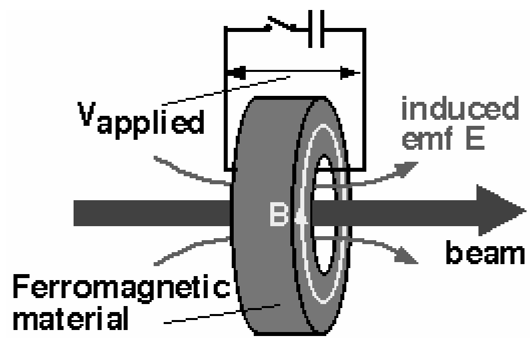
[72] The definition of heavy ions is not always consistent. Krane 1988, p. 431 defines heavy ions as having a mass number greater than 4. However, in the context of ICF, lithium ions (with A>4) are defined as light ions. In the context of ICF, light ions range from protons to lithium ions, while heavy ions are generally in the region of lead or bismuth (that is, atomic number about 80).

[73] Krane 1988, p. 560.

a. Induction Accelerators

In an induction accelerator the ion beam is accelerated through the use of "pulsers." This figure is only schematic but it provides the basic idea of how the technology works. A doughnut shaped magnet (called a toroid) surrounds the beam. When the circuit is closed and the capacitor discharges, a magnetic field is created in the toroidal magnet. This changing magnetic field creates an electric field in a metal cavity surrounding both the beam and the toroid. These electric field lines accelerate the ions. Many techniques are then used to focus the beam, raise the current, and manipulate the beam in various ways.[74]

Figure 9: Ion Beam Induction Accelerator



Source: LBL HIF Website

b. Radio-Frequency Accelerators

A radio-frequency (RF) accelerator works on the same basic principle as an induction accelerator; but the method of creating the electric field which accelerates the ions is different. In an RF accelerator the electric field occurs in the gap between successive tube electrodes. The electrodes are fed by a radio-frequency source. The alternating current of the source means that the electrodes continuously switch back and forth from positive to negative. Since successive electrodes have opposite charges, an electric field is created in the gaps. The accelerator is designed so that ions pass through the electrode gaps at exactly the correct times so as to be accelerated by the electric field in pulses which are coordinated to occur when the field lines are in the direction of beam travel.[75] While RF accelerators are a well-established technology, they face certain limitations. Aside from expense, the RF accelerator by definition is tied to the frequency of its RF generator, which can be doubled or tripled, but is essentially limited. Since the

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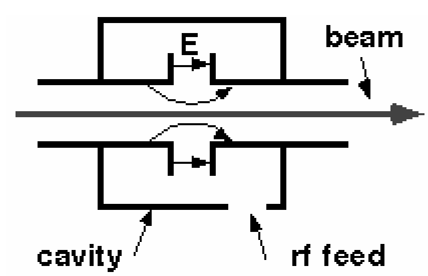
[74] Bangerter and Bock 1995, p. 130-134.

[75] Krane 1988, p. 588-589.

beam current is proportional to the frequency, this imposes limitations on the beam current.[76]

Heavy ion beam accelerators have some significant advantages as drivers for ICF energy schemes. Indeed, it seems to be the prevalent view in the literature that while laser drivers are necessary for the experimental and demonstration phases of target development, ignition, and other developmental research, heavy ion beams would be used if fusion energy were ever commercialized. The main advantages of heavy ion beams are their long life-times and fast repetition rates. Heavy ion beams can achieve their peak power levels with relatively lower current levels, reducing some of the development problems as compared to light ion beams which require currents significantly higher than now achievable. A commercial fusion plant would probably need to explode around 5 to 10 D-T capsules a second for many years. Heavy ion linear accelerators (linacs) have pulse rates of 10 to 1000 pulses per second.[77] Therefore, the power plant would not be limited by the repeatability of the driver. By contrast, lasers and some light ion beams require far longer times between pulses. For instance, the maximum rate for NIF is projected to be 600-1200 per year. On the other hand, it remains to be demonstrated whether heavy ion accelerators can reach the high peak power necessary for fusion and be able to adequately focus the beams on small targets.

Figure 10: Ion Beam Radio-Frequency Accelerator



Source: LBL HIF Website

2. Light Ion Beams

Light ion beam accelerators use a single acceleration gap to achieve the necessary particle energies (~10-30 MeV). This acceleration gap consists of a negative and positive electrode (cathode and anode) which are supplied with pulse power. Unlike heavy ion accelerators, the ion source is part of the accelerator, since the lithium (or other light ion) source forms part of the anode material.

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[76] LBL HIF website.

[77] Muller 1993, p. 439.

The light ion beam hohlraum would be constructed of a high Z material outer wall and filled with a carbon-based foam. Unlike laser hohlraums, however, the ions are not converted into X-rays by the wall material, but rather by the foam fill. The ions pass through the thin wall of the hohlraum and the foam converts their energy to soft X-rays. The fusion target is then uniformly irradiated by the X-rays, which are now contained by the high-Z hohlraum wall. This means that the target must be carefully designed so that the energy is deposited at the proper depth in the target.[78]

Like heavy ions, light ion beams have the advantage of higher efficiencies than laser systems. Current light ion beam efficiency is around twenty percent.[79] However, there are still significant gaps between current performance and the requirements for commercial power from inertial fusion (called IFE or inertial fusion energy).

Table 3: A Comparison of Current Light Ion Fusion Technology and Projected Requirements for Energy from Inertial Fusion

Parameter	Particle Beam Fusion Accelerator-II (as of 1995)[80]	Inertial Fusion Energy[81]
Energy	0.1 MJ	4-6 MJ
Power	10 TW	300-500 TW
Foam Deposition	1500 TW/g	1000-8000 TW/g
Hohlraum Diameter	0.6 cm	1.5 cm
Outer Hohlraum Layer (gold or lead)	1-2 µm	10-30µm
Foam Density	3-10 mg/cm^3	5-30 mg/cm^3

A number of practical difficulties prevent light ion beams from being closer to the requirements of fusion power. The diode ion source must produce a beam of uniformly charged ions of a single type. This must be done at high power levels and efficiencies. Some problems are similar to those for heavy ion beams. The ion beam must be focused

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78 Imasaki et. al 1995, pp. 137-139.

79 VanDevender and Bluhm 1993, p. 457.

80 Imasaki et al 1995, p. 138. The PBFA-II facility is a light-ion research facility at Sandia National Laboratory. It was modified to allow the pulsed power generators to drive both light-ion and wire-array z-pinch experiments (see Section C in this chapter).

81 Imasaki et al 1995, p. 138.

on a small spot. This limits the size of the initial beam radius and therefore, the size of the acceleration gap used to extract the ions. A long acceleration gap results in higher energy ions, but the ions have a longer distance over which to spread out, increasing the spot size. In order to focus the beam, various problems of beam divergence must be overcome (some of which result from the positive charges on the ions). A further problem with light ion diodes is the creation of significant numbers of free electrons due to the large electric field. These free electrons can prevent high currents by neutralizing ions (a potentially significant problem considering that the light ion beam approach requires high beam currents). Magnetic fields are often applied to minimize the flow of electrons.[82]

Repetition rates also need to be improved for light ion systems. As of 1995 Sandia's HERMES III pulse power system could operate at about seven pulses per day. A repetitive system was in the test phase which had managed to reach 120 Hz for 18 minutes, although at a slightly lower energy and current.[83] However, this indicates that research towards a useable repetitive pulsed power system for light ion beams is progressing.[84]

Thus, there are still significant advances that need to be made in light ion beam and target technology in order to achieve the proper energies and powers while overcoming problems such as beam divergence.

C. Z-pinch

While useful for fusion research ion beams and lasers cannot function as drivers for pure fusion *weapons.* However, a pulsed power device known as the "wire-array z-pinch" has this potential. The name of the device derives from the fact that it is a cylindrical array of wires (the vertical direction of a cylinder is usually denoted by the letter "z", for z axis) and the fact that the cylinder is "pinched" to a very small diameter. The potential of the device arises from its already established capacity to generate x-rays at energy levels significant for pure fusion explosions and from the possibility that it could be miniaturized.

Significant improvements in the wire-array z-pinch have occurred at the Sandia National Laboratory over the past few years, where a device called the Particle Beam Fusion Accelerator-Z (PBFA-Z) has reached levels that had previously been thought to be unattainable. In particular, recent laboratory reports state that PBFA-Z has generated 2 MJ x-rays, a level comparable with that planned for the National Ignition Facility.

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[82] Imasaki et al 1995, p. 139.

[83] Imasaki et al 1995, p. 148.

[84] Pulsed power sources could also be used for developing other types of weapons, such as particle beam weapons. These are beyond the scope of this report.

In the z-pinch wire-array experiments a large current is passed through a large number of very thin wires arranged in a cylindrical bundle. As the current rises, the magnetic field associated with it increases. This in turn compresses the array of wires into a cylinder of progressively smaller diameter. At the same time, the high current is rapidly heating the wires, evaporating the wire material, and turning it into a plasma. As this plasma is compressed further by the magnetic field, the electrons and ions forming the plasma come to an abrupt stop (this is called stagnation). This abrupt stop converts the kinetic energy of the particles into x-rays. The process is somewhat analogous to the conversion of the kinetic energy of a car into heat during sudden braking.

Since x-rays can be used to compress a fusion fuel pellet, the high level of x-ray energy achieved by the wire-array z-pinch makes it very interesting to fusion researchers. The initial energy source for the z-pinch experiments at Sandia was a pulsed-power generator used for light ion research. This apparatus was called PBFA (Particle Beam Fusion Accelerator). A large capacitor bank was used as the electrical energy source. By September of 1996 this capacitor bank was converted for use as the energy source for the wire array z-pinch experiments discussed above.[85] The recent performance levels announced for PBFA-Z (290 TW) demonstrate the potential of this technology. The experiments have exceeded most of the milestones that have been set in a relatively short period of time.

Sandia National Laboratory has officially requested permission from DOE to design the next generation of x-ray facility, the X-1. While no official design has been produced, there are articles indicating that conceptual designs have been completed. These indicate that X-1 would produce x-rays of approximately 16 MJ.[86]

D. Chemical Explosives

Chemical high explosives (HE) are an integral component of current nuclear weapons, since they trigger the fission primaries of these weapons. However, the requirements of high explosives for current nuclear weapon use are much less stringent than those for pure fusion weapons. In the latter case, they would have to meet performance requirements similar to those of other fusion drivers. They must not only deposit sufficient energy into the device, but also be powerful enough to compress the fuel to fusion densities and temperatures fast enough to avoid premature disassembly, and be uniform enough to avoid instabilities.

High explosives in pure fusion weapons would likely have to be used in combination with other techniques. The two major problems with using chemical

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[85] Matzen 1997, p. 1525. The wire-array z-pinch experiments do not require the accelerator portion of the PBFA apparatus.

[86] Ramirez 1997, p. 159.

explosives alone as fusion drivers are their comparatively low energy densities and their slow detonation velocities. We explore them here because their use in combination with electromagnetic approaches to plasma compression could be crucial to miniaturizing pure fusion devices.[87]

High explosives are complex molecules generally consisting of carbon, hydrogen, nitrogen, and oxygen. The generic abbreviation for these explosives is CHNO. CHNO explosives can also contain other elements, such as fluorine. The energy release from explosives occurs by a process called oxidation. A variety of chemicals are produced during this oxidation process, including nitrogen, water vapor, carbon monoxide, and carbon dioxide. The amount of each element in the starting explosive will determine how much of each product is formed (largely depending on the availability of oxygen) and whether the explosive is under- or over-oxidized. When the explosive is exactly oxygen-balanced, it will have the highest energy density (energy per unit weight) possible for that type of explosive. TNT, for example, is under-oxidized. In other words, it is not as efficient an explosive as it could be. The composition of an explosive also has a bearing on its detonation velocity (see below).[88]

The relatively low energy density of current high explosives limits their use as drivers for pure fusion weapons. High explosives have energy densities in the range of 5-6 kilojoules (kJ)/gram. The energy necessary to ignite the core of a 1 milligram D-T fuel pellet is on the order of 10 kJ.[89] Assuming a one percent efficiency in the coupling of the energy in the explosive to the fuel pellet, about one megajoule of explosive energy would be required, amounting to about 200 grams of high explosive. This poses severe physical problems because the volume of the explosive (on the order of 100 to 150 cc) would be more than five orders of magnitude larger than the volume of the D-T fuel that it is supposed to ignite(about 0.005 cc).[90] This makes the need for a fast and efficient coupling between the release of explosive energy and the fuel pellet a central problem in the use of high explosives in pure fusion weapon development.

At the same time, high explosives are far more compact than lasers, ion beams and other energy storage devices that are used in ICF research, a key factor making them more favorable for fusion weapons use. Much of the practical problem of creating pure fusion weapons can therefore be viewed as the exploration of ways in which the energy of high explosives can be transformed so as to create a sufficiently efficient and rapid coupling with a relatively small fuel pellet. For instance, this is the central idea in the use of high explosives in magnetized target fusion experiments.

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[87] For a discussion of this issue, see Garwin 1997, p. 10.

[88] See Cooper 1996, Chapter 2 for more detailed discussion of oxidation in explosives and problems of over and under-oxidized explosives.

[89] Assuming the central two percent of the fuel pellet is ignited. Lindl 1995, p. 7.

[90] We assume that the high explosive has a density of about 1.5 g/cm^3.

E. Advanced materials manufacturing

Advanced materials manufacturing may radically improve the prospects for pure fusion weapons by possible making smaller, more efficient, more precise, and less costly components such as drivers and ablators (the outer layer of the fuel pellet which is evaporated). A variety of advanced manufacturing techniques may affect the field. Development of new materials, lasers, explosives, electrical devices, and other components of explosive confinement fusion devices may also dramatically alter the prospects of developing these weapons. The consequences of radically new technologies, materials, and manufacturing processes are notoriously difficult to predict, and we do not attempt to do so here. The purpose of this section is simply to point out that emerging processes and materials may substantially and rapidly increase the feasibility of pure fusion weapons. Just as it would have been impossible to forecast the present state of the Internet and personal computers from the vacuum tube era of the 1940s, we cannot accurately predict where fusion technology will be in the next decades given the continued tremendous pace and variety of technological change. We will illustrate the possibilities by discussing a few processes and technologies that may have particular bearing on the development of pure fusion weapons.

For instance, a reduction in the size of capacitors by an order of magnitude appears possible with technologies now being developed by the Pentagon. New manufacturing techniques and improved dielectric materials could combine to make possible capacitors with energy densities on the order of 10 joules per cc.[91] Thus, one megajoule of driver energy could be stored in a volume of 0.1 cubic meter. This is still far greater than the volume for the same energy in a chemical explosive, yet it is small enough to enable a wire-array z-pinch device using a few milligrams of D-T fuel to be portable. Development of efficient coupling of both capacitor stored energy and chemical drivers, via techniques such as magnetized target fusion, could result in practical pure fusion weapons. Based on current projections of fusion yield from MTF, Jones and von Hippel calculate a total yield of 0.5-2.5 tons of HE for a device weighing three tons.[92]

1. Nanotechnology

The development of manufacturing by precise manipulation of small numbers of molecules or even single atoms provides another example of new techniques whose potential is not possible to project at present, but which may have substantial impact. The approach goes under the rubric "nanotechnology," which means technology

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[91] Rzad et al. 1992.

[92] Jones and von Hippel 1998. The yield of 0.5-2.5 tons high explosive equivalent comes from 0.2-2 metric tons of yield from the 3-30 mg fusion pellet plus 320 kg of actual high explosives used in the device.

operating at a scale of one-billionth of a meter. This is thousand times smaller than the micro-scale technologies that gave us the computer chip. Nanotechnology may have substantial implications for pure fusion weapons, ranging from development of improved explosives to more efficient ablators.

Nanotechnology is a relatively new, but rapidly growing, field combining physics, chemistry, material science, and engineering. K. Eric Drexler defines molecular manufacturing, a goal of nanotechnology, as "the construction of objects to complex, atomic specifications using sequences of chemical reactions directed by non-biological molecular machinery."[93] This would involve synthesis of a fundamentally different nature than current methods of chemical synthesis. Atoms and molecules would be guided to react with one another in a highly controlled fashion at the individual molecule level. Therefore, unlike conventional synthesis, the reactions would not be dependent on collisions proportional to reagent concentrations, spatial effects, and electronic interactions between reagent molecules. Instead, reactions would result from proper positioning of individual reagent molecules.[94] Precise positioning (albeit using macroscale instruments rather than nanoscale molecular machines) of atoms and molecules has been demonstrated.

One potentially very important application of nanotechnology to the development of pure fusion weapons is in the development of chemical explosives. The current process of developing high explosives begins with a theoretical exploration of possible candidates for a new highly energetic material. Both theoretical and synthesis chemists (who would be responsible for making the explosive) determine candidate molecules worth further exploration. Using powerful computers, the candidate molecule's shape and binding energy are modeled and its explosive properties (e.g. detonation velocity, energy) are predicted. Lawrence Livermore scientists are already taking advantage of the capabilities of the Accelerated Strategic Computing Initiative (ASCI) program for advanced modeling capabilities and these capabilities can be expected to expand as the ASCI program is further developed.

The next step after computer modeling (assuming the models show the candidate molecule is worth pursuing) is to synthesize a small amount of the explosive. This appears to be one of the most difficult steps, since the material has never been synthesized before and the chemists must begin from scratch using a trial and error process (although based upon previous experience).

In some cases, the necessary reagents to produce the explosive are too expensive, harmful to the environment, or dangerous. If it is possible to synthesize the new explosives, small quantities are made for laboratory testing. These tests not only

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[93] Drexler 1992, p. 1.

[94] Drexler 1992, pp. 5-6.

determine its explosive parameters, but also test for its safety, stability against degradation and other factors. According to a Livermore article on chemical explosive research at the laboratory, the potential safety problems are the most common cause of rejecting candidate materials.

The final stages of explosive development are to mix the explosive with other materials (the "formulation" stage) and to scale up the process to production levels. The formulation step also requires a certain amount of trial and error. At the end of the development process only a fraction of the possible explosives are actually developed. The rest are discarded for reasons such as difficult synthesis, poor performance, or safety. As the Livermore article states, "Developing new energetic materials is a complicated process in which many candidate molecules are considered, a few synthesized, even fewer formulated, and only a small handful adopted by the military or industry."[95]

The problem of synthesis seems to be a particularly vexing one for the explosives industry. Livermore can create a computer model of a candidate explosive in about a week. However, it may take a year or more for the chemist to develop the right synthesis scheme.[96] Chemical synthesis of explosives, like most chemistry, is done in what is called the gas or liquid (also called "solution") phase. This means that the chemicals being mixed, heated, stirred, etc. are either gases or liquids. The molecules in each reagent react with the molecules in the other reagents, essentially in a statistical fashion (i.e. by random collisions). The two reagents mix, the molecules move around one another, bumping into each other, and in some cases reacting with one another to form a new molecule. As one scientist noted, "traditional manufacturing methods spray atoms about in great statistical herds."[97] This process can be aided by various techniques, such as applying heat to increase the reaction rate. This must be regulated since too great a temperature can result in degradation of the reagents. This new molecule must then be extracted if it is to be used. The synthesis scheme must include a number of intermediate reactions before the final product is synthesized.

The synthesis process is an inherently inefficient one. The resulting product is never produced at 100% efficiency, the existence of impurities can be a problem for both the reaction and the final product, and other reactions can take place producing unintended or undesired side-products. Furthermore, as discussed above, it may not always be possible to synthesize the desired product due to reagent unavailability, toxicity, cost, and other reasons.

The ability to manipulate single molecules using nanotechnology may affect the development of chemical explosives in two ways. On a manufacturing level, explosives

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[95] Livermore 1997, p. 7.

[96] Livermore 1997, p. 8.

[97] Merkle 1993, p. 1

could be manufactured more easily and closer to their theoretical maximum density. This comes from moving away from solution-phase chemistry in which reagents are mixed to get a certain yield of end-product. More significantly, however, nanotechnology could open up the possibility of a new generation of explosives. As discussed above, explosives development is not always constrained by what is theoretically possible, but by what is practically possible in the laboratories trial and error process of synthesizing candidate materials.

It may not always be clear how a new energetic material could be synthesized, the reagents may be too costly or dangerous, or the number of synthesis steps may not be practical for full-scale manufacturing.[98] Molecular manufacturing might be able to eliminate those problems by relying on raw materials that are easier to acquire and use. In general, reagents must be able to react with other molecules in order to form a new product. The problem in conventional synthesis is that a reagent which too readily reacts with other molecules will result in unwanted reactions. Therefore, reagents must be chosen which will be selective in their reactions with other molecules. In the case of molecular manufacturing, as stated above, highly reactive reagents will be able to be controlled and their reactivity can become an asset (potentially increasing reaction frequencies).[99]

2. Metallic Hydrogen

Another development which may have significance in the future for the development of pure fusion weapons is the reported, but as yet unconfirmed, experimental discovery of metallic hydrogen. The higher density of metallic hydrogen may provide benefits for the design of fusion weapon capsules (and may reduce the amount of fuel necessary for larger pure fusion weapons).[100] Metallic hydrogen was first theoretically postulated in the 1930s. Since then there have been a variety of attempts to achieve the high pressures and other conditions necessary for hydrogen to become a metal. Various researchers have claimed success, but have had their discoveries overturned upon further experimentation.[101] Most recently, a group of researchers at Livermore claimed to have made metallic liquid hydrogen in a shock experiment using a

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[98] Cooper 1996, p. 27-28.

[99] Drexler 1992, p. 206-207.

[100] A Deuterium-Tritium liquid hydrogen mixture has a density of 0.21 g/cc while metallic hydrogen's density would be ~1-1.3 g/cm^3 (see Ross and Shishkevish 1977, p. v).

[101] Livermore 1996, p. 13.

gas gun.[102] While this experiment has not been repeated by other laboratories, there appears to be some evidence that the hydrogen was metallicized, although for a very short period of time.[103]

The Livermore experiments could also have a significant impact on the study of fusion and pure fusion weapons. The improved understanding that these experiments provide of the behavior and properties of hydrogen (and its isotopes) at high pressures and temperatures could aid fusion scientists in tuning their lasers, improving their computer codes, and designing better targets for NIF. This could result in higher fusion energy yields and make the NIF target performance range "broader and more flexible."[104] This would occur whether or not metallic hydrogen were ever brought to a stable room pressure and temperature form. However, if it were possible to produce metallic hydrogen in a useful form, then the implications for fusion weapons could be greater. Metallic hydrogen may also be an extremely powerful explosive, releasing large amounts of energy.[105] However, this is at present speculative, given the uncertain state of metallic hydrogen research. It is unknown at this time whether metallic hydrogen could ever be produced in a useful form.

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[102] For a description of the experiment and the results see Livermore 1996. Metals are generally found as solids at ordinary temperatures and pressures. However, some elements are metallic at ordinary temperatures, such mercury. A metal is not defined according to its physical state (solid, liquid, gas), but rather by its properties (e.g., heat conductivity, electrical conductivity, appearance, malleability).

[103] This experiment is also an interesting example of the surprises science holds. While the researchers were conducting their experiment in order to observe the change in hydrogen under pressure from an insulator (resists the flow of electricity) to a conductor (allows electricity to flow readily), they did not set out to create metallic hydrogen. In fact, they did not think it would be possible in their experiment. Their method had never been used to try to metallicize hydrogen, their material was in liquid form while it was expected that metallicized hydrogen would be found in solid form, and their temperature range was higher than the expected temperature of metallicized hydrogen.

[104] Livermore 1996, p. 17.

[105] Metallic Hydrogen Common Questions, http://www-phys.llnl.gov/H_Div/GG/ComQuest.html, p. 3.

Chapter 4: The Prospects for Pure Fusion Weapons

There are currently two approaches to fusion being researched that could lead to pure fusion weapons, or more broadly, to nuclear weapons that do not require a fission trigger. They are inertial confinement fusion (ICF) and fusion driven by various combinations of electrical, electromagnetic and chemical compression of plasmas, such as Magnetized Target Fusion (MTF). Neither of these technologies is sufficiently developed to demonstrate the scientific feasibility of these weapons. But the research paths and the stated goals for both of them are such that, if successful, the prognosis for such weapons could change dramatically. None of the projects have the development of pure fusion weapons as their officially stated goal. In view of the many commitments that the nuclear weapons states have made to stop developing new nuclear weapons, most recently as part of the Comprehensive Test Ban Treaty, these same states could hardly announce that they are developing radically new nuclear weapons.

The questions then revolve not around stated intentions, but around the technical capabilities that the pursuit of high power ICF and MTF programs will give the nuclear weapons states, and in particular the United States, France, and Russia. If the technical potential for building these weapons is developed, or even if their scientific feasibility is established, the pressures to build them, especially in times of crisis, would be immense.

For these reasons our evaluation of these technologies and their implications for nuclear disarmament and non-proliferation focuses on the development of technical capabilities. In this chapter, we will examine the technical goals of these projects as they relate to the requirements for building pure fusion weapons and to a lesser extent non-fission triggered nuclear weapons.

A. Requirements for pure fusion weapons

Fusion weapons that do not need a fission trigger have been considered mainly for two military and technical advantages that they would provide over fission triggered weapons:

1. Pure fusion explosives can be made small enough to replace conventional munitions and also to fill the gap between conventional and current thermonuclear weapons. This advantage has diminished with time as nuclear weapons of smaller yields have been developed.[106]
2. Pure fusion weapons would produce no fission products. Most of the radioactivity produced would be in the form of short-lived activation products (notably argon-41).

[106] Large conventional bombs range in total weight from about 500 pounds to 5,000 pounds (about 220 kilograms to 2.2 metric tons), including the casing. The W54, one of the smallest nuclear warheads developed, is believed to have a yield as low as 10 tons of TNT equivalent (see NRDC 1984, p. 60).

This would reduce political unacceptability and dangers to soldiers while maintaining the lethality of these weapons.

Achieving both of these advantages simultaneously poses very great technical challenges. A smaller challenge may be to first develop hybrid fusion-fission devices that would not require a critical mass or the use of a fission explosion as a trigger. Jones and von Hippel have discussed such types of possible weapons in which the role of the primary and secondary in present-day nuclear weapons would be reversed.[107] A fusion primary would supply a sufficient number of neutrons to trigger a large number of fission reactions in uranium-238. Since neutrons from D-T reactions are highly energetic, they can fission U-238 (which cannot sustain a chain reaction, but which releases a large amount of energy when fissioned). Since each fission releases more than ten times as much energy as each fusion reaction, the fission secondary would serve to amplify the primary fusion explosion.

This approach to nuclear weapons would negate one of the main reasons for seeking pure fusion weapons -- avoiding heavy radioactive fallout. But it could more easily achieve the first goal -- overcoming the "tyranny of critical mass"[108] -- by using a fusion explosion as the primary part of the bomb.

Once fusion-fission weapons are developed, the next “logical” step in the technical progression would be pure fusion weapons. Pure fusion also have a military “advantage” over conventional explosives in that the lethal radius is far larger than the range of explosive lethality alone (see below).

B. Overall assessment of non-fission-triggered nuclear weapons

There are two broad requirements for establishing the technological feasibility of non-fission-triggered nuclear weapons. First, non-fission heating and containment of a plasma must be achieved so as to generate sufficient fusion reactions to yield a net energy output. Second, a driver must be developed which both supplies the necessary power and can be made compact enough to be feasible as a weapon. We will evaluate each of these issues and then given an overall assessment of the technical prospects for non-fission-triggered nuclear weapons.

1. Ignition

Existing ECF devices are being scaled up or modified to achieve ignition of a thermonuclear plasma. The explicit goal of a number of devices that are being built or designed is to achieve ignition. The National Ignition Facility, which is part of the US

[107] Jones and von Hippel 1998.

[108] Dyson 1960.

Science Based Stockpile Stewardship (SBSS) program, is among them. The Magnetized Target Fusion Program's status in relation to the SBSS program also aims to provide "scientifically exciting" research opportunities for scientists engaged in nuclear weapons design and testing. Its explicit goal is also to achieve ignition.

If the National Ignition Facility achieves its stated design goals it should produce around 5-20 MJ of output energy during “high-gain” experiments. Its peak energy output would be approximately 45 MJ. The Laser Mégajoule project should have similar performance (though its peak energy output is estimated to be 60 MJ).[109] The energies and pressures of the NIF experiments can be compared to both previous fusion facilities and to nuclear weapons tests (Figure 11 and Figure 12). As can be seen, many of the performance parameters approach nuclear weapons tests. For example, the energy density of NIF is very similar to nuclear weapons tests. What is different is that the total energy output is much lower in NIF. It should be noted that while NIF may approach weapons tests in a number of ways and thus could provide useful weapons design information, there are enough significant differences that applying information from NIF to *existing* nuclear weapons is highly problematic.

Magnetized Target Fusion devices have already achieved neutron production of 10^{13} (10 trillion) neutrons per shot in the “warm” plasma even before implosion (separate implosion experiments have taken place to test the implosion of the liner).[110] A full test of the MTF/MAGO system (formation of a D-T plasma followed by implosion of the liner) is scheduled for 2000.[111] According to Jones and von Hippel’s review of the MTF literature, this technology could achieve energy outputs equal to 1-10 gigajoules or 0.2-2 metric tons of high explosives.[112]

The technical results achieved in the NOVA laser program at Livermore and the GEKKO XII program in Japan are comparable to those achieved in the MTF program, since they have also produced on the order of 10^{13} neutrons in one shot. However, in order for the ICF program to achieve ignition, a larger driver is needed, among other things. This is the objective in building NIF in the US, Laser Megajoule in France, as well as other proposed large ICF programs.

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[109] Schirmann and Tobin 1996, p. 513.

[110] Jones and von Hippel 1998.

[111] Jones and von Hippel 1998.

[112] Jones and von Hippel 1998.

Figure 11: Comparisons of NIF with Previous Facilities and with Nuclear Tests

Source: Lawrence Livermore National Laboratory

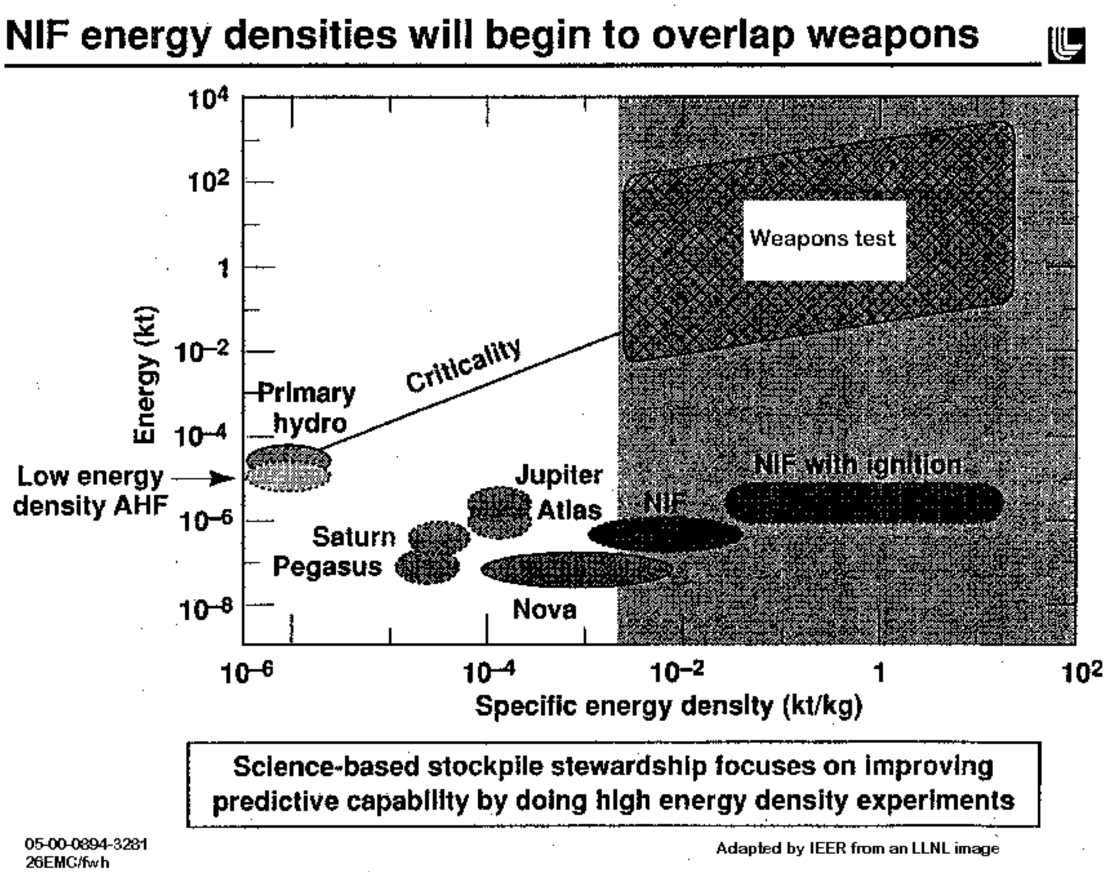
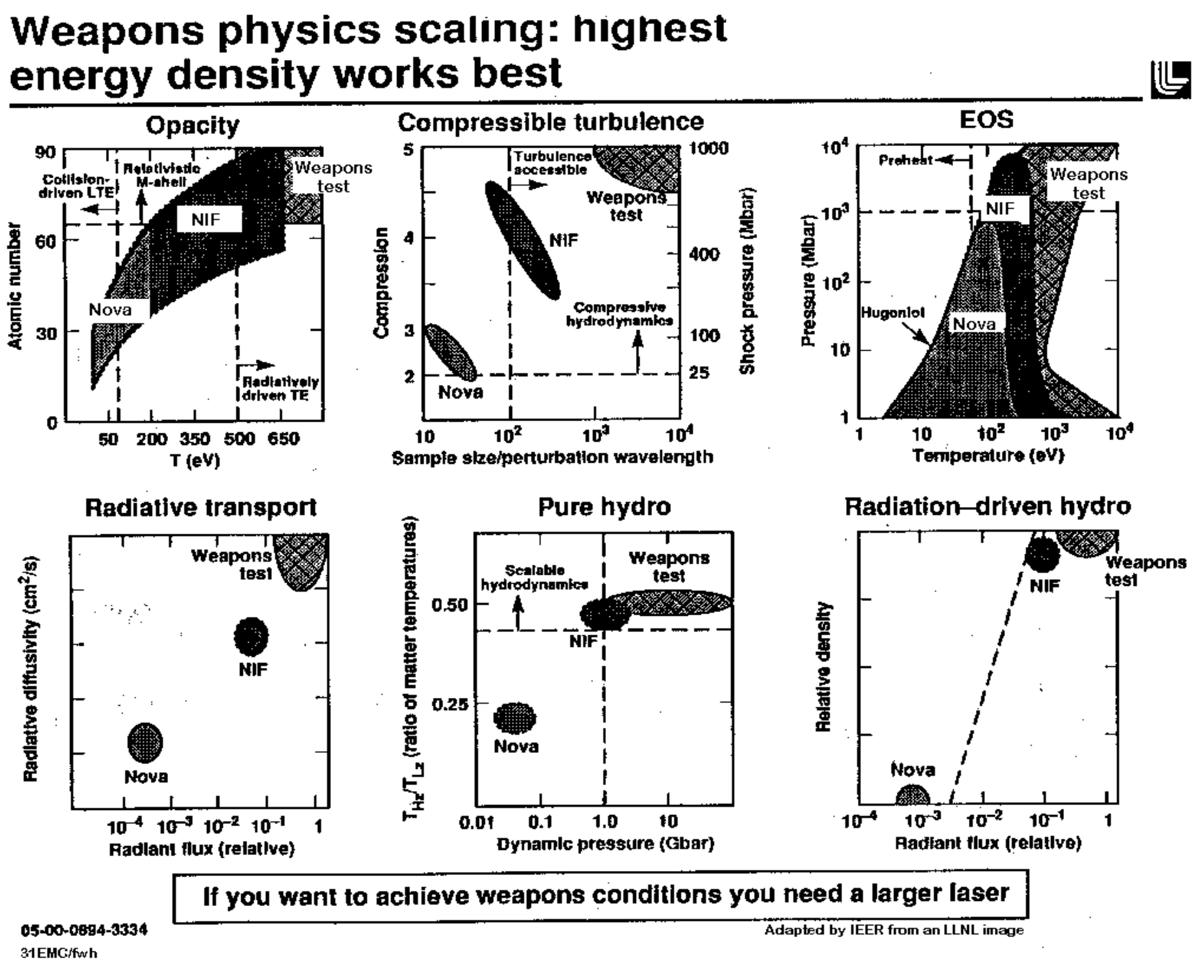


Figure 12: Comparisons of NIF with Previous Facilities and with Nuclear Tests

Source: Lawrence Livermore National Laboratory



The MTF and NIF programs have somewhat different characteristics. Though the confinement time requirement for MTF is less stringent than for ICF, the physics of MTF is more complex and the MTF program only plans for a very limited number of shots. And the goal of MTF in its present configuration is ignition of the whole volume of fuel at once, which is inefficient and requires a large amount of driver energy.[113] In contrast, NIF will be able to fire one shot every four to eight hours and its aim is to achieve spark ignition -- that is, an ignition of the central core of the fuel pellet.

The programs are complementary in some respects. Since NIF uses precise lasers which can be fired frequently, it can be used to develop pellet designs for various applications, including MTF. Similarly, the results of NIF experiments could also be used to create advances in pellets for X-ray technologies such as Sandia's wire-array z-pinch, which may be more suitable for pure fusion weapons. For instance, NOVA and NIF can be used to study the temporal shaping of x-ray pulses far better than the wire-array z-pinch. As another example, the MTF and wire array z-pinch are complementary, since the frequency of MTF experiments is very low. Hence, design of MTF devices driven by explosives could be helped greatly by experiments at other facilities such as PBFA-Z at Sandia because the MTF and wire-array z-pinch are the same in principle. They both use electromagnetic compression of a plasma by using a conductor carrying a high current.

The pulsed power experiments at Sandia and ICF experiments with lasers are also complementary. For example, experimental results from the Saturn pulsed power facility (at Sandia) are being combined with experimental results from the NOVA laser at Livermore. The resulting information is similar to that expected to be generated by experiments to be generated at NIF.[114] Similarly, one can expect that results from NIF will be combined with results from Saturn, PBFA-Z, and X-1 to yield even more information about fusion ignition. For example, rather than seeing NIF and X-1 as competitors, they are considered complementary and research on NIF would aid in designing experiments for X-1. According to Donald Cook, director of Sandia's Pulsed Power Sciences Center, "Without the knowledge of target experiments from NIF, it would take considerably longer to achieve high yield on X-1, and the risk of failure would be greater."[115]

Computers, such as those being developed for the Accelerated Strategic Computing Initiative (ASCI) would likely be used to achieve a high degree of coordination between various fusion programs. For instance, the data from NIF could be modeled using the software and hardware of ASCI. This could then enable design of

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[113] Jones and von Hippel 1998. The possibility of eventually using a "spark ignition" mode in MTF has been discussed in Siemon 1996.

[114] Olson et al 1997.

[115] Feder 1998, p. 57

targets that more closely match the requirements of the pulse shape from the x-ray machines.

This kind of coordination between various kinds of initiatives and computer modeling has precedent in the design of thermonuclear weapons. The energy release from the primary (analogous to the driver in ICF and MTF) has a certain temporal and spatial profile. In the development of thermonuclear weapons, the design of the secondary must take this profile into account. The design of pure fusion weapons could proceed along similar lines, once the scientific feasibility of the concept has been established.

2. Drivers

In addition to a properly designed target, a driver powerful enough to dump sufficient energy into a small fuel pellet to ignite the thermonuclear explosion is necessary. Many problems associated with the driver need to be solved to ignite a pure fusion explosion:

- The driver must deliver the energy to the fuel pellet uniformly to within a very narrow tolerance, so as to achieve a symmetrical explosion.
- The driver and its coupling to the ablator must be efficient enough to reduce the gap between scientific and technical feasibility.
- For weapons applications, the driver must be compact enough so that the weapon can be delivered.

Neither present nor planned ICF drivers meet all of these criteria. Therefore, even if ignition is achieved in an ICF device, it could not be used directly to make weapons. The main obstacle after achievement of ignition would be to miniaturize the driver sufficiently to make pure fusion weapons into deliverable devices.

Of the drivers that are used in research that could be applied to pure fusion weapons, lasers and accelerators are clearly ill-suited, since they probably cannot be made small enough in the near future. Therefore, the main function of these technologies for the development of pure fusion weapons is to demonstrate that ignition is possible and to study and replicate the specific conditions under which ignition is achieved. Each shot in laser fusion or accelerator devices is relatively inexpensive once the machines are built and a commitment to operate them has been made.

At the present stage, the potential drivers for pure fusion weapons are:

- Chemical explosives
- Magnetic fields or high electric currents
- Combinations of chemical explosives and electromagnetic fields

The use of chemicals alone is impractical for achieving ignition in ICF systems because of the slow speed of detonation and the difficulty of transferring the energy from the chemical explosive to the fuel pellet. However, various high-explosive-driven systems can be coupled with other electrical, magnetic or electromagnetic systems to create more suitable design approaches for pure fusion weapons. In all such systems, advanced materials manufacturing approaches as well as advanced materials could make the achievements more feasible -- for instance via the development of faster chemical explosives, smaller capacitors, and better ablators. Advanced technology using "engineered multilayers" could result in power electronic capacitors that are up to a hundred times more compact than those made with more conventional technology.[116] The most immediate prospects for miniaturization of the driver would appear to be the use of a combination of chemical explosives and miniaturized capacitors for generating high electrical currents.

Drivers could also be made smaller by improving the efficiency of the driver-ablator system. The overall efficiency of the accelerator-driven driver-ablator system is at best only on the order of one percent in the case of accelerators. It is even lower with lasers. The low efficiency stems from both the low efficiency of energy conversion in the driver itself and the low efficiency of the coupling of the driver to the ablator.

C. Overall technical prognosis for non-fission triggered nuclear weapons

Since the breakeven point between driver energy output and fusion energy output has yet to be achieved, the scientific feasibility of pure fusion weapons has not yet been established, as we have discussed. However, advances in research in the last decade, and notably in the last few years, have brought the field to the point where the development of such weapons is, for the first time, a distinct possibility.

The MTF apparatus is at present the most compact device available, if used with chemical explosives. A battery and a chemical explosive can be used as the sources of energy for the driver. A substantial neutron output has already been achieved. And no further basic conceptual breakthroughs appear to be necessary for the achievement of ignition. Jones and von Hippel have made comparisons of the lethal effects of a MTF device based upon current technologies with other weapons in order to evaluate the weapons potential of MTF. According to their calculations a system weighing 3 metric tons would have a total yield of 0.5-2.5 metric tons (with about 320 kg coming from actual high explosives). Assuming a one-ton TNT equivalent explosion, the blast effects would only come from about one-fifth of that yield. The rest of this energy would be in the neutrons. This is obviously of very little (if any) advantage over conventional high explosives if blast alone were the criteria. The blast effects could be improved by placing

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[116] Livermore 1997a, p. 14.

a layer of U-238 around the device which would fission due to the fast neutrons from the fusion reaction. Of course, this would also increase the weight of the device.

Even such a crude fusion weapon would be militarily far more lethal than a conventional explosion because the neutrons increase the lethal radius of the weapons. They would deliver a lethal dose of radiation out to a radius of 100-500 meters depending on the presence of buildings. Table 4, taken from Jones and von Hippel compares the lethal effects of conventional high explosives, an MTF weapon and sarin. Their conclusion is that MTF would be comparable to chemical weapons in lethality. The advantage of MTF weapons could increase if researchers are able to achieve fusion in a "spark ignition" mode similar to ICF rather than the less efficient "volume ignition" mode which is the expected characteristic of MTF technology. Finally, it is crucial to note that the radius of lethality of small pure fusion weapons per unit of explosive power would be far greater than that of large nuclear weapons.[117] For instance, the destructive area per ton of TNT equivalent of the Hiroshima bomb was about 0.5 x 10^{-3} km^2, which is a hundred times smaller than the lethal radius of a one ton TNT equivalent pure fusion bomb.[118]

Table 4: Lethality of Weapons

Weapon	Yield (metric tons HE)	Lethal area (km^2)[c]
1-ton high explosive	1.0	~10^{-3}
MTF device (0.5-2.5t)[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

Source: Jones and von Hippel 1998, Table 3. Reprinted with permission.
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.

It is significant to note that these calculations are based on current technology and do not take into account future technological development and potential improvement in chemicals, batteries, or the magnetic flux compression generator itself. It also does not include the dramatic increases in efficiency, and hence yield, that could be achieved if magnetic of electrical compression could be used to generate "spark ignition" in a plasma. As discussed above, the driver energy required would then be greatly reduced for the same fusion energy output. Thus, the overall energy gain would be much higher, increasing the practicality of a pure fusion weapon.

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[117] As nuclear weapons get larger, the destructive area per unit of explosive power declines.

[118] The preceding section comes from Jones and von Hippel 1998, Appendix B

Moreover, it is remarkable that it appears that an existing apparatus could, in principle, be used to make a pure fusion explosive, though it should be kept in mind that ignition has not yet been achieved. The very possibility shows that we may be on the verge of a qualitatively different era in nuclear weapons. This is because there is generally a far smaller gap between the achievement of technical feasibility and a workable weapon than between initiation of scientific research and the establishment of technical feasibility. Recall that the first fission-driven thermonuclear explosion was not a weapon at all, since it was far too large to be deliverable. It required considerable design changes to achieve a deliverable weapon. Yet such changes were accomplished in less that one-and-a-half years. This is largely because data from the successful explosion enabled a critical revaluation of pre-explosion experiments and theory.

Another technology that complements ICF and MTF programs is the wire array z-pinch developed at Sandia National Laboratory (see Chapter 3). It has already achieved an x-ray energy of 2 MJ and power of 290 trillion watts (terawatts), for a few nanoseconds.[119] This huge x-ray power could be focused on the ablating surface of a fuel pellet. Since this closely follows the Teller-Ulam approach to ignition of the secondary, the wire array z-pinch is considered an important tool for weapons research. Note that the x-ray energy already generated in the wire-array z-pinch is larger than the 1.8 MJ of laser energy planned for NIF several years into the next century. The next z-pinch facility desired by researchers is called the X-1; it aims for an x-ray output of about 16 MJ.[120]

In sum, Magnetized Target Fusion, the ICF experiments in NIF and Laser Mégajoule, and x-ray generation and plasma compression experiments in the wire-array z-pinch at Sandia could together provide powerful ways in which pure fusion weapons or fusion-driven nuclear weapons could be designed. Experimental results from these programs could yield pure fusion weapons designs on a far shorter time-scale than would be possible with the MTF program alone.

D. Fusion power and fusion weapons - comparative requirements

Once the technical feasibility of pure fusion weapons is established, the weapons could be created in a variety of sizes. If a laboratory-scale D-T mixture is burned with an efficiency of thirty-three percent (a typical efficiency for planned ICF machines), then the explosive yield would be equivalent to about 20 kilograms of TNT[121] A surface

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[119] The duration is calculated from the total energy of 2 megajoule divided by the power output of 290 terawatts. See Singer 1998.

[120] Ramirez 1997, p. 159.

[121] In a commercial energy production scheme, the unused deuterium and tritium would be recovered outside the reaction chamber.

explosion of this size would create a crater about ten feet in diameter.[122] At the other end of the spectrum, huge megaton-size explosions can also be created from fusion reactions. This happens when thermonuclear weapons are detonated. Hence, in contrast to fission weapons, where even "small" explosions are very large – usually the equivalent of hundreds of tons of TNT -- pure fusion weapons could range in explosive power from small to huge.[123]

ICF has also been proposed as the basis for possible commercial power production because explosions of tens or even hundreds of kilograms of TNT equivalent can be contained inside vessels. In an ICF scheme using five-milligram fuel pellets, about 5 explosions per second would be sufficient for a 1,000-megawatt (electric) power plant (about the size of a commercial nuclear reactor). However, achieving this rate of explosions in a practical ICF machine and extracting the energy contained in the neutrons from the reaction chamber poses severe technical challenges

Most of the problems that need to be solved to produce pure fusion weapons are the same as those that face power production from inertial confinement fusion. As a result, though the initial impetus for ICF programs was weapons design (more specifically to help in the design of conventional two-stage thermonuclear weapons), they have, in time, come to have a dual justification -- one for the development of weapons and the other for the development of commercial power from thermonuclear reactions. Even today, producing pure fusion weapons (as opposed to conventional thermonuclear weapons with fission triggers) is not a stated goal of the program, so far as public information goes.

However, the degree of difficulty of producing pure fusion weapons, while enormous, is lower in most respects than that confronting commercial power production from ICF. There are two broad sets of reasons that pure fusion weapons could be built before pure fusion power plants. The first involves economics, the second the technology needed for fusion power production.

First, economics is not as much a central consideration in weapons development as it is with commercial power applications. For instance, the efficient use of tritium and deuterium, central to commercial power production, does not pose the same severe constraints when the objective is to develop pure fusion weapons. The reduced efficiency requirements for pure fusion weapons, while still enormously challenging, could probably be achieved sooner than the very high efficiency explosions needed for commercial ICF devices. Another economic consideration relates to fuel pellet design

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[122] Cooper 1996, page 425, Figure 29.4.

[123] Small fission explosions are possible, but they usually waste almost all the fissile material needed to start the chain reaction. It should be noted, however, that in most fission-triggered thermonuclear weapons a substantial part of the explosive energy from the secondary derives from fission reactions. "Small" fission explosions have been brought down to the range of 10 tons of TNT equivalent.

and cost. Commercial fuel pellets must be very cheap to be competitive – far cheaper than need be the case for fusion weapons.

Secondly, there is no energy capture and conversion step needed for weapons. The arrangements to capture the neutron energy from the D-T reactions outside the reaction chamber, the generation of tritium fuel on a continuous (or near-continuous) basis, considerations of durability of machines under heavy bombardment of macroscopic explosions and of neutron radiation together constitute formidable obstacles to ICF fusion power development. Finally, there is a further loss of efficiency by a factor of two or three in conversion to electricity. Weapons design does not have to contend with any of these problems. The main technical issue that is more difficult with weapons than power is that weapons require compactness. Specifically, the miniaturization of the driver that is required for pure fusion weapons poses major challenges.

Similar arguments can also be made for MTF research. In fact, as Jones and von Hippel have noted, the more efficient a laboratory device becomes, the greater the concern regarding the potential of the device to lead to pure fusion weapons.[124]

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[124] Jones and von Hippel 1998, Appendix C.

Chapter 5: Nuclear Disarmament and Non-Proliferation Issues Related to Explosive Confinement Fusion

One of the central military and disarmament issues facing the international community today is to decide whether pursuit of research whose aim it is to achieve pure fusion explosions in the laboratory is compatible with disarmament goals and treaties, including, most importantly, the Comprehensive Test Ban Treaty. The development of pure fusion weapons is now a distinct possibility, though it is not a certainty, since their scientific feasibility remains to be established. One central challenge to disarmament and non-proliferation today is that the scientific feasibility of such weapons could be established using the same devices that are being promoted as essential for the ratification of the Comprehensive Test Ban Treaty (the treaty has been signed by about 150 countries, with the notable exceptions of India and Pakistan, since September 1996). The nuclear weapons powers, notably the United States and France, have programs for the "stewardship" of their existing stockpiles of nuclear weapons. As part of their stewardship programs they are building or operating facilities that will be used to maintain the skills of nuclear weapons designers, and which could be sued to develop a qualitatively different class of nuclear weapons. ICF facilities and research are an important part of these programs. Since its May 11 nuclear tests, India has also announced its own stockpile stewardship program.

The stated goals of the US stockpile stewardship program are to maintain the safety and reliability of existing weapons. We have shown in a previous report that most of the US program of SBSS is marginal or irrelevant to nuclear safety.[125] We have also argued that fusion facilities such as NIF and the proposed X-1, are not relevant to maintaining the reliability of current nuclear weapons, particularly if the United States were to adopt a nuclear policy based upon deterrence rather than first-strike. The evidence for this conclusion is summarized below.

Pursuit of programs with explicit potential for designing new nuclear weapons is counter to Article VI of the NPT and to the CTBT. This applies whether the new weapons follow on current generation fission-triggered weapons or are part of an entirely new class of weapons, such as pure fusion weapons. In this context, it is worthwhile to recall that Article VI of the NPT relates, among other things, to the "cessation of the nuclear arms race at an early date."

ICF researchers claim that their research could also lead to commercial power production from fuels that are widely available and plentiful. However, the energy applications of any explosive fusion research should be justified on their own merits and

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[125] Zerriffi and Makhijani 1996. See below for a discussion of some of the findings of this report.

in comparison to other energy projects. Many environmentally sound energy technologies are much further ahead than ECF and yet receive far fewer resources. Further, ECF approaches will take decades to develop into economical energy sources, if they prove feasible at all. The fact that large resources have been spent over decades on fusion power research without even establishing scientific feasibility needs to be more carefully considered, given the urgency of reducing greenhouse gas emissions. Military rationalizations and the relatively great pull of nuclear bureaucracies on governmental energy programs seem to be the forces driving ECF programs rather than serious evaluations of the world's energy and environment needs.

There is no question that NIF, pulsed power devices like the wire array z-pinch, and MTF have nuclear weapons design as one of their goals, as the following two quotes from a 1986 National Research Council Report Illustrate.

> "The objective of the ICF program is to achieve a small thermonuclear (TN) explosion in the laboratory for the purpose of weapons physics studies, for studies of weapons effects on systems, and, in the longer term, as a possible energy source."[126]

> "A convenient laboratory source of 1000 MJ [megajoule] thermonuclear explosions would be an extraordinary tool for exploring the physics of thermonuclear weapons. Some concepts on how to use nuclear weapons as sources of directed-energy-like x-ray lasers or microwave beams could be tested in a laboratory setting quickly and interactively….Extensive experimental campaigns and careful systematic studies of physics issues, which would be prohibitively expensive for underground testing, could be carried out with an ICF facility."[127]

Weapons physics and nuclear weapons design is still a goal of the ICF program, now under the rubric of the Stockpile Stewardship program. Allowing nuclear weapons designers to gain greater experience in design is one of the goals that has been declared necessary for the stewardship of existing weapons. While the weapons design goals that have been announced relate to fission-triggered warheads, the same research will also advance the establishment of the scientific feasibility of pure fusion weapons. That goal has not been announced, as it would be provocative to do so and would make international opposition far more likely and the pursuit of pure fusion weapons research far more difficult.

The legality of ICF, wire-array z-pinch, and MTF programs under the Comprehensive Test Ban Treaty remains in question. The DOE has determined that the Stockpile Stewardship program in general and NIF in particular are not proliferation risks. The JASON committee, which evaluated the stockpile stewardship program for DOE, concluded that NIF is "an extremely sophisticated challenge, not one which could conceivably be undertaken by, or be useful to, a potential proliferator," especially since

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[126] NAS-NRC 1986, p. 2.

[127] NAS-NRC 1986, p. 35.

the basics of simple nuclear weapons designs are already widely available.[128] The JASON report also concluded that the SBSS program would actually contribute to the goals of non-proliferation by allowing the United States to sign the CTBT.[129] A specific review of NIF done for the DOE by the Department's Office of Arms Control and Nonproliferation reached similar conclusions.[130] A report done by Dr. Ray Kidder, a former nuclear weapons designer and one of the originators of the ICF program at Lawrence Livermore National Laboratory, for the Arms Control and Disarmament Agency concluded that an ICF research team constituted a de facto weapons research team and that information would come from the following three source:

- A technical library with information on the basic science necessary for designing nuclear weapons. This would be the most important source of information;
- Publication of ICF research from non-nuclear weapon states with advanced ICF research projects;
- The ICF programs of the nuclear weapons states. This would be the least useful due to the classification of large portions of ICF research in the nuclear weapons states.[131]

Kidder concluded that information relevant to nuclear weapons design would become public. However, he concludes that projects such as NIF don't form a proliferation risk because they are not replacements for full-scale nuclear tests. He also concludes that existence of an ICF research team in a non-nuclear weapon state would increase the readiness of that state to design nuclear weapons, but would not "represent nuclear weapons proliferation per se."[132] However, it should be noted that all of these conclusions, whether one agrees with them or not, were made in the context of present generation thermonuclear weapons and did not take into account the relevance of ICF research to advanced weapons, such as pure fusion weapons.

Though significant technological hurdles to successful ICF development still exist ICF and other fusion programs pose a number of important proliferation problems that deserve far more public debate than they have received:

- In the short-term, inertial confinement fusion programs can be used to develop new thermonuclear weapons with fission triggers, thereby undermining the spirit of the Comprehensive Test Ban Treaty and Article VI of the Nuclear Non-Proliferation

[128] Drell 1994, p. 55.

[129] Drell 1994, p. 54.

[130] DOE 1995.

[131] Kidder 1995, p. 5.

[132] Kidder 1995, p. 5

Treaty which commits the recognized nuclear weapons states to good faith efforts to end the nuclear arms race and towards disarmament.

- Fusion power for commercial applications is likely to be more technically feasible and more economical if it is combined with fission power development and the production of plutonium. Thus, the development of fusion power technologies could, in the long-term, provide new arguments for creating an infrastructure for plutonium production, processing and use.
- The achievement of ignition in ICF and similar devices is likely to result in the injection of even larger amounts of money into technological improvement of ICF technology, making pure fusion weapons more feasible.

A. The Science Based Stockpile Stewardship Program

The Science Based Stockpile Stewardship (SBSS) program is a multi-billion dollar effort encompassing a variety of facilities and sites, including all three weapons laboratories, and the Nevada Test Site. Facilities will be built or upgraded to allow weapons physicists to study all stages of a nuclear explosion, as well as providing the capabilities to create realistic 3-D models of weapons through the Accelerated Strategic Computing Initiative (ASCI). One of the main stated objectives for the SBSS program is to maintain the safety and reliability of the existing arsenal as the weapons age. This would be accomplished by developing a complete understanding of the physics involved in thermonuclear explosions and the modeling of weapons. (Another is to maintain weapons design teams and give them interesting work to do.)

A detailed examination of the safety and reliability justification for SBSS, based upon DOE's historical data concerning problems found with warheads in the arsenal, can be found in Zerriffi and Makhijani 1996. In the context of the present discussion, it suffices to note that fusion facilities such as NIF play no role in maintaining the safety of aging weapons. Nuclear weapons safety is an issue which affects the primary of the warhead (specifically, preventing accidental detonation of the primary). Fusion reactions (whether they be D-T fusion in the boosted primary or in the secondary) do not occur until after the fission detonation has already occurred. Safety is, at that stage, a moot point. Furthermore, DOE's own data has shown that aging has not affected the safety of a single nuclear component (either primaries and secondaries) in the entire history of the weapons program. Aging can affect the safety of some non-nuclear components, but this is a separate issue. The National Ignition Facility, the MTF program, the wire-array z-pinch are also all irrelevant to these non-nuclear safety issues. This leaves the issue of warhead reliability.

1. Reliability

The DOE's reliability justification for the SBSS program is problematic on three counts:

a) the DOE's definition of reliability

b) the expectation of future reliability problems

c) the relevance of NIF to addressing reliability problems of stockpiled weapons.

We will discuss these three issues in turn.

<u>a. Reliability definition</u>

DOE considers a warhead unreliable if it does not explode at its stated yield and at the correct target parameters (e.g. burst height). This definition of reliability is only necessary if the stated objective is to eliminate the hardened silos containing an adversary's nuclear weapons. Moreover, the DOE also considers a warhead unreliable even if the yield is above the design rated value, but if the accuracy is less than the warhead's specifications. In brief, the DOE's definition of reliability corresponds to a nuclear force maintained for the purpose of counterforce strikes, first use, and nuclear war-fighting capability.

If the objective is simply to deter a nuclear attack, then it is reasonable to assume that the belief on the part of a potential adversary that US warheads would be used in retaliation for an attack and that they would perform reasonably well would be sufficient. Declines in primary yield up to a certain point would be unlikely to cause the failure of the secondary to detonate. Hence, any overall performance decreases (resulting from lowered primary yield which is still sufficient to detonate the secondary) would be irrelevant to second strike deterrence.

This leaves the issue of threshold effects that may cause the failure of the secondary if the yield of the primary drops below a certain level. Adopting this level as a criterion, coupled with a substantial relaxation of accuracy requirements, would provide a different approach to reliability that would not be so clearly linked to counterforce doctrine. This would be more than sufficient for second-strike deterrence. Even in the case of the failure of the secondary and the primary fusion booster, the fission portion of the primary would still provide a huge explosion, estimated to be between several hundred tons and a few kilotons of TNT equivalent.[133] Such explosions, while far smaller than design basis explosions of several hundred kilotons typical for strategic warheads, would be hundreds of times larger than the terrorist bomb that destroyed the Alfred P. Murrah Federal Building in Oklahoma City. Thus, second-strike deterrence

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[133] Martin Kalinowski and Lars Colschen calculate that eliminating the booster and hence the secondary from US warheads would reduce their yields from a typical level of several hundred kilotons to figures in the range of a few hundred tons to a few kilotons of TNT equivalent in all but one case. In the case of the W89, the removal of the tritium bottle would cause the warhead not to operate. The overall effect of removing tritium from all warheads is estimated to be a reduction of cumulative yield by roughly two orders of magnitude. Kalinowski and Colschen 1995, p. 191.

does not actually require consistent secondary detonation or even the consistent functioning of the booster in the primary of a nuclear warhead. No adversary of the US would strike first under the assumption that the secondaries of the weapons used for retaliation would be less likely to go off.

Another major issue is the US nuclear weapons posture in light of its obligations under Article VI of the NPT. In its advisory opinion on nuclear weapons and war, the World Court unanimously decided that this article of the NPT required nuclear weapons states parties to actually achieve complete nuclear disarmament.[134] One reasonable way to approach this goal so far as nuclear weapons reliability is concerned would be to remove permanently from the stockpile weapons that are deemed unsafe or unreliable.

Finally, we should also note the destabilizing effects of pursuing the SBSS program with a counterforce reliability definition. A counterforce definition of reliability would be dangerous at any time, but is especially so in a time when command and control in Russia are thought to be deteriorating. Fear of a first strike is a central reason for the US and Russia to keep their nuclear forces on hair-trigger alert. This launch on warning posture (commonly called a "use-it-or-lose-it" policy) is highly dangerous because it could result in large-scale accidental nuclear war.[135] The United States, in its own self-interest should abandon a policy of that increases fears in Russia of a possible first strike because it would reduce the incentive for Russia to keep is forces on hair-trigger alert. DOE's definition of reliability sends the contrary message and hence increases nuclear dangers.

b. Future reliability problems

The historical data analyzed by IEER in its report *The Nuclear Safety Smokescreen*[136] indicate that aging-related reliability problems do not appear to be significant when it comes to nuclear components, particularly secondaries. Of the 186 different types of reliability problems found with the arsenal, only eight affect secondaries. However, even that overstates the problem. Seven of those eight were actually operation (performance/yield) problems. These problems are not related to whether or not the weapon will explode, simply whether it will explode at its rated yield. This returns to the question of the definition of reliability used by DOE. It should be

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[134] The Court stated that "[t]here exists an obligation to pursue in good faith and *bring to a conclusion* negotiations leading to nuclear disarmament in all its aspects under strict and effective international control." (emphasis added) The obligation of all states is to "achieve a precise result - nuclear disarmament *in all its aspects* - by adopting a particular course of conduct, namely, the pursuit of negotiations on the matter in good faith." *Legality of the Threat or Use of Nuclear Weapons,* General List No. 95 (Advisory Opinion of 8 July 1996), paras. 99, 105(2)(F). See also Burroughs 1997, pp. 2-3, 48-51.

[135] Blair 1995.

[136] Zerriffi and Makhijani 1996.

noted that only one reliability problem type affecting secondaries was related to aging. Therefore, since the early 1950's when the Stockpile Evaluation Program was started, there has been only one type of aging-related reliability problem found. What should be more relevant to the DOE is the larger number of aging-related reliability problems found with non-nuclear components, components which can be replaced and/or redesigned and tested separately from the rest of the warhead. NIF would have no relevance to these problems.

c. Relevance of NIF to reliability of the current stockpile

Even if reliability problems do occur in secondaries and they are deemed important enough for action to be taken, it has not been demonstrated that fusion facilities such as NIF would be of material benefit. The most prudent approach in such a case would be to either replace the secondary with a spare or to remanufacture the component. Remanufacture as a means of maintaining the stockpile has been put forward by a number of experts in the field as the proper means to achieve the goal. Furthermore, using NIF to fix problems with the secondaries could actually result in more problems, and perhaps create a push for resumption of nuclear testing. If a problem were found with a secondary and NIF experiments were designed to study aspects of the problem, it would result in modification of the computer codes used to model the weapons. Currently, the computer codes have been validated by comparison to data from underground tests. It is possible that, as the codes are modified to reflect experimental data from NIF (or other facilities), they will deviate more and more from the phenomena occurring in the weapons, which are different and, in some ways, more complex. In particular, NIF fuel pellets will be driven by lasers, while nuclear weapon secondaries are driven by the nuclear explosions in the primaries of the warheads. While the geometries of indirect-drive ICF and thermonuclear weapons are similar, and both are compressed by x-rays, there remain differences which need to be accounted for in transferring knowledge about one to the other. These differences, such as the geometry of the devices and the use of uranium casings in weapons, will likely create uncertainties that could lead to a push to re-validate the revised computer codes with new underground tests. This would require a US withdrawal from the CTBT – a step that would be likely to have major adverse proliferation consequences. It is crucial that the ban on testing be maintained by CTBT signatories and extended to all other states. Factors that would aggravate the risk of a CTBT breakdown should be eliminated as far as possible. Stopping the construction of NIF would be one step in that direction.

2. The US laser fusion program as a weapons development program

The US laser fusion program has traditionally been a component of the weapons development program. Prior to the cessation of nuclear testing, NOVA and other facilities of a similar nature were used to explore the same physical processes as NIF, albeit at lower pressures, temperatures, and energies. This information was used in the weapons design process; final proof of designs slated to enter the US nuclear arsenal was always through nuclear testing.

Official DOE statements on the SBSS program and the National Ignition Facility demonstrate the inconsistencies inherent in the program. On one hand, there are many statements that refer to the necessity of underground testing for developing new weapons, thereby implying that new designs cannot now be developed in the context of a CTBT. DOE also point to the fact that there are no requests from the DOD for new weapons designs as "proof" that SBSS is not aimed at weapons design. On the other hand, one of the stated purposes of the SBSS program is to attract and retain weapons designers and to provide them with the opportunity to practice their skills. According to the DOE, this is necessary in the eventuality that requirements for new nuclear weapons (presumably originating from the military) develop.

The DOE's Stockpile Stewardship and Management Plan, also known as the "Green Book," provides a good indication of the view DOE takes towards future weapons design work. It states:

> The nuclear weapons design capability will be maintained by pursuing an understanding of the underlying physics of nuclear weapons and exercising the process of design of nuclear weapons. This includes material properties, hydrodynamics, radiation transport, and neutron transport as well as many other physical processes that occur in the operation of a nuclear weapon. Advanced computational capabilities will be required to adequately address concerns if the design laboratories are forced to deviate from designs that have been verified through nuclear testing.[137]

The National Ignition Facility is supposed to play a key role in maintaining the design expertise for new weapons. This desire to maintain *and exercise* design capabilities is not an abstract conjecture. The Green Book also discusses two replacement nuclear designs, one of which would require fabrication of new plutonium pits. It would not, however, require nuclear testing:

> The technical approach for the new design candidate warhead is to use large design margins for critical components; warheads would be certifiable without nuclear testing. … Both of the replacement design options will be prototyped and flight tested, but no final development activities will be initiated until a decision is made to proceed. The nuclear design activities of this program will be broadly based and will provide present and future weapon scientists and engineers with the opportunity to exercise the complete set of skills required to design and develop a stockpile warhead.[138]

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[137] DOE 1996 "Green Book", p. VII-3.

[138] DOE 1996 "Green Book," p. V-10.

In view of the statements, it is quite conceivable that DOE weapons scientists would conduct at least preliminary design investigations of pure fusion weapons if and when the necessary data become available. DOE's rationale allows nuclear weapons scientists the opportunity to practice their design skills. The design of pure fusion weapons would fit in with this DOE policy.

3. Other countries

The United States is not the only country with an active research program into ICF or MTF. All five of the declared nuclear weapons states have facilities for conducting experiments in ICF. Other countries also have ICF research facilities. A half dozen additional countries have either laser or particle beam facilities that are, at least partly, devoted to the study of ICF. In some cases, these facilities are fairly small, such as the single beam facilities in India, South Korea, and Israel. (Nonetheless, India and Israel have probably used the research done at these facilities to design their nuclear weapons.) However, other operating or planned facilities rival the capabilities present and planned for the US ICF program. In France, a facility very similar to NIF is planned. Laser Mégajoule would be built near Bordeaux, and like NIF in the US, it is considered a part of the French program for stewardship of their nuclear arsenal (the equivalent of SBSS, called Palen).

The Japanese in particular appear to have reached a high level of sophistication in their ICF laser program. In Osaka, the twelve beam Gekko-XII facility operates between 15 and 30 kJ with pulses between 0.1 and 10 nanoseconds. This facility has already reached a neutron production level of approximately 10^{13} neutrons per shot. The planned facilities in Japan are almost as ambitious as those of the National Ignition Facility or laser Megajoule. The Kongoh laser facility would use 92 beams to achieve 300 kJ in 3 nanoseconds

Germany's research efforts have been focused largely on heavy ion beam fusion. Beam research is ongoing at a number of facilities and a working group has been organized to develop a design of a heavy ion beam facility to achieve ignition. This research group involves scientists from a number of countries but is organized at a German institute.

B. Proliferation

Controlling the proliferation of fission or thermonuclear weapons is already a challenging task. It involves complex inspection systems and the monitoring of facilities which produce the basic elements necessary for weapons: highly enriched uranium and/or plutonium.

The materials accounting process for fusion research would also pose significantly greater challenges. The enrichment of uranium or the separation of plutonium involve large, costly, and readily identifiable facilities, making access to weapons-usable fissile materials the central restraint on proliferation (hence the concern over the availability of fissile materials from the former Soviet Union). In countries with light water reactors, it is possible to determine when fuel was removed since the reactor must be shut down for refueling. The radioactivity of the fissile materials also allows for certain techniques of monitoring. In short, the difficulties of obtaining fissile materials or concealing production facilities for them are the main ways to control the proliferation of fission weapons.

While fission power and fission-based nuclear weapons share obvious links, the operation of fission power plants and civilian fission research does not involve creating fission explosions. Hence, commercial nuclear fission is one more step removed from weapons work than ICF programs.

Pure fusion weapons, if developed, would present far stiffer challenges. Unlike fission reactor research, there is no separation of weapons and energy research in ICF. Explosions are needed for both applications. Therefore, any research into fusion explosions for energy purposes necessarily and directly provides information on fusion explosions for military purposes. While there can be some separation through experiment design (as there is supposedly going to be at NIF), this is not inherent in the facilities' capabilities. Furthermore, fusion research is occurring in a large number of countries and a wide variety of institutions under the rubric of commercial energy research. Much of the literature is already unclassified and will continue to be so. Some of the most advanced machines are planned for countries that are not now nuclear weapons states.

If pure fusion weapons were developed, the restraints on proliferation via materials control would be weak and, in the long term, could disappear altogether. Initially, control of tritium production might provide an avenue for limiting proliferation. But tritium can be produced in commercial reactors (through the use of lithium target rods in light water reactors or by the extraction of the tritium produced in heavy water reactors, like CANDUS, due to the conversion of deuterium to tritium).[139] Separation facilities are also needed to extract the tritium for the target rods, but these are less complex than those for extracting plutonium from irradiated reactor fuel and could be more readily developed and operated.

Tritium is hard to detect if it is properly shielded and put into appropriate containers, making development of effective radioactive and monitoring systems very difficult, although not impossible. Further, tritium is currently not under international safeguards and there are no official plans for such safeguards. In fact, the US is in the process of greatly loosening restraints. It has initiated a program to produce test

[139] See Makhijani and Saleska 1996.

quantities of tritium for its weapons program in commercial nuclear reactors and may initiate a large-scale program for military tritium production in commercial reactors owned by the Tennessee Valley Authority. Even more troubling, however, is the possible future use of lithium and deuterium in either fusion research or in potential fusion weapons programs. While this is speculative at present so far as pure fusion weapons are concerned, it is important to note here that the thermonuclear component of fission-triggered nuclear weapons consists of a combination of these two elements in the form of lithium-deuteride. Both lithium and deuterium are non-radioactive and are readily available. There will be essentially no way to control their production or to keep track of it.

In the short term it is necessary to bring tritium stockpiles under international safeguards. This would provide a small but not sufficient measure of restraint. Perhaps more importantly, tritium production for weapons should be halted as it is inconsistent with nonproliferation and disarmament goals. (Commercial requirements are far smaller than weapons and can be met from current stockpiles and by-products from Canadian heavy water reactors).[140] Certainly, the program in the United States to develop a new tritium production source should be halted since it is unnecessary. Current tritium supplies are more than adequate to meet US stockpile needs if further efforts towards reducing the number of nuclear weapons are made.[141]

C. CTBT and ICF

Article I of the Comprehensive Test Ban Treaty states:

1. Each State Party undertakes not to carry out any nuclear weapon test explosion or any other nuclear explosion, and to prohibit and prevent any such nuclear explosion at any place under its jurisdiction or control.
2. Each State Party undertakes, furthermore, to refrain from causing, encouraging, or in any way participating in the carrying out of any nuclear weapon test explosion or any other nuclear explosion.[142]

The United States government, both in previous judgments and in its submission of the treaty to the US Senate for ratification, has stated that ICF and other similar experiments are not covered by the treaty's ban on explosions. The rationale is that these are not nuclear weapons explosions. The United States is not alone in this interpretation.

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[140] See Kalinowski and Colschen 1995.

[141] It is estimated that tritium stocks for the US stockpile could last until 2032 if the United States were to reduce its arsenal to 1,000 warheads (a level above the most recent National Academy of Sciences recommendation). At a level of 500 warheads tritium stocks could last a little beyond 2040. See Zerriffi 1996 for details on tritium requirements for US nuclear weapons under various scenarios.

[142] U.S. Senate 1997, p. 124.

Germany also regards experiments in controlled thermonuclear fusion to be exempt from the treaty. However, the design implications of stockpile stewardship programs, including NIF and similar programs, has caused widespread concern and is one reason India was not a signatory to the CTBT in 1996 (though it may now sign in the context of its own nuclear tests and planned stockpile stewardship program).

The main US statement in regard to pure fusion was made in the context of an interpretation of the Non-Proliferation Treaty. In 1975, in response to Swiss concerns about laser fusion research, the United States declared: "Such contained explosions area not 'other nuclear explosive devices' in the sense of the NPT and research in this area is allowed under Article IV.1."[143] A more detailed statement followed and was quoted in the transmittal of the CTBT to the U.S. Senate for its advice and consent:

> Concerning ICF, the U.S. statement made at the 1975 NPT Review Conference established that energy sources "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" do 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." Thus, such energy releases at the planned National Ignition Facility, as well as at existing facilities such as the NOVA laser facility, are not considered nuclear explosions and are not prohibited by the Treaty.[144]

The thrust of the NPT was to bar non-nuclear weapon states from acquiring "nuclear explosive devices." The US statement was only to the effect that laser facilities are not such "devices" and their operation by non-nuclear weapon states is therefore permissible under Article IV, allowing them to conduct research into "peaceful" uses of nuclear energy.

The CTBT negotiations have created a different record and a different set of restraints. First, the CTBT does not concern "nuclear explosive devices." Rather it bans *any* "nuclear explosion," including "peaceful nuclear explosions," by *any* state, and is intended to constrain weapons development. It also requires signatories to "prevent" nuclear explosions from occurring in their jurisdiction. Second, the negotiations involved extensive discussion of allowing some fission explosions. Specifically, the US position initially was that the CTBT should allow for hydronuclear testing which would yield up to four pounds of nuclear explosive energy. Eventually, a treaty was signed that excluded all nuclear explosions, including low yield hydronuclear tests. The US stated

[143] NPT/CONF/C.II/SR.5, 1975

[144] U.S. Senate 1997, pp. 4-5.

that sub-critical tests would be permitted under the CTBT because they did not achieve self-sustaining nuclear reactions and did not involve nuclear explosions.

This negotiating record indicates that fusion nuclear explosions equivalent to fission hydronuclear tests would be prohibited under the CTBT. Even planning for such explosions would appear to be prohibited, since the treaty requires parties "to refrain from causing, encouraging, or in any way participating in the carrying out of any nuclear weapon test explosion or any other nuclear explosion." Yet, facilities such as NIF would, if they work as their designers hope, cause nuclear explosions that are considerably larger than four-pound hydronuclear tests.

In light of the possible illegality of facilities such as NIF and LMJ, greater discussion over the interpretation of Article I is necessary. A number of factors could go into the interpretation of Article I, such as results of future CTBT Review conferences and, possibly, an opinion by the International Court of Justice. In any event, this is a question that should be answered before further work proceeds on NIF, MTF and other projects designed to achieve thermonuclear ignition.

At the heart of interpreting Article I is the definition of a nuclear explosion. Determining a workable definition is actually quite complex and somewhat arbitrary because an explosion is an interplay between total amount of energy released, energy density, and the time in which the energy is released. The time factor is perhaps the easiest. While there is no single definition of reaction time suitable for all explosions, we adopt the approach suggested by Richard Garwin and use one millisecond for the purposes of this discussion of nuclear weapons.[145] This is long enough to cover experiments most likely to assist in pure fusion weapons development. It would also automatically exclude chain reactions in fission reactors as well as fusion research based on steady-state magnetic confinement (e.g., tokamaks which are doughnut shaped facilities that use magnetic fields to confine the plasma for relatively long periods of time) from the definition of nuclear explosions. These exclusions are necessary since steady state nuclear reactions are clearly not prohibited by the CTBT, which is confined to banning nuclear explosions.

It is more difficult to pin down an exact number for the total amount of energy released and energy density that would characterize an explosion. Nuclear explosions have been defined in various ways. However, these definitions have only been made for fission explosions. In addition, limits have been proposed for fusion research under the CTBT. However, these limitations have not been based upon a technical definition of fusion explosions.

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[145] Garwin 1997, p.9. Garwin proposes that one millisecond be used to separate the explosive regime from the steady-state regime.

We can begin our exploration of the definition of fusion explosions by reference to better established fission explosion guidelines. The following are two definitions of fission nuclear explosions based upon two different physical criteria:

- Criticality Definition: As we have noted above, the US has used the threshold of criticality (the achievement of self-sustaining fission reactions) to define nuclear explosions of fissile materials. Under this definition the sub-critical experiments involving high explosives and fissile materials conducted at the Nevada Test Site are deemed to be allowable under the CTBT. While the sub-critical experiments pose their own problems in that they allow for continuation of weapons design, they provide a convenient starting point for determining a definition of fusion explosions.
- Specific Energy Release Definition: A 1987 Los Alamos report on the testing moratorium of 1958-1961 states that "a nuclear explosion has never been defined officially, but we consider a reasonable definition to be a specific fission energy release that is comparable to or greater than that of high explosive itself, about one kilocalorie per gram."[146] In other words, the release of nuclear energy in an explosive fashion is not really an explosive unless the energy released is greater than the energy used to initiate the explosion.

A technical definition of a fusion nuclear explosion is needed in order to determine what experiments meet the letter of the CTBT. We recognize that, as with fission explosions, any definition will be arbitrary to a certain degree. Our review of the issue leads to the conclusion that the best definition for fusion explosions should rely upon the concept of ignition. Ignition has been defined in two different ways:

1. The creation of a self-propagating burn wave in the fuel pellet. This is a concept analogous to the concept of criticality in fission explosions.[147]
2. A gain of one. In other words, the fusion energy output of the fuel pellet is equal to the driver energy output. A gain of one is needed to demonstrate scientific feasibility of ignition.[148]

Ignition as a concept is analogous to both the definitions of fission explosions discussed above. However, it is far more difficult to define because there is no unambiguous physical phenomenon to which we can tie the practical onset of a fusion explosion. A propagating burn wave (our first definition) can be achieved at gains different from and less than one. For instance, it is projected that burn propagation in NIF would occur at a gain of about 0.3.[149] In a physical sense the first definition more

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[146] Thorn and Westervelt 1987, p. 4.

[147] Lindl 1995, p. 6.

[148] NAS-NRC 1997, pp. 10-11.

[149] NAS-NRC 1997, p. 11.

directly corresponds to the concept of criticality. However, the precise gain at which the self-propagating burn wave is created is device dependent, and the onset of a burn wave would be difficult to measure and verify.

For the purposes of CTBT compliance, a minimally satisfactory definition of a fusion explosions would be a gain of one. Under this limit the energy released would always be less than the driver energy input into the fuel pellet. The conditions for establishing scientific feasibility would also not be achieved. The advantage of this proposal is that it is not limited to any particular technology or an arbitrary yield, but rather is based on a definition of explosions. This limit would therefore ban all ignition experiments. However, any definition of fusion explosions geared to ignition would still allow a considerable loophole for pure fusion weapon development even though the letter of the CTBT would be met. This is because a large number of neutrons per shot can be achieved at gains just under one – that is, just below the ignition threshold. Therefore, other limitations are likely to be required to prevent the development of pure fusion weapons.

Such limits on fusion research have been proposed. They are based either on total energy output, or on specific materials or devices used in the fusion research. The following two proposals have been made by nuclear weapons experts.

- The Garwin Limit: One proposal, by Richard Garwin, would limit neutron production to 10^{14} neutrons/shot. This corresponds to an explosion of 0.1 gram of high explosives. Since this limit has already been approached by MTF experiments (10^{13} neutrons) and by Russian high explosive research (10^{14} neutrons), this would effectively freeze these programs until such time as a review of fusion experiments has been completed.[150] Similarly, experiments on facilities such as NIF would be limited, but not prohibited, by this proposal.
- The Kidder Proposal: Another proposal would ban tritium use in systems driven directly or indirectly by high explosives. The rationale behind the tritium portion of the ban is that while the deuterium plasma will undergo a number of fusion reactions, the higher threshold for D-D reactions would make it highly unlikely to achieve ignition or burn in machines designed for igniting plasmas containing both tritium and deuterium.[151] High-explosive-driven components will most likely be an essential component of the miniaturization of pure fusion devices. However, such a ban would not impose any limits on laser-driven or ion-beam driven research or even the Sandia wire-array z-pinch – all of which can contribute to the development of pure fusion weapons.

[150] See Jones and von Hippel 1998.

[151] See Jones and von Hippel 1998.

The limits proposed by Garwin and Kidder are not sufficient to meet the letter of the treaty on their own. A ban on ignition is required for that. However, the Garwin and Kidder limits are helpful in setting limits in order to constrain the development of new weapons.

Application of all these limitations would allow for the continuation of most experiments at NOVA and similar facilities while halting the construction of new facilities such as NIF and Megajoule whose goals are to achieve ignition. This is not to say that such a course is without its dangers for nuclear disarmament and non-proliferation. But it would at least be compatible with the letter and spirit of the CTBT.

Given the immense consequences of the development of pure fusion weapons, an indefinite delay of planned MTF experiments and a moratorium on the construction and planning of large ICF projects designed to achieve ignition (NIF, Laser Mégajoule)[152] is necessary. If the US halts NIF it would be in a position to persuade other countries, such as France, Japan, and Germany, to halt their ICF projects designed to achieve ignition until a review process is undertaken which is comprehensive, inclusive, and world-wide. It could do this by arguing for an interpretation of the CTBT ban to include ICF ignition. The potential near-term and medium-term risks of continuing research with such machines are too great not to pursue restrictions.

The following limitations should be placed on fusion experiments in order to meet both the letter and spirit of the CTBT:

- Ignition of the fusion fuel should be used as the definition of a fusion nuclear explosion, thus prohibiting all ignition experiments, and planning or construction of all facilities designed to achieve ignition should be halted. In theory , the construction of devices such as NIF could proceed if there were a prior verifiable commitment under the CTBT to confine research to deuterium and ordinary hydrogen fuels, with which NIF and similar projects could not achieve ignition. Of course this would make such machines essentially useless since their main purpose is to achieve ignition. Experiments that do not achieve ignition can be done on existing machines.
- The total fusion energy output should be limited to 10^{14} neutrons/shot as proposed by Richard Garwin. This would prevent attempts to gain weapons-related information by increasing the energy of the driver and fusion energy output while staying below ignition.
- The use of tritium should be banned in all systems that use high explosives, as proposed by Ray Kidder.

[152] See Table 2

In the long term, facilities such as the National Ignition Facility and MTF facilities pose even greater threats to both the CTBT and the disarmament process. As discussed above, if ignition is demonstrated in the laboratory, the weapons labs and the DOE would likely exert considerable pressure to continue investigations and to engage in preliminary design activities for a new generation of nuclear weapons (even if it is just to keep the designers interested and occupied). Ignition would also boost political support and make large-scale funding of such activities more likely.

Even without the construction of actual weapons, these activities could put the CTBT in serious jeopardy from forces both internal and external to the United States. Internally, those same pressures, which could lead to the resumption of testing of current generation weapons, could also lead to the testing of new weapons (to replace older, less safe or less reliable weapons). Externally, the knowledge that the United States or other weapons states were engaging in new fusion weapons design activities could lead other states to view this as a reversal of their treaty commitments. Comparable pressures to develop pure fusion weapons would be likely to mount in several countries. This would have severe negative repercussions for both non-proliferation and complete nuclear disarmament. The time to stop this dangerous thermonuclear quest for explosive ignition is now, before its scientific feasibility is established.

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