The physical principles of thermonuclear explosives, inertial confinement fusion, and the quest for fourth generation nuclear weapons

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Some minor modifications were made in order to achieve a proper linking of the figures, which could not be modified so that a double numbering scheme had to be used.

A few papers, Refs. [591] to [596], which appeared after 2002 are appended to the bibliography as additional references.

To Theodore B. Taylor

and Marek Thee

Executive summary

This report is an assessment of the prospect of developing new (i.e., *fourth* generation) nuclear weapons in the context of the Comprehensive Nuclear Test-Ban Treaty (CTBT) that was adopted by the UN General Assembly in 1996 and of the current moratorium on nuclear testing in effect in all nuclear-weapon States.

The first chapter is a primer on thermonuclear weapons based on a scientific understanding of the physical principles of existing nuclear weapons and on the results of ISRINEX, a simple thermonuclear explosion simulation program specially developed for independent disarmament experts. Using this insight, it is shown that the construction of hydrogen bombs is in fact much less difficult than is generally assumed. Using present-day nuclear and computer technology, almost any modern industrial country could, in principle, build such a weapon. Similarly, it is shown that "boosting," i.e., the technique of using a small amount of tritium to enhance the performance of a fission bomb, is also much easier than generally assumed. In particular, using this technique, building highly efficient and reliable atomic weapons using reactor-grade plutonium is straightforward. Moreover, independently of the type of fissile material used, the construction of "simple" and "deliverable" tritium-boosted nuclear weapons can be easier than the construction of primitive Hiroshima or Nagasaki type atomic bombs. In May 1998, both India and Pakistan showed that they had successfully developed boosted fission weapons. Moreover, India claimed to have tested an advanced hydrogen bomb concept, and it is believed that two of their other four devices have used plutonium that was not classified as weapons grade.

The second chapter is a technical and legal analysis of the nuclear tests which are allowed by the CTBT: microexplosions and subcritical experiments. It is found that this treaty explicitly forbids only nuclear explosions in which a divergent fission chain reaction takes place. Therefore, it is possible to develop new types of fission explosives in which subcritical fission-burn is the yield generation mechanism. Similarly, new kinds of fusion explosives, in which the trigger is no longer a fission explosive, are legal under the CTBT.

The third chapter is devoted to the military applications of inertial confinement fusion (ICF) and other pulsed-power technologies. The capabilities of modern

laboratory simulation techniques for weapons physics research are shown to significantly overlap with those of underground nuclear testing. Moreover, these technologies are found to enable the study of a number of physical processes — especially electromagnetic energy cumulation techniques and advanced nuclear processes that are not restricted by existing arms control treaties — which are useful in refining existing nuclear weapons and essential in developing fourth generation nuclear weapons.

The fourth chapter is devoted to fourth generation nuclear weapons. These new fission or fusion explosives could have yields in the range of 1 to 100 ton equivalents of TNT, i.e., in the gap which today separates conventional weapons from nuclear weapons. These relatively low-yield nuclear explosives would not qualify as weapons of *mass* destruction. Seven physical processes which could be used to make such low-yield nuclear weapons, or to make compact non-fission triggers for large scale thermonuclear explosions, are investigated in detail: subcritical fission-burn, magnetic compression, superheavy elements, antimatter, nuclear isomers, metallic hydrogen and superlasers (i.e., ultrapowerful lasers with intensities higher than 10^{19} W/cm^2).

The conclusion stresses that considerable research is underway in all five nuclear-weapon States (as well as in several other major industrialized States such as Germany and Japan) on ICF and on many physical processes that provide the scientific basis necessary to develop fourth generation nuclear weapons. Substantial progress has been made in the past few years on all these processes, and the construction of large ICF microexplosion facilities in both nuclear-weapon and non-nuclear-weapon States is giving the arms race a fresh boost. The world runs the risk that certain countries will equip themselves directly with fourth generation nuclear weapons, bypassing the acquisition of previous generations of nuclear weapons.

In this context, the invention of the superlaser, which enabled a factor of one million increase in the instantaneous power of tabletop lasers, is possibly the most significant advance in military technology of the past ten years. This increase is of the same magnitude as the factor of one million difference in energy density between chemical and nuclear energy.

A major arms control problem of fourth generation nuclear weapons is that their development is very closely related to pure scientific research. The chief purpose of the CTBT is to freeze the technology of nuclear weapons as a first step toward general and complete nuclear disarmament. In order to achieve that, it is necessary to implement effective measures of preventive arms control, such as international legally binding restrictions in all relevant areas of research and development, whether they are claimed to be for military or civilian purposes.

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Acknowledgments

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Introduction

There are many good reasons for having independent expertise on nuclear weapons. The main reason, however, is simply that there are no scientific secrets on their physical principles: a State or organization wanting to make nuclear weapons can easily find the necessary basic information in the open literature. Access to modern computers of moderate capacity is therefore sufficient to *design* a nuclear weapon. Similarly, the same information is available to those who oppose nuclear weapons and wish to improve the quality of their arguments.

On the other hand, the *manufacture* of a thermonuclear weapon, together with the special nuclear materials it is made of, has always been (and remains) a formidable engineering challenge, especially for technologically less advanced countries. For this reason, as long as independent expertise concentrates on scientific principles and not on engineering details, there is little risk it will contribute to horizontal proliferation.[1] With this in mind, chapter one gives an introduction to the physics of thermonuclear weapons. We believe there is no compelling reason why such knowledge should remain the privilege of government experts working behind the curtain of secrecy.

The main anti-proliferation impact of independent expertise on nuclear weapons is potentially on vertical proliferation. A good understanding of nuclear weapons physics is important to evaluate the future evolution of nuclear weapons technology, especially in the context of international agreements, such as the Comprehensive Nuclear Test-Ban Treaty (CTBT) and the Nuclear Non-Proliferation Treaty (NPT), which are supposed to put a halt to the development of new nuclear weapons.

[1]The term "proliferation of nuclear weapons" covers (i) the increase in the number and the quality of such weapons within the five nuclear-weapon States (namely China, France, Russia the U.K. and the U.S.A.); and (ii) the spread of nuclear weapons to other countries. While the former is known as *vertical* proliferation, the latter is called *horizontal* proliferation.

In particular, such an understanding is essential for the assessment of the links between modern simulation techniques[2] and nuclear weapons, and for the analysis of *fourth generation nuclear weapon* concepts. These topics are the subject of chapters two, three and four.

The concluding chapter of this report is followed by a bibliography containing more than 500 items. This bibliography is not exhaustive. It contains only those references that we have studied and which are *cited* in this report. These references (which comprise a number of review articles) have been selected in view of their scientific, technical, strategic, or historical importance, as well as for their pedagogical utility for acquiring a deeper understanding of the subject matter. To help those who are interested in one particular subject, the references have been assembled by subjects, and are listed in chronological order.

Finally, the question, "Why fourth generation nuclear weapons?" is not directly addressed in this report. In effect, trying to answer this most important question would require taking into account many strategic, economic, social and political aspects that go beyond the scope of this technical report. Nevertheless, we hope that the report will positively contribute to a thorough discussion of fourth generation nuclear weapons, and that it will provide a sound technical basis to this continuing debate.[3]

[2]Such as megajoule-scale inertial confinement fusion, ultrahigh-intensity lasers (i.e., "super-lasers"), pulsed-power technology, subcritical testing, supercomputing, etc.

[3]The second edition of this report was translated in Russian in 1998 by the Russian Foreign ministry and approved for public release in March 1999. This translation is not just a recognition of the value of the efforts made at ISRI and INESAP in order to raise the technical understanding on the very serious concern represented by the development of new types of nuclear weapons, but also a signal that the Russian Foreign ministry wants its own concern on the subject to be known.

Units, conversion factors and metric prefixes

The international system of units (MKSA) is used throughout. However, in the case of plasmas, practical units are used for the temperatures (electron-Volts instead of degrees Kelvin) and pressures (Megabars instead of Pascals).

In the case of energies, electron-Volts are often used instead of Joules. And, in the case of explosions, the yields are expressed in kilogram or kiloton equivalents of TNT (to avoid confusion, while weights are written kg or kt, explosive yields are written kg or kt). Sometimes we use calories, e.g., in the definition of the kt.

The following definitions and conversion factors apply:

1 eV = 11604 ^{o}K

1 eV = 1.602×10^{-19} J

1 bar = 10^{5} Pa

1 Mbar = 100 GPa

1 $kg \equiv 10^{6}$ cal

1 kg = 4.184 MJ

1 kg = 2.61×10^{19} MeV

1 $kt \equiv 10^{12}$ cal = 4.184×10^{6} MJ

1 kt = 2.61×10^{25} MeV

International system of units (SI) prefixes					
prefix	symbol	factor	prefix	symbol	factor
milli	m	10^{-3}	kilo	k	10^{3}
micro	μ	10^{-6}	mega	M	10^{6}
nano	n	10^{-9}	giga	G	10^{9}
pico	p	10^{-12}	tera	T	10^{12}
femto	f	10^{-15}	peta	P	10^{15}
atto	a	10^{-18}	exa	E	10^{18}
zepto	z	10^{-21}	zetta	Z	10^{21}
yocto	y	10^{-24}	yotta	Y	10^{24}

Table 1: Metric prefixes

Chapter 1

The Physical Principles of Thermonuclear Explosives

1.1 Introduction

This chapter is a *self-contained introduction* to the physical principles of modern thermonuclear weapons: hydrogen bombs and boosted fission weapons.[1] This introduction assumes some basic understanding of nuclear physics, and is backed up by results of ISRINEX,[2] a thermonuclear explosion simulation program running on an IBM personal computer [44].

In its current form, ISRINEX does not simulate the complicated hydrodynamic phenomena which take place in the compression and expansion phases preceding and following the ignition and burn of the thermonuclear fuel. The capabilities of ISRINEX are therefore limited to the study of ignition and burn of uniform thermonuclear plasmas under conditions of ideal confinement. Nevertheless, these capabilities are sufficient to determine the approximate values of the temperatures, densities, pressures, durations, etc., which are typical of the working conditions of boosted fission weapons and of two-stage fusion weapons. Using these results, some conclusions will be drawn (i) on the development of new types of weapons in recognized nuclear weapon states, and (ii) on the implications of sophisticated nuclear activities in non-declared nuclear weapon states for the development of modern thermonuclear weapons.

[1] For an introduction to fission weapons, i.e., "atomic bombs," see [58, 61, 82, 9, 66, 68].

[2] A short description of this program and of its main results was presented at the 1996 INESAP Conference, Gothenburg, Sweden, May 30 to June 2, 1996 [43].

1.2 ISRINEX 2.6 physics

Version 2.6 of ISRINEX is designed to study the ignition and burn phases of thermonuclear plasmas found in the center of fusion-boosted fission weapons and within the second stage of two-stage fusion weapons. To this end, a first approximation assumes that the thermonuclear plasma is uniform and nearly at rest. This implies that all hydrodynamic effects are neglected: the plasma is supposed to be perfectly confined within fixed boundaries and ISRINEX calculates the time evolution of the numerous nuclear and electrodynamic reactions taking place during ignition and burn. This approach is possible because, in nuclear weapons, the thermonuclear reactions take place under conditions of *inertial confinement*, i.e., in such a way that the duration of thermonuclear burn is short compared to the time required for the materials to be set into motion by the pressure generated during the explosion.

With ISRINEX, it is possible to determine the initial and final states of a thermonuclear plasma, i.e., its density, temperature, pressure and composition at the beginning of ignition and at the end of burn. These data may then be used as inputs for other calculations, either analytical or numerical. In particular, they enable one to specify the requirements a primary system[3] has to satisfy to put the fusion plasma into its initial state and to identify how the conditions suitable for thermonuclear burn can be maintained as long as possible.

However, consistent with what was said in the introduction, ISRINEX is not very useful for building a nuclear weapon. This is because ISRINEX deals solely with ignition and burn of thermonuclear plasmas and not with the complex material's phase transitions which take place during the implosions of the primary and of the secondary. This is particularly important for the design of the primary which requires a theoretical as well as an empirical basis that goes much beyond what is incorporated in ISRINEX. According to one U.S. weapons designer: "The primary is less well understood than the secondary. Material physics is cleaner in the secondary: everything happens at high temperatures and pressures. The primary involves transitions from cold metal at low pressure and temperatures to high pressures and temperatures," Delmar Bergen, quoted in [29, p.60].

In order to achieve reliable results, a considerable effort has been made to develop a comprehensive model including all the relevant physical phenomena. Therefore, the emphasis in developing ISRINEX has been on describing the various phenomena and their interplay with a uniform degree of precision in order to obtain

[3] In present-day thermonuclear weapons, energy from a fission explosive (the trigger — the first stage or the *primary*) is used to compress and ignite a physically separate component (the main explosive charge — the second stage or the *secondary*) containing thermonuclear fuel.

a consistent simulation of their synergy. Thus, besides the basic phenomena — thermonuclear reactions, neutron interactions, and ordinary plasma physics (which are well known from unclassified research in astrophysics, nuclear physics, and controlled thermonuclear energy) — the more difficult phenomena of high-energy-density radiation transport had to be included as well. This was done by studying scientific publications dealing with radiation transport in the context of astrophysics and inertial confinement fusion.

The elementary reactions included in ISRINEX 2.6 belong to three classes:

(i) Thermonuclear fusion reactions:

$$T + D \longrightarrow n + {}^4He \quad + (17.6\ \mathrm{MeV}) \tag{1.1}$$
$${}^3He + D \longrightarrow T + {}^4He \quad + (18.3\ \mathrm{MeV}) \tag{1.2}$$
$$D + D \longrightarrow p + T \quad + (4.0\ \mathrm{MeV}) \tag{1.3}$$
$$D + D \longrightarrow n + {}^3He \quad + (3.3\ \mathrm{MeV}) \tag{1.4}$$

These are the four reactions between the three basic fusion fuels (deuterium: D, tritium: T and helium-3: ${}^3He$). They produce energy, additional fusion fuels (T, ${}^3He$), neutrons, and inert products (helium-4: ${}^4He$, protons: p) which do not react anymore. As is well known, achieving conditions for thermonuclear burn requires creating enormous temperatures (on the order of one keV, i.e., 10^7 degrees) simultaneously with enormous pressures (on the order of 100 TPa, i.e., 10^9 atmospheres). This is in sharp contrast with fission reactions which take place at ordinary temperature and pressure.

(ii) Neutron reactions:

$$n + i \longrightarrow n' + i' \tag{1.5}$$
$$n + {}^6Li \longrightarrow T + {}^4He \quad + (4.8\ \mathrm{MeV}) \tag{1.6}$$
$$n + {}^{238}U \longrightarrow {}^{237}U + n + n' \tag{1.7}$$
$$n + {}^{238}U \longrightarrow X + Y + n + n' \quad + (180\ \mathrm{MeV}) \tag{1.8}$$

Reaction (1.5) indicates that in the highly compressed plasmas occurring in thermonuclear weapons, the neutrons produced by the fusion reactions interact with the ions of the plasma. In reaction (1.6) tritium is produced from lithium-6. This is the key reaction which enables high yield hydrogen bombs to produce

tritium *in situ* and thus to "burn" the naturally occurring elements D and Li. In such weapons, the thermonuclear fuel initially consists of deuterated lithium, LiD, a solid with a density of 0.8 g/cm^3 at standard temperature and pressure. Under conditions of sufficient temperature and compression reactions (1.5) and (1.6) combine into a closed-chain reaction called the *Jetter cycle* [78]:

$$\begin{array}{llll} T & +D \longrightarrow {}^4He+ & n \\ \uparrow & & \downarrow \\ T & +{}^4He \longleftarrow {}^6Li+ & n \end{array} \tag{1.9}$$

The relative importance of this coupled reaction grows exponentially during thermonuclear burn because of the neutrons produced in reaction (1.4). However, to compensate for neutron losses, and to get the Jetter cycle going at a high pace, requires a neutron multiplier (such as a uranium blanket surrounding the fusion plasma) to produce additional neutrons by the $(n, 2n)$ reaction (1.7) and the fast-fission reaction (1.8).

(iii) Electromagnetic reactions:

$$e + i \longleftrightarrow e' + i' \tag{1.10}$$
$$e + i \longleftrightarrow e' + i' + \gamma \tag{1.11}$$
$$e + \gamma \longleftrightarrow e' + \gamma' \tag{1.12}$$

A correct description of the interactions between electrons (e) and photons (γ) is especially important in nuclear weapons physics. This is because during thermonuclear burn, most of the energy released by fusion reactions is first transferred from ions to electrons by elastic ion-electron collisions, reaction (1.10), and then from electrons to the electromagnetic field by the process of bremsstrahlung emission, reaction (1.11). As a result, during thermonuclear burn, more and more energy accumulates in the form of electromagnetic radiation, i.e., photons.[4] As photons increase in number, they interact with electrons through the inverse-bremsstrahlung process, reaction (1.11), as well as through the Compton and inverse-Compton[5] reaction (1.12). The discovery in 1949-1950 at Los Alamos of the crucial importance of electron-photon interactions in thermonuclear burn,

[4]This is also the case in the final stage of as fission explosion, shortly before disassembly. In this stage expression (1.13) also applies.

[5]In the Compton process a photon gives part of its energy to an electron, while in the inverse-

and in particular of inverse-Compton processes, has almost put an end to research on the hydrogen bomb. The reason is that while a thermonuclear plasma is essentially transparent to electromagnetic radiation at low density, it becomes more and more opaque to photons as its density is increased. Instead of escaping, the photons are trapped and accumulate within the fuel. Moreover, in a weapon, the thermonuclear fuel is surrounded by a heavy material acting both as a neutron multiplier and as a tamper for the thermonuclear explosion. Because this heavy material is also opaque to electromagnetic radiation, most of the photons escaping from the burning plasma are reflected back into it. Under these conditions, the thermonuclear plasma can be described by a three-component fluid consisting of ions, electrons, and photons. The energy density is then the sum of three terms:

$$E = \frac{3}{2} N_i k T_i + \frac{3}{2} N_e k T_e + \frac{4\sigma}{c} T_r^4. \tag{1.13}$$

N_e and N_i are the electron and ion number densities, *k* and σ the Boltzman and Stefan constants, and T_e, T_i, T_r the electron, ion, and radiation temperatures. In this equation the last term depends on the fourth power of the temperature. Hence, as the radiation temperature rises, the energy density is increasingly dominated by the radiation term. Since the Compton and inverse-Compton reaction rates also increase with the fourth power of T_r, energy is more and more rapidly exchanged between photons and electrons, and then between electrons and ions because of electron-ion collisions. Therefore, when the radiation term dominates, the plasma tends towards *thermonuclear equilibrium*, in which case

$$T_i \approx T_e \approx T_r = (\frac{c}{4\sigma} E)^{1/4}. \tag{1.14}$$

In this regime, the rise in ion temperature (which determines the fusion reaction rate) is strongly limited by the radiation effects which dictate the electron temperature.[6] This is a stumbling block for projects involving thermonuclear reactions — Teller's "Super" and energy production by fusion [58, p.40]. These processes require extremely high temperature, but, as equation (1.14) shows, doubling the temperature requires sixteen times the energy density.

In ISRINEX reactions (1.1–1.6, 1.10–1.12) and equation (1.13) are modeled

Compton process it is the electron which gives part of its energy to the photon. In a high density electron-photon plasma, these processes are the dominant energy exchange mechanisms. The first comprehensive unclassified discussion of the role of Compton effects in the establishment of thermal equilibrium between photons and electrons was published in 1956, i.e., [73].

[6] In ordinary "thermal equilibrium," where the radiation energy density is small, the opposite situation arises: it is the matter temperature which dictates the radiation temperature.

by eight coupled simultaneous differential equations. Three of these correspond to the energy densities from which the corresponding ion, electron, and radiation temperatures are calculated. The other five equations keep track of the plasma composition, i.e., of the number densities of D, T, ^3He, Li, and the total number density of the charged fusion products. The coupling between the differential equations is determined by numerous effects such as fusion, electron-ion and electron-photon collisions, fusion products and neutron energy deposition, etc.[7]

The electromagnetic radiation effects (i.e., the bremsstrahlung and Compton processes and their inverses) are described according to the model of Hurwitz used by Fraley et al. [128], including a fit to the Hurwitz function $G(\gamma)$ that is improved over the one provided by Kirkpatrick [137]. Since there is some discrepency in the published literature on the details of the Hurwitz model of bremsstrahlung/inverse-bremsstrahlung interactions, we have published in *Physics Letters* a brief review of the underlying physics [106].

The calculations published by Fraley et al. [128] are simulations of high compression inertial confinement fusion pellets which embody significant aspects of radiation-transport physics. These simulations were very useful in debugging ISRINEX and checking that its results are consistent with those obtained with more sophisticated models and programs.

Hydrodynamic effects, in general, and second order thermodynamic effects such as electron thermal conduction, are not included in ISRINEX at this stage. Estimates for corrections arising from these effects are therefore calculated by ISRINEX in order to insure that it is not used outside of its domain of validity. However, since the publication of the simulations on which this chapter is based [44], a verification of ISRINEX's results has been made using an up-to-date version of MEDUSA, one of the best unclassified ICF simulation programs available today. Using this code, it was found that the results of ISRINEX, e.g., the time evolution of the plasma temperature with all hydrodynamic effects switched off, were in reasonable agreement with those of MEDUSA.

Finally, essential inputs to ISRINEX are the boundary conditions which determine the interactions of the thermonuclear plasma with the surrounding medium. Most important are the "plasma size," which is used to calculate the neutron and radiation loss rates, and the "loss reduction factor," which enables the effect of the surrounding material on the electromagnetic radiation losses to be taken into account. Other boundary conditions simulate the time-varying photon and neu-

[7]For an introduction to the relevant physical background see, for example [139]. For two recent reviews of advances in ICF research, see [156, 160]. Possibly the most comprehensive review (theory, experiments, diagnostics, simulations, etc.) of laser driven ICF is the three-parts, five-volumes collection (3'096 pages in total) published by the French CEA in 1993 [148].

tron fluxes from a fission explosion. This enables one to study plasma heating and tritium breeding by an external source, such as in "boosting" of a fission-bomb or in "sparkplug ignition" of the secondary of a fusion-bomb.

1.3 Fission explosives and boosting

A boosted fission bomb is a device in which a small amount of thermonuclear fuel is ignited by a fission reaction and produces neutrons that in turn enhance the fission reaction rate. Boosting was successfully developed in the early 1950s. It proved so advantageous that all modern fission explosives are boosted fission bombs. These advantages stem from the fact that the conditions for ignition of the thermonuclear fuel can be reached at a time occurring significantly before the end of the nuclear chain reaction. The final yield of the explosion is then determined primarily by the number of neutrons produced in the fusion reaction rather than by the details of the chain reaction. This enables one to avoid the use of a thick neutron reflector and heavy tamper, and to build low-weight fission explosives which have a very good fission efficiency. Moreover, because of some favorable plasma-physical circumstances, the conditions for ignition of the fusion reaction are rather insensitive to several critical parameters (compression factor, tritium amount, neutron background). As a result, boosted fission bombs are intrinsically much more reliable, robust, and safer than unboosted fission bombs.

Before investigating boosting, it is worthwhile recalling the main characteristics of non-boosted implosion weapons. Such devices are most likely to be used by new proliferating countries without the technological basis to build boosted weapons. They also provide a reference to which the advantages of boosted weapons can be compared. The implosion technique is necessary if the fissionable material is plutonium, and preferable to the gun-assembly method if enriched uranium has to be used economically.

A detailed quantitative description of the dynamics of a uranium implosion device was published in Switzerland as a sequel of the Swiss atomic weapon program [63].[8] The device consists of a 25 kg solid sphere of ^{235}U surrounded by a 200 kg depleted uranium reflector/tamper. Using a spherical implosion driven

[8]The Swiss atomic weapons program was secretly initiated in 1946 by the Swiss Military Department and definitively terminated in 1988, eleven years after Switzerland acceded to the Non-Proliferation Treaty. Although safeguards agreements with the International Atomic Energy Agency came into force on September 6, 1978, unlawful nuclear weapons activities continued until November 1, 1988, when the program was finally terminated by the Federal Council. An official historical account of the Swiss atomic program was declassified and published on April 25, 1996 [71].

by detonating high explosives, a maximum average compression of $\chi = 1.6$ is achieved. The calculated nuclear energy yield is 22 kilotons.[9] This corresponds to a fission efficiency of $\eta = 0.05$ (i.e., about 5% of the uranium, which yields 17 kt per kg,[10] is fissioned). Since about 300 kg of high explosives are necessary to compress 225 kg of uranium,[11] the total weight of a bomb based on such a design is on the order of 500 to 1'000 kg.

The calculations presented in [63] include the time evolution of many important physical parameters during the nuclear explosion. These results can be used for a preliminary analysis of the possibility of igniting thermonuclear fuels with fission explosives. In this perspective, a key parameter is the temperature during the final phase of the chain reaction. It is found, for instance, that the temperature in the center of the core is about 1 keV when it starts expanding. At this time, the energy yield is about 0.2 kt (i.e., $\eta = 0.05\%$). The temperature then continues to rise as more energy is produced and reaches a maximum of about 5 keV when the yield is about 2 kt (i.e., $\eta = 0.5\%$). From then on, the temperature starts decreasing as more and more thermal energy is converted into kinetic energy or is transferred from the core to the reflector and then from the reflector to the outside.

In first approximation, as long as the energy remains confined to the fissile material, the temperature of a fission explosive is given by a very simple model. This is because heavy materials are essentially opaque to electromagnetic radiation. For a uranium or plutonium plasma, equation (1.13) can therefore be used with $T_e = T_i = T_r$. Writing the energy density in terms of the compression factor χ and the fission efficiency η, two limiting cases lead to simple expressions of the temperature.

First, in the low temperature limit (below 4 keV in fissile materials), the radiation term can be neglected. The temperature is then approximately

$$kT = \frac{2}{3}\frac{\eta}{Z_{eff}}E_f. \tag{1.15}$$

Here Z_{eff} is the effective electric charge of the ions (for heavy materials such as uranium or plutonium $Z_{eff} \approx 60\sqrt{kT}$ for $kT < 2$ keV) and E_f the fission energy,

[9] The total energy released in a nuclear explosion is measured in kiloton equivalents of TNT. By definition, 1 $kt \equiv 10^{12}$ cal = 4.18×10^6 MJ = 2.61×10^{25} MeV.

[10] See Table 1.1.

[11] This estimate assumes that only 30% of the specific energy of the chemical explosive is converted into compression energy, and that the tamper and the core are both uniformly compressed to the same density. This provides an upper limit to the required amount of high-explosives because the core will be more compressed than the tamper during implosion by converging shock waves. On this point, and for more informations on nuclear weapons technology, see [9].

about 180 MeV per nuclei. Thus, a temperature of 1 keV is reached at a fission efficiency of only 0.05%, in good agreement with the simulation [63].

Second, in the high temperature limit (above 4 keV), which corresponds to the end of the chain reaction, the radiation term dominates. The temperature is then approximately

$$kT \approx 18[\mathrm{keV}]\sqrt[4]{\eta\chi}. \tag{1.16}$$

Taking $\chi = 1.6$ and $\eta = 0.5\%$, we find $kT = 5.4$ keV, in good agreement with the calculation [63] for the maximum temperature at the center of the core.

Expression (1.16) shows that the maximum temperature of a fission bomb is a very slowly increasing function of compression and efficiency. In practice, by using chemical explosives, it is difficult to get compression factors much larger than 2 to 3 in fissile materials. On the other hand, substantial radiative loss and conversion of thermal into mechanical energy start when η is on the order of 1% . Thus, in any fission explosion, there is a maximum temperature of about 5–10 keV which is very difficult to exceed.

Regarding thermonuclear burn, there is a minimum temperature for ignition that is well known from controlled thermonuclear fusion research: in the absence of external heating, thermonuclear burn is only possible if the temperature of the fuel is above some critical temperature at which the thermonuclear power release is equal to the energy radiated by the heated fuel in the form of bremsstrahlung photons. For the DT, $D\,^3He$ and DD reactions (1.1, 1.2, 1.3–1.4), this critical temperature is respectively 4.2, 18, and 25 keV.[12] Hence, while the maximum temperature of a fission bomb is certainly sufficient to ignite the DT reaction, it may not be high enough to start the $D\,^3He$, and DD reactions.

To find out whether thermonuclear fuels other than DT can be ignited by a fission explosion, it is necessary to investigate the processes which contribute to the heating of a fuel sample placed in the center, or possibly on the surface, of an exploding fission device. As the fissile material warms up, the sample is first heated by thermal conduction, and, as temperature rises, increasingly by radiation. When the temperature rises above 0.1 keV, radiation turns into x-rays and the main heating mechanism becomes inverse bremsstrahlung. (There is also some heating due to neutron interactions, but this is small.) At such temperatures, thermonuclear fuels (which are low-Z materials) are essentially transparent to x-rays. Heating is rather weak but fairly uniform over the sample. The fusion fuel temperature

[12]The first open publication of this argument is by J.D. Lawson [79]. The critical temperatures listed here are calculated using recently published thermonuclear cross-sections.

therefore closely follows the fission bomb temperature. Ignition is then determined by a simple energy balance, with thermonuclear energy production and inverse bremsstrahlung heating on the one side, and bremsstrahlung loss on the other. The calculation leads to a remarkable result: the critical temperature for ignition is found to be determined primarily by fundamental parameters (such the fusion reaction cross-section) and to be only a weak function of extensive parameters (such as the density or the size of the fuel sample).

For DT, $D\,^3He$, and DD, the critical temperatures for ignition with external heating by x-rays are found to be 2.4, 9, and 10 keV, respectively.[13] [14] Hence, $D\,^3He$ or DD ignition by the x-rays of a fission explosive is only possible in the high temperature limit where the chain reaction is very close to its end. On the other hand, DT can be ignited in the low temperature limit where the fission efficiency is still low enough for the neutrons of the fusion reactions to have a strong effect on the final outcome of the chain reaction. In other words, we conclude that DT is the only thermonuclear fuel that can be used for boosting. This makes tritium an absolutely necessary ingredient of modern fission explosives.

Moreover, as shown in the simulation [63], the maximum temperatures obtained in a fission explosive are approximately 5 keV in the core center and about 2 keV at the outer reflector boundary. While these temperatures are sufficient to ignite the DT fusion reaction (1.1), they are not high enough to ignite the DD reactions (1.3,1.4) or to initiate the Jetter cycle (1.9) in LiD.[15] In fact, for this and several other reasons, it is not possible to build a hydrogen bomb by simply putting some fusion fuel nearby a fission bomb. To burn a large amount of inexpensive thermonuclear fuels such as DD or LiD, a more clever design is required!

[13] The reasoning leading to these numbers is similar to the derivation of "Lawson's criterion" [79]. As was explained in the previous paragraph, it amounts to adding an inverse bremsstrahlung term on the heating side of Lawson's energy balance. Apparently, the consequences for boosting of this trivial reasoning have never been published.

[14] These Lawson-type temperatures are derived assuming local thermal equilibrium (LTE), $T_i \approx T_e \approx T_r$, which implies instanteneous energy transfer between the ion, electron and photon populations. Under non-LTE conditions (i.e., simulations like those shown in Fig. 1.2) lower ignition temperatures can be found, although only in slowly burning plasmas which correspond to physical conditions that cannot be realised in practice.

[15] However, a *small* amount of ^6LiD at the center of a 10–30 kt fission bomb can increase its yield to 100–300 kt. This was done, for example, in the third Chinese nuclear explosion [26].

1.4 Modern boosted fission explosives (Figs. 1.1–1.2)

Figure 1.1 is a simplified diagram of a boosted fission device. Its core consists of a plutonium and/or enriched uranium shell (the "pit") surrounded by a stainless steel case and possibly a beryllium neutron reflector, and by chemical explosive lenses. This corresponds to the present-day concept of sealed pits, with the fissile material permanently sealed within the high explosives. A short time before detonating the device, the pit is filled with a DT gas mixture at a pressure of a few tens of atmospheres.[16] In comparison with a first generation fission bomb, such as considered in [63], a major difference is the absence of the thick reflector/tamper responsible for most of the weight. As typical figures, we assume that the case consists of 4 kg of steel, the pit of 4 kg of fissionable materials and that the amount of DT is 2.2 g. (This corresponds to 1.3 g of tritium, a relatively small amount considering that stockpiled thermonuclear weapons contain on average about 4 g of tritium per warhead[17].) For imploding such a device, about 10 kg of high explosives is sufficient.

When the weapon is detonated, the pit and the case are imploded by the high explosives at the same time as the DT gas. As the pit collapses into a solid ball, the DT is compressed into a sphere of a few mm radius with a density tens of times greater than its solid-phase density. If we assume that the pressure over the DT is nearly equal to the pressure at the center of the fissile material, and that in this region the compression of uranium is about 2.5 times its normal density,[18] we find from the respective equations of state [203] that the density of DT is about 7 g/cm^3, over 30 times its solid density. In fact, a compression of 33 is the maximum possible compression from a single convergent shock wave in spherical geometry [139, p.80] (see also [195]). Thus, by using a sufficiently sophisticated implosion technology, compressions between 20 and 50 (and possibly as large

[16] Before arming the device, the DT mixture, or just the tritium, is stored in a separate reservoir. This facilitates maintenance and insures that boosting will not happen in case of an accidental detonation of the high explosives.

[17] In May 1995, the U.S. Government declassified the statement that "the amount of tritium in a reservoir is typically less than 20 grams" (RDD–3, January 1, 1996, update of [22].) However, one of the most authoritative unclassified source gives an average of 4 grams of tritium per U.S. warhead. See note 3, in [88]. The uncertainty on the amount of tritium actually used in a weapon comes from several facts: (i) the amount may vary considerably from one weapon type to another, (ii) tritium may be used in thermonuclear primaries *and* secondaries (e.g., to boost the "sparkplug" and possibly to facilitate "volume" or "hot spot" ignition), and (iii) the total tritium inventory necessary to maintain a stockpile is possibly several times larger than the total amount of tritium used in the warheads. Our choice corresponds to 1 liter of DT gas at a pressure of 10 atmospheres.

[18] In principle, using a relatively sophisticated implosion technique, the average compression of the fissile material could be on the order of 3 to 4 [70].

as 100) can be achieved in a small sphere of DT at the center of a collapsing shell of heavy material. High compression of the DT mixture is important for the thermonuclear burn to be as fast as possible.

Figure 1.2 presents the results of ISRINEX for the heating, ignition and burn of a 2.2 g DT sphere of 9 mm diameter (compression $\chi = 30$) at the center of a fission bomb. The purpose of the calculation is to verify (i) that the fusion fuel temperature rise is fast enough to follow the fission bomb temperature, (ii) that a fission bomb temperature on the order of 2 keV is really sufficient to start thermonuclear burn in DT, and (iii) that burning is fast enough for most of the DT to be burnt in a time that is on the same order as a fission generation time, i.e., about 2–5 nanoseconds. To achieve this, the temperature of the fission bomb is set to some fixed value (e.g., T_b = 1.5, 2.0 or 2.5 keV) and the time evolution of the burnup (i.e., the amount of fuel burnt relative to the initial amount of fuel) is followed. With an initial DT temperature of 0.2 keV, and a fission bomb temperature between 1.5 and 2 keV, it is found that ignition occurs in about 1.5 to 2 ns, and that burning of about 50% of the DT takes about 2 ns. Hence, with a fission explosive temperature of 2 keV, as predicted by simple analytic calculations, boosting is indeed possible. However, if the temperature is below about 1.5 keV (for which ignition is still marginally possible after a x-ray heating period of 7 ns), boosting is not possible.

Having confirmed that a temperature of 2 keV is adequate to ignite DT at the center of a fission explosive, the effect of the fusion neutrons on the yield of the device can be estimated. First, it is of interest to calculate the yield at ignition ignoring the fusion neutrons. Since 2 keV is in the low temperature limit, expression (1.15) applies, and the efficiency is found to be 0.15%. As there are 4 kg of fissile material, ignition corresponds to an unboosted yield of $4 \times 0.0015 \times 17 \approx 0.1\,kt$. This is a very low yield, almost the yield of a "fission fizzle." It shows that reaching the conditions for boosting is not very demanding from a neutronic point of view: this is why a thick neutron reflector is not necessary. Moreover, even if the chain reaction starts at the worst possible time (for example in case of preinitiation by neutrons from spontaneous fission, or by neutrons from the explosion of a nearby nuclear weapon) such a yield can always be achieved before the complete disassembly of the bomb.

Since burning of the DT is very fast (i.e., on the order of 2–4 ns), it is possible to estimate the absolute minimum yield of a boosted device by ignoring in first approximation its hydrodynamic expansion.[19] Assuming that the total

[19]This approximation is possible because, with boosting, the yield is primarily controlled by the very fast neutron burst from the thermonuclear reactions, and the fissile material (apart from heating the fusion fuel to ignition) functions essentially as a neutron and energy amplifier in the final stage of the nuclear explosion.

and fission cross-sections of plutonium by 14 MeV neutrons are respectively $\sigma_t = 5.8 \times 10^{-24}$ cm^2 and $\sigma_f = 2.3 \times 10^{-24}$ cm^2, the probability of fission per DT fusion neutron is:

$$P_f \approx \frac{\sigma_f}{\sigma_t}(1 - \exp(-n\sigma_t R)\,). \tag{1.17}$$

With $n = 1.2 \times 10^{23}$ cm^{-3} and $R = 2.7$ cm the number density and radius of the compressed plutonium pit in Fig. 1.1, one finds $P_f \approx 0.33$. Each of these primary fissions produces about 4.5 fast neutrons which have a secondary fission probability of about 0.22 (this assumes $\sigma_t = 7.5 \times 10^{-24}$ cm^2 and $\sigma_f = 1.8 \times 10^{-24}$ cm^2). Thus, the total number of fissions is $0.33 + 0.33 \times 4.5 \times 0.22 = 0.66$ per DT fusion neutron. However, this crude estimate neglects neutron multiplication effects in the plutonium, as well as neutron reflection and production in the iron [64][20] and beryllium [62] surrounding the plutonium core. Therefore, a conservative estimate is to assume that each fusion neutron in the device depicted in Fig. 1.1 will produce at least one fission in the plutonium, so that the minimum yield will be 180 MeV / 17.6 MeV $\times$ 1.1 g $\times$ 0.08 kt/g $\approx$ 1 kt .[21]

In other words, a fission *fizzle* which would have a yield on the order of 0.1 kt without boosting, will have a yield on the order of 1 kt with DT boosting. In fact, if the plutonium in Fig. 1.1 was replaced by depleted uranium, 14 MeV neutron fission in ^{238}U would already boost the fusion yield by a factor of about five,[22] the remaining factor of two being essentially the consequence of the fission cross-section of plutonium (or ^{235}U) being about twice that of ^{238}U. However, the fissile material is essential in order to heat the fusion fuel to ignition.

In order to obtain higher yields, neutron multiplication in the fissile material is necessary. This requires the plutonium to be made highly "super-critical", i.e., to be substantially more compressed than required to barely reach criticality. This implies using an advanced implosion technology, and insuring that the device will remain critical long enough before disassembly. If we take as the key figure the neutron multiplication factor μ normalized to the number of 14 MeV neutrons produced by DT fusion, and assume that there is enough time for a few fission generations, we have $\mu \approx 5$. The minimum boosted fission efficiency is then the

[20] This is the first open publication on the time and energy behaviour of fast neutrons in iron using a 14 MeV source.

[21] This assumes 50% burn of the 2.2 g of DT which has an energy content of 80 kt/kg (see Table 1.1).

[22] The factor of five boost provided by a 6 cm thick non-fissile ^{238}U blanket can be derived from since long declassified data, e.g. [60], or precisely calculated by using publicly available computer programs, e.g. [466, p.16].

ratio of the number of fusion-induced fissions to the total number of fissile nuclei, i.e.,

$$P_f \approx \mu \frac{N_n}{N_f} = \mu \frac{m}{M} \frac{A}{a}, \tag{1.18}$$

where $m = 2.2$ g and $M = 4000$ g are the fusion and fissile material weights, and a = 5 and A = 239 their atomic weights. For $\mu = 5$ we obtain P_f =0.13, which corresponds to a minimum yield of $\approx$ 10 kt. Hence, compared to the minimum unboosted yield of 0.1 kt, boosting has the effect of multiplying the yield of a fission device by a factor of about 100 in a time on the order of 5 neutron generations, i.e., $\sim$10 nanoseconds. Since this is less than the 20–30 ns it takes for an untampered fission bomb to disassemble, boosting can occur rather late in the chain reaction and still produce a significant nuclear yield.

Of course, calculating the precise yield of a boosted device requires a much more complicated simulation program than ISRINEX. Moreover, building a boosted device is not an easy task — especially if it is a high-yield (i.e., larger than a few kt) one. A major difficulty is that the DT filled hollow pit structure implies that there must necessarily be an *external* neutron generator to start the chain reaction. Since the DT and the plutonium do not reach maximum compression at the same moment, the timing of the neutron burst from the external generator has to be carefully adjusted. Finally, in order to obtain the full benefit of boosting (i.e., to economize as much as possible on costly materials such as tritium and high-grade plutonium, to push safety to the extreme, or to make the best possible primary for an H-bomb) the design of boosted devices has to be pushed "near the cliff," close to the region where performance becomes very sensitive to internal and external conditions. Near the cliff, the design and engineering of boosted devices is very difficult, and may require nuclear explosive testing or experienced judgment by a nuclear weapons designer. But further away from it, in the design of more basic, physically larger weapons, "much of the physics of nuclear weapons is quite forgiving" (Carl Haussmann, quoted in [29, p.66]).[23]

Having described the scientific principles of boosted fission explosives, we can now infer the technical and strategic consequencies that derive from this very important advance in fission weapons:

• Boosting is the most important feature of second-generation fission-explosives and the *only* fusion fuel to be used effectively for this purpose is DT. This is the basis of the concept of a cut-off in tritium production as an effective measure

[23] Referring to problems with boosting, a Los Alamos weapons designer acknowledges that weapons built before the 1958 moratorium "were considered 'forgiving' relative to their modern counterparts" [7, p.62].

of thermonuclear weapon disarmament [88, 19, 32]. However, boosting is also possible with antiprotons which produce about twenty neutrons per stopped annihilation in uranium [243, 307]. It follows that a very small amount of antiprotons is sufficient to initiate a chain reaction in a highly compressed pellet of plutonium or uranium. This possibility and its consequences will be discussed in section 4.4.

• With boosting, it is possible to build a relatively high yield fission explosive which is fairly compact because it uses only a relatively small amount of high explosives to implode the fissile material. The device can also be made relatively light-weight because a thick neutron reflector and/or a heavy tamper surrounding the fissile material are not necessary — which implies that x-rays can easily escape from the surface of the fissile material. For these reasons, boosted devices are particularly suited to applications such as hot x-ray devices for antiballistic missile (ABM) systems, and thermonuclear weapons primaries.[24]

• In an actual weapon, before arming the device, the DT mixture, or just the tritium, is stored outside of the pit in a separate reservoir. This facilitates maintenance and insures that boosting will not happen in case of an accidental detonation of the high explosives. Since the amount of high explosives needed to implode a boosted-device is only on the order of a few kilograms, a boosted fission-weapon is extremely safe because an accidental nuclear explosion is almost impossible to take place. This increased safety is the most important single factor which enabled so many nuclear weapons to be deployed for so many year. It is also the main reason why threshold nuclear States such as India,[25] Israel and Pakistan[26] rely on tritium-boosting technology to maintain a credible nuclear arsenal.[27]

[24] According to two U.S. weapons designers, boosted fission bombs are "lower-bounding the size and mass of hydrogen bombs" [11, p.313].

[25] India has built a plant near Mysore to produce tritium. On 11 and 13 May 1998, India exploded five first- and second-generation nuclear devices (including a two-stage hydrogen bomb) [52]. The actual size and nature of these tests is still disputed [53].

[26] Like India, Pakistan has acquired tritium technology and knowhow during the 1980s [17, 16, p.195]. On 28 and 30 May 1998, Pakistan exploded six nuclear devices. According to an interview given on 31 May 1998 by Abdul Quader Kahn, the architect of Pakistan's nuclear program, the devices were high efficiency, highly reliable enriched uranium devices. "One was a big bomb which had a yield of about 30–35 kilotons [...]. The other four were small, tactical weapons of low yield." In an interview to *The News*, he confirmed that "the devices tested on 28 May were boosted weapons, as were some of the Indian tests" [51].

[27] The gun-assembly type enriched-uranium weapons that were built by South-Africa is an example of a very unsafe design. This reduces substantially the merit of the South-African government of having dismanteled these weapons. In the case of Pakistan, it is unlikely that their nuclear deterrent would be based on primitive gun-assembly or implosion type weapons: besides from being unsafe, they would be much too heavy and cumbersome to be delivered by the aircrafts available in their air-force, or by their 1500 km range "Ghauri" missile that was tested for the first time shortly before the Indian government decided to become a declared nuclear power.

• The performance of a boosted fission device depends much more on the quality of the implosion of the pit by means of chemical explosives than on neutronics or other nuclear details. This is due to the fact that the time-scale of DT ignition is only a few nanoseconds, while the Rayleigh-Taylor instability[28] growth rate at the fissile-material/DT boundary during implosion is on the order of 100 ns. Moreover, the duration of DT burn is also only a few nanoseconds, significantly less than the fissile-material/DT mixing time, which is on the order of 5 ns at the moment of ignition. Therefore, the most important aspects of boosting (e.g., that the fusion fuel gets sufficiently compressed without mixing with the fissile material during the course of the implosion) can be tested *without* actually starting fission or fusion reactions. Obviously, this can be done outside of the scope of the CTBT, and only requires conventional equipments (such as powerful radiographic hydrodynamic test facilities) that are available in most high-explosive research laboratories. In fact, with the help of advanced hydrotest facilities, such as DARHT in the U.S.A. or AIRIX in France [511, 512], it is certain that the present stage of essentially total predictability in boosted explosives physics will be maintained. In the case of new proliferating countries, or of the three "non-official" nuclear powers,[29] such perfection might not easily be achieved. However, just like it is generally accepted that the nuclear deterrent of India, Israel, and Pakistan [16, p.195] are based on boosted fission bombs, it is safe to assume that any country with access to tritium and high-power x-ray imaging technology could easily develop and weaponize simple boosted fission explosives without nuclear testing.

• When actually exploding an experimental boosted device for testing purposes, there are several advantages in keeping the yield as low as possible. This enables: (1) to insure that the technique of using an implosion device that would be a fission-fizzle without tritium gives the calculated yield with only a minimum amount of tritium in the pit, (2) to enhance the contribution of the delicate initial fission-fusion phase relative to the final fusion-fission phase which is a simple nuclear amplification process, (3) to minimize the background signals which may overload the measuring instrumentation, (4) to be able to explode the device at a relatively low depth into the ground and to minimize the damage to the test range and its vicinities, and, finally, (5) to waste as little precious tritium as possible. This explains why most of the tests performed par India and Pakistan in May 1998 were of very low yield, i.e., of only a fraction of a kiloton.

[28] For an introduction to plasma instabilities see, e.g., [148, Chap.VII]. For a review of Rayleigh-Taylor instabilities, see [218, 219, 220].

[29] Article IX of the Nonproliferation treaty of 1968 defines a nuclear-weapon State as "one which has manufactured and exploded a nuclear weapon or other nuclear explosive device prior to 1 January 1967."

• Boosting can also be used to make efficient and reliable fission weapons in which *reactor grade* plutonium is used instead of *weapons grade* plutonium. The reason is that — with boosting — the problem of the preinitiation of the chain reaction, which creates difficulties in making a non-boosted fission bomb [66, 69], is no longer a serious problem. As was explained above, even if the chain reaction starts at the worst possible time, the temperature that can be reached in the fissile material is easily sufficient to ignite the DT mixture.[30] The preference for weapons-grade plutonium is therefore mainly a matter of convenience (e.g., to simplify the design because reactor-grade plutonium may require some kind of cooling to evacuate the ^{240}Pu decay-heat) and a way to produce warheads that can be kept in storage or on alert for relatively long periods of time before recycling. Moreover, independently of the type of fissile material used, the construction of "simple" and "deliverable" tritium-boosted nuclear weapons can be easier than the construction of primitive Hiroshima or Nagasaki type atomic bombs: the main problem is to acquire the few grams of tritium that are needed for every weapon. Two of the five devices tested by India in May 1998 are believed to have used plutonium that was not classified as weapons grade [54].

To conclude this section, we quote some appreciations of boosting.

First, an appreciation given by Lowell Wood and John Nuckolls in a short — but very informative — account [11] of the history[31] of the development of U.S. nuclear explosives:

> "Boosting thus constituted a signal advance in fission weapons: their yield could be made relatively large and stable from weapon to weapon of a given kind, and the absence of boosting could be used to diminish weapon yields to militarily negligible values (thereby greatly enhancing stockpile safety and controllability). Relatively high yields enhance military utility, relative to high compression implosion, and reproducible (and potentially more flexibly controllable) yields increased military utility still further" [11, p.312-313].

[30] In 1999 the U.S. Department of Energy declassified a statement of great importance in the context of implosion type fission weapons: "The concept of existence of preinitiation-proof nuclear weapons and the term 'preinitiation-proof weapon' (98-2)" [22, B.2.k.(1)]. Since the definition of such weapons had previously been given as "weapons, the yield of which is not sensitive to initiation of the nuclear reaction at a time earlier than the planned time (72-11) [22, B.2.k], this statement definitely supports the conclusions of this section.

[31] Most historical accounts of the development of U.S. nuclear weapons are based on interviews and biographies, and on a small number of written documents. As most of these documents have been written by scientists from the Los Alamos National Laboratory (LANL), e.g., [80, 83, 84], the article of Wood and Nuckolls [11] is particularly interesting because it tells the same story from the perspective of the Lawrence Livermore National Laboratory (LLNL). See also, [14, 33, 104, 105].

Second, two appreciations by Lev Petrovich Feoktistov, one on the stabilizing effect of boosting on the yield, and a second on its hardening effect against neutrons from other nuclear explosions:

> "A universal solution — a very dramatic one — was found later. The general idea was to combine reactions of fission with fission-fusion-fission thermonuclear reactions. (...) The greatest challenge facing nuclear arms designers was to cause a thermonuclear DT-reaction in the worst conditions and at the lowest initial efficiency, which stabilizes the yield in general. This is the reason why tritium is used alongside plutonium, at least in the most advanced types of nuclear arms" [56, p.57].

> "One of the chief targets of research was to enhance friendly nuclear arms resistance capacity to hypothetical enemy arms. (...) (R)esearch had been conducted under the guidance of Ya.B. Zeldovich into mutual support of fission and thermonuclear reactions in one unit. The chief idea was to prevent a decline in yield should enemy neutrons trigger an early, incomplete explosion" [56, p.84–85].

1.5 The principle of the hydrogen bomb

One of the original motivations to make the hydrogen bomb is that unlike fissile materials, which are rare and expensive, deuterium is abundant and inexpensive. If deuterium is burnt at a temperature of 20 keV, its maximum energy production (assuming that T and ^3He are burnt as soon as they are produced) is about $Q = 7$ MeV per fused deuteron, i.e., 80 kt per kg.[32] Hence, if we assume a fusion efficiency of 25%, a hypothetical pure-fusion bomb of one megaton requires about 50 kg of deuterium as fuel.

Today, because of the recent publication [97, 98] of two detailed accounts written by Arzamas-16[33] specialists who participated to the making of the Soviet H-bomb,[34] we know that both the American and Russian programs started by

[32] See Table 1.1.

[33] Arzamas-16, founded in the 1946, is the main Soviet nuclear weapons research laboratory.

[34] In the abstract of [97], the editors mention that this article was prompted by the polemic started by the publication of an article by D. Hirsch and W. Matthews first published in the Bull. of the Atom. Sci. (Jan./Feb. 1990) [89], translated and annotated in Sov. Phys. Uspekhi (1991) [90]. Earlier comments on the article by Hirch and Matthews were included in the same issue of Sov.

studying the possibility of heating deuterium in a shock-wave initiated by an atomic explosion. Since the device was essentially a cylinder of liquid deuterium heated at one end by an exploding fission bomb, from which thermonuclear burn would propagate to the other end, this concept had the prospect of an explosion of an unlimited power. While this concept was in Edward Teller's mind since about 1942 — the so-called "Super" — it was independently rediscovered in the Soviet Union. In particular, it was explicitly put forward in a remarkable unclassified report [72] written in 1946, practically at the same time as a secret conference was held at Los Alamos in April 1946 to review the results of American H-bomb efforts since 1942.

However, after considerable theoretical work, it was realized in 1950 in the United States (and in 1954 in the Soviet Union) that ignition and longitudinal propagation of a thermonuclear detonation in a cylinder of liquid deuterium was very difficult, if not impossible.[35] Consequently, other possibilities were given a fresh look. These included ideas derived from concepts that had been successfully tested in the meantime, such as "boosting," or Andrei Sakharov's "layer-cake." We will not try to describe these attempts or go into the details of their history.[36] Instead, we will examine the conditions under which uniform ignition and burn of a device containing on the order of 10 to 100 kg of thermonuclear fuel is possible.

In order to assess the feasibility of such a bomb, the first important consideration is to ensure that the fusion fuel is confined long enough for a substantial fraction of it to burn before it is dispersed by the explosive pressure (i.e., the pressure that accumulates within the burning fuel as a result of energy production). From thermodynamics, this pressure is between 2/3 and 1/3 of the energy density (1.13), depending on whether the kinetic or the radiation term is dominating. In the low temperature limit, the pressure is thus simply $p \approx N/V\, kT$.

Phys. Uspekhi, viz [92, 93]. See also the article by Lars-Erik De Geer [91] and the series of articles in Bull. of the Atom. Sci. (May 1993) 18-19, 20-31, 32-36, 37-39.

[35] In the 1970s, however, the feasibility of this concept was demonstrated in detailed computer simulation; only experimental complexity prevented its full-scale demonstration [11]. Referring to a "number of alternative designs (that) were considered and rejected as technically doubtful or infeasible prior to the success of the hydrogen bomb," Edward Teller stated in 1987 that, "since that time, further research proved all of these possibilities feasible, though not preferable to the actual solution" [87, p.726].

[36] Since the writing of the report [44] on which this chapter is based, an edited version of Goncharov's article [98] was published in Physics Today [99]. This prompted an open debate with two authors of [97] about the details of the history of the Russian H-bomb program [102, 103]. Similarly, new details of the history of the American H-bomb program, highlighting for instance the role of Carl Haussmann at the Livermore laboratory, have recently been published [104, 105]. It would therefore be of great interest now to have *professional* historians study all the material published to date and write a consistent history of thermonuclear weapons in Russia and the United States.

Temperatures characteristic of chemical explosions are on the order of 0.5 eV, and those of thermonuclear explosions in the 10 keV range. Hence, typical pressures of thermonuclear explosions are at least 20'000 times larger than those of chemical explosions! As nothing can oppose such pressures, the confinement time (also called the disassembly time) is entirely determined by inertia. In order to increase inertia and slow down the expansion of a mass m of fusion fuel, a standard method is to surround the fuel by a heavy tamper of mass $M > m$. Assuming that the effect of the internal pressure is to push out the tamper like a piston, Newton's law can be used to derive an estimate of the disassembly time. In first approximation,

$$\tau_d \approx \frac{R}{c_s}\sqrt{\frac{M}{m}}, \tag{1.19}$$

where R is the radius of the fuel and $c_s = \sqrt{\gamma p/\rho}$ the sound velocity[37]. At $kT = 10$–30 keV, which are typical of thermonuclear burn, the pressure p is dominated by the radiation term, a function of kT alone. In cylindrical geometry, R/c_s is then independent of the fuel density ρ. For m = 10–100 kg, and M/m = 10–100, expression (1.19) gives inertial confinement times on the order of 5–20 ns. This is the fundamental time scale to which the burn time has to be compared.

The thermonuclear burn time is difficult to estimate because it is strongly dependent on the temperature that can be reached in the fuel, taking all nuclear and electrodynamic interactions into account. For this purpose, a program like ISRINEX is essential. Anticipating the results of the simulations presented in section 1.7, it can be assumed that the burn temperature of deuterium is 20 keV. The burn time is on the order of the time necessary to burn 50% of the fuel at a constant temperature. For deuterium, assuming that T and ^3He are burnt as soon as they are produced, the burn time is then

$$\tau_b \approx \tau_{DD} = \frac{1}{2N_i < \sigma_{DD} v >}, \tag{1.20}$$

where $N_i = \chi N_o$ is the initial ion number density and $< \sigma_{DD} v >$ the Maxwell averaged reaction rate, 5×10^{-24} m^3/s at kT=20 keV. At solid density ($\chi = 1$, $\rho = 180$ kg/m^3), the burn time of deuterium is thus 2 μs. Hence, to match the

[37]This is the general definition of the sound velocity, i.e., the speed of propagation of a small disturbance. γ is the specific heat ratio, i.e., the so-called "adiabatic exponent." In a matter dominated plasma γ = 5/3 and $c_s \approx 3 \times 10^5\sqrt{kT}$ m/s for DD, DT and LiD, and $c_s \approx 2.5 \times 10^5\sqrt{kT}$ m/s for fissile materials, with kT expressed in keV in both cases. In a radiation dominated plasma γ = 4/3 and $c_s \approx 2.5 \times 10^6 (kT)^2/\rho^{1/2}$, where kT is expressed in keV and ρ in kg/m^3.

disassembly time, i.e., to have $\tau_d = \tau_b$, we find that the compression of deuterium has to be between 100 and 400 times solid density.

If we have a means for compressing the fuel to very high densities, the remaining problem is ignition. As seen in the section on boosting, radiation losses are such that the ignition temperature in low density (i.e., $\chi < 30$) deuterium is 25 keV. This temperature is too high for ignition by means of an atomic bomb. However, by increasing the fuel density, ignition becomes easier. For instance, if the density is large enough for most of the energy of the neutrons produced in the fusion reactions to be deposited within the fuel, the ignition temperature is reduced to 10 keV. An even larger reduction is obtained by compressing the fuel to the point where it becomes opaque to its own radiation. Radiation losses are then minimum and at most equal to the blackbody energy loss. In cylindrical geometry, the energy density balance is then

$$\frac{Q}{2N_o^2 < \sigma_{DD} v >} \quad > \quad \frac{1}{\chi^2}\frac{2}{R}\sigma T^4. \tag{1.21}$$

This expression shows that for sufficient amounts of fuel (R large) and sufficiently high compressions ($\chi \gg 1$), there is a limit in which the ignition temperature can in principle be made as low as desired. This limit corresponds to the maximum compression required for low temperature ignition to be possible. In the case of 50 kg of deuterium, this maximum is about $\chi = 500$, i.e., of the same magnitude as the compression factor required for the burn time to match the inertial confinement time.

However, these considerations still do not take into account the effect of the heavy tamper surrounding the fuel. In a hydrogen bomb, this tamper is made of uranium, a high-Z material opaque to radiation which prevents radiation from leaving the space occupied by fuel. As a result, the losses to the tamper are substantially lower than those given by the bremsstrahlung or blackbody laws. These reduced losses are described by a radiation-driven heat wave (a Marshak wave [185]) traveling into the tamper [187]. For high-Z materials and radiation temperatures larger than 100 eV, the re-emission factor (the ratio of the re-emitted flux and the truly absorbed flux that feeds the heat wave) is on the order of ten [145]. Thus, at the temperatures and pressures corresponding to thermonuclear ignition and burn, it turns out that these losses are on the order of 10%, and can therefore be ignored in a first approximation [149]. The compression required for ignition will thus be significantly lower than the maximum implied by (1.21).

Consequently, taking into account the reduction of losses due to fuel compression and to radiation re-emission by the tamper, it is possible to assure that

fusion energy production in large fuel samples can overcome radiation losses in a wide range of parameters. "Bootstrap heating" starting at low temperature is therefore possible. If the fuel is brought to an initial temperature of, say, 2 keV, its temperature will rise because of self-heating, and, after some period of time, reach a self-sustaining burn temperature of 15–25 keV. Of course, for this to happen, the self-heating period must be shorter than the disassembly time of the compressed fuel [150, 151]. This mode of ignition, in which the fuel is highly compressed and initially at a relatively low temperature, is called the "Wheeler" or "equilibrium" ignition mode [150, 151].[38] In the context of inertial confinement fusion, this mode of ignition is also called "volume" ignition to distinguish it from the more difficult "spark" (or "hot spot") ignition concept. In this latter mode, a small central volume of a fusion pellet is ignited first, which in turn ignites the outer material via burn propagation [149, 144].

To summarize, very high compression is the main condition for successful ignition and burn of inertially confined thermonuclear fuels: compression must be high enough for both the self-heating time (in the ignition phase) and the burn time (in the burn phase) to be short compared to the confinement time. That these conditions are met can be verified with a simulation program such as ISRINEX. In practice, the problem is that high compressions are very difficult to realize. In effect, as seen in investigating boosting, compressing small amounts of hydrogen isotopes to densities larger than 30 times solid density is already at the limit of what can be achieved using chemical explosives. Obtaining compression on the order of 100–300 in large amounts of deuterium is therefore impossible using this technique. A method using fission explosives had to be invented.

1.6 The Teller-Ulam method (Fig. 1.3)

After many unsuccessful attempts to design a hydrogen bomb, a method to achieve very high compressions was discovered by Teller and Ulam in 1951. J. Robert Oppenheimer said later (1954) of this method: "The program we had in 1949 was a tortured thing that you could well argue did not make a great deal of sense. The program in 1951 was technically so sweet that you could not argue about that" [84, p.162]. Indeed, as will be stressed much later (1983) by Carson Mark, the Los Alamos physicist who led the theoretical work on the first hydrogen bomb: "Almost immediately [the Teller and Ulam method] gave promise of a

[38] John Archibald Wheeler worked on thermonuclear research at Princeton and Los Alamos in 1950-1951. He proposed with Teller a new model of the "Alarm Clock" in 1950 and directed the team who furnished the detailed thermonuclear design of the "equilibrium thermonuclear," i.e., Mike, in 1951. In 1981 he applied similar ideas to ICF targets [138].

feasible approach to thermonuclear weapons, *provided only the design work be done properly*" [84, p.162].

Thus, a major feature of the Teller-Ulam design is that it provides a straightforward and intrinsically fail-safe method for making a thermonuclear bomb. In fact, this method is so good that *all* the first hydrogen bombs worked the *first time*. Moreover, the Chinese were able to detonate their first full-yield hydrogen bomb after only three fission bomb tests, one boosted-fission test, and one preliminary two-stage hydrogen bomb principle test [26]. This demonstrates that a rather primitive technology is sufficient to construct a megaton-yield hydrogen bomb with the Teller-Ulam method. On 17 May 1998, Indian officials claimed that one of the devices detonated on 11 May was a two-stage hydrogen bomb with a yield of about 45 kt.[39] Since a relatively low-yield H-bomb is more difficult to make than a high-yield one, this test means that India was capable to detonate a sophisticated thermonuclear device 24 years after it made its only previous nuclear test — a 12 kt fission bomb [65].

The basis of this method is the use of x-rays produced by a primary nuclear device to compress and ignite a physically *distinct* secondary nuclear assembly containing thermonuclear fuel.[40] The first more or less correct and complete description of the Teller-Ulam method is due to Howard Morland in an article drafted at the end of 1978 and published in November 1979 after the U.S. Government tried to suppress it [81]. Possibly as a reaction to Morlands' article, the following statement was declassified in February 1979: "In thermonuclear weapons, radiation from a fission explosive can be contained and used to transfer energy to compress and ignite a physically separate component containing thermonuclear fuel" [22].

Referring to Fig. 1.3, the Teller-Ulam method is as follows: a fission bomb and a container filled with fusion fuel (the secondary) are placed within a common enclosure (the radiation case); while the radiation case and the envelope of the secondary (the pusher/tamper) are made of heavy materials opaque to x-rays, the remaining space within the radiation case (the hohlraum) is filled with light-weight materials transparent to x-rays; as the primary fissions, large amounts of x-rays are radiated ahead of blast and instantaneously fill the hohlraum; x-ray radiation trapped within the hohlraum rapidly reaches its equilibrium blackbody spectrum and turns the hohlraum filling into a hot plasma; radiation-driven thermalization insures that this plasma has very uniform pressure and temperature so that its effects on the secondary are the same from all sides; the plasma reradiates longer

[39] Press conference by R. Chidambaram, A.P.J. Abdul Kalam, Anil Kakodkar and K. Santhanam.

[40] This is in contrast with earlier devices in which fusion fuel was packed around fissile material and which, in fact, were cumbersome boosted fission weapons.

wavelength x-rays that are absorbed by the surface of the secondary; the surface of the secondary (the pusher/tamper) is heated to the point where it vaporizes and material is ejected from it; the material ablated from the pusher/tamper causes by reaction a pressure which pushes the tamper inwards, imploding the fusion fuel to very high densities.[41]

A crucial idea in Teller-Ulam's method is the use of a radiation-heated low density plasma as a buffer to create very uniform driving conditions to compress the secondary equally and simultaneously form all sides. Lack of uniformity would result in instabilities during compression, or in the secondary just being blown away. The method is also applicable if the hohlraum is not filled with a low density material: the role of the buffer is then played by thermalized blackbody radiation. The advantage of the low density filling is that it allows energy of the primary to be stored as plasma thermal energy, which may later be released to the secondary to drive the ablation process [85, 86]. This is important as the primary is a time-varying radiation source with a time dependence which is not optimum for adiabatic compression.[42] Moreover, since the x-ray pulse from the primary is of relatively short duration, energy storage allows longer-sustained compression of the fusion fuel to higher compression. In any case, in a nuclear warhead, the hohlraum has to be filled by a very strong material in order to support the primary and the secondary. In gravity bombs, the filling may consist of a rigid urethane foam [584, 579, p.354], and in artillery shells or earth-penetrating warheads a strong low density metal such as beryllium.

A remarkable thing about the Teller-Ulam method is that the resulting compression mechanism is very simple and effective, even though it is based on a very complex radiation transport process. In order to check that radiation-driven ablative compression can be used to compress a large amount of fusion fuel at the same time as a the heavy tamper surrounding it, some estimate of the ablation pressure is required. Such an estimate is provided by the observation that, in first approximation, the exploding boundary layer at the surface of the pusher is a plasma whose temperature is determined by the hohlraum temperature T_h , and whose density is equal to the pusher density N_p. Hence, in first approximation,[43]

[41]The first ever published scientific paper describing an experiment in which x-ray ablative compression is used to generate very high pressure is [433].

[42]Adiabatic compression, i.e., without loss or gain of heat, minimizes the amount of energy needed to achieve a given compression.

[43]This estimate [127, p.345] can be written in various more less equivalent forms. Possibly the first published calculation of the ablation pressure gives $p_{abl} \approx I/v$, where I is the radiation energy flux and v the material escape velocity [124]. If the driving radiation has a blackbody energy spectrum, $I = \frac{1}{2}\sigma {T_h}^4$. With $v = c_s$, this gives the standard formula used in indirect drive ICF [153, p.2136].

$$p_{abl} \approx Z_{eff} N_p k T_h. \tag{1.22}$$

To compress deuterium to 300 times its solid density requires a pressure of 150 TPa (1500 megabars) [203]. If the pusher is made of uranium (which has an effective charge $Z_{eff} \approx 60\sqrt{kT}$), we find from (1.22) that the corresponding hohlraum temperature has to be 0.4 keV.[44] The hohlraum temperature needed to drive ablative compression is therefore on the order of 0.2 to 2 keV. This is lower than the maximum temperature of a fission explosive, which can therefore be used as the energy source for that purpose. Moreover, this temperature range is compatible with a hohlraum filling made of a low-density low-Z material.

In Fig. 1.3, there is an optional element not yet discussed: the *sparkplug* at the center of the secondary. It consists of a subcritical amount of fissionable material compressed at the same time as the secondary. Because of the intense neutron background resulting from the explosion of the primary, a fission chain reaction starts in the sparkplug as soon as it becomes critical (in order to avoid a fizzle, the sparkplug is boosted by a small amount of DT). Hence, with a careful design, the sparkplug will explode just when the thermonuclear fuel is imploded to its maximum density. It will then provide, in the form of x-rays, neutrons and additional compression from within, a large amount of energy sufficient to insure that ignition will start even in the worst case. Consequently, when Teller invented the sparkplug concept, soon after discovering with Ulam a means for achieving very high compressions, the whole scheme became thoroughly convincing.

The ignition mode in which a fissionable sparkplug is used to help ignition and improve the efficiency of thermonuclear burn is called the "Teller mode." In this mode, the design constraints are much less stringent than in the other modes. This is because, in the latter, heating of the fuel to thermonuclear ignition is achieved during compression by hydrodynamic conversion of kinetic energy into thermal energy. For instance, the concept of central spark ignition relies on the formation of a hot spot in the center of the imploding fuel where the decelerating motion of the material is converted into heat. If the temperature is high enough, the hot spot ignites and initiates a thermonuclear burn wave that propagates to the outer cold fuel layers. In the case of DT, the hot spot ignition temperature is 10 keV, and in the case of DD about 40 keV [144]. To obtain such high central temperatures, the implosion has to be very symmetric and the time-dependence of the ablation pressure has to have a very precisely defined profile in order for compression to be adiabatic. In this respect, the other hydrodynamic mode, volume ignition, is much less demanding [149]. In effect, provided it is high and fast enough,

[44] This estimate is in good agreement with detailed calculations [194] because the increased density of the compressed pusher is compensated by its lower temperature.

compression may be less symmetric and not necessarily adiabatic. As shown by elaborate calculations [150, 151], and confirmed by ISRINEX, the Wheeler mode ignition temperature is about 1 keV in DT and 2 keV in DD, but at the expense of a compression factor at least ten times larger.[45] Hence, while the Teller mode of ignition was used in the first thermonuclear explosives, the Wheeler mode is certainly the one used in the more modern weapons. On the other hand, there is no unambiguous information on whether or not spark ignition is used in the most modern weapons. This is one reason why the mastering of this technique in the context of inertial confinement fusion (ICF) research with megajoule laser facilities may lead to further improvement in thermonuclear weapons technology.

Having shown that Teller's ideas provide a solution to the problems of compression and ignition of a secondary, it remains to verify that they are compatible with the overall timing of a complete device. In particular, the compression and burn of the secondary has to be complete before the blast from the primary reaches the secondary. The radius of the shock wave from the center of the primary can be estimated by assuming that the full primary yield Y is concentrated in a point. This leads to the expression

$$r(t) = (Y/\rho)^{1/5} t^{2/5}, \tag{1.23}$$

where ρ is the average density of the material surrounding the fissile core and t the time [184]. For yields in the kt range and densities of a few kg/m^3, equation (1.23) shows that the shock wave is 30 cm away from the center of the primary after about one microsecond. On the other hand, the longest time involved in the functioning of the secondary is that taken by compression. This time is determined by considerations similar to those which led to expression (1.19). In first approximation the compression time is given by

$$\tau_c \approx R/c_s, \tag{1.24}$$

where now R is the radius of the secondary before compression and $c_s \approx c_s(kT_h)$ the sound velocity in the ablation layer. For R = 0.1 m and kT_h = 0.5 keV, this gives about 0.5 microsecond. Thus, there is just enough time for compressing and burning the secondary before its eventual destruction by the primary.

In the Soviet Union, work on "atomic implosion" of a secondary started in January 1954. Within a few weeks, the concepts of radiation confinement within

[45] In the case were the fuel is initially doped with 1% of tritium, further calculations show that the volume ignition temperature required remains about 2 keV for DD, but that about 3 keV is sufficient to ignite D^3He [167].

a radiation case, and of radiation implosion of a secondary, were discovered by Ya.B. Zel'dovitch and A.D. Sakharov [97, 98].[46]

To conclude this section, we summarize in Table 1.2 the sequence of events in a thermonuclear explosion and give for each event the relevant time scale.

1.7 "Mike," the first hydrogen bomb (Figs. 1.4–1.7)

The first hydrogen bomb explosion ("Mike"), on November 1, 1952, is unique because it is the only one in which liquid deuterium was used: all subsequent devices used LiD as thermonuclear fuel. It is also unique as it is the thermonuclear device for which there is, at present, the largest amount of unclassified information available. This facilitates the process of reverse-engineering and provides the data required to check that the concepts developed in the previous sections are indeed correct.

A first class of information available on Mike is of historical and descriptive nature. This type of information is compiled in Richard Rhodes's book on the making of the hydrogen bomb [95] and in Chuck Hansen's CD-ROM [96]. It confirms that Mike was a two-stage thermonuclear device of the kind Morland had previously described [81]. Rhodes's book gives a detailed qualitative description of the main components and of the functioning of Mike, as well as the few basic numbers (i.e., yield, weights, dimensions, etc.) corresponding to the overall characteristics of the device which have been declassified. It recalls, for instance, that the total yield of Mike was 10.4 *megatons*, and of these only 23% (i.e., 2.4 Mt) came from fusion, while 77% (i.e., 8 Mt) came from the fission of a heavy uranium tamper, which explains the heavy fallout produced by the explosion.

A second class of information available on Mike is a consequence of the discovery of new elements of atomic number 99 and 100, einsteinium and fermium, in the radioactive fallout from the device [224, 225]. Since these discoveries implied "that the Mike explosion had been a unique and important scientific experiment" [228, p.324], some qualitative and quantitative information on Mike was declassified after 1955. In particular, it was confirmed that the synthesis of the new elements was the result of multiple neutron capture in ^{238}U, and that this nucleosynthesis happened in a mass of ^{238}U irradiated by the large neutron flux released in the explosion of a hot compressed deuterium plasma. Moreover, it was made clear that the deuterium burn happened in such manner that the explosion

[46] The year of the 1954 seminal note of Ya.B. Zel'dovitch and A.D. Sakharov to Yu.B. Khariton is misprinted as 1955 in [97].

involved also the production of 14 MeV neutrons through DT fusion and of neutrons by the fast-fissioning of uranium. Among the quantitative information, it was specified that the neutron concentration in the ^{238}U blanket exceeded 6×10^{23} neutrons per cm^3 for 10 ns [229] (which implies a thermonuclear burn time on the order of 10 ns, see also [228]) and that the time-integrated thermal neutrons flux was 1.2×10^{24} n/cm^2 and their average thermal temperatures 5 keV [230]. See also [227].

Despite all this information, it is impossible to fully reverse-engineer Mike. This is because many details of any complicated device depend on reasonable, but somewhat arbitrary choices which are used as inputs for calculating other details. This means that in reverse-engineering such a device, the only possibility is to find the main characteristics of one (among others) plausible design. Such a design is presented in Fig. 1.4, and the main steps taken to get it are as follows:

• The general shape of Mike is that of a cylinder of 1 m radius and 6 m length. One end is rounded with the primary at the center. The total weight of the device is 82 tons. The external surface area being 41 m^2, this weight would correspond to an average thickness of 25 cm of steel, assuming that all the mass is concentrated in the envelope. Considering that a thick layer of lead was lining the inside surface of the envelope to make it opaque to the radiation, an average thickness of 10–15 cm of steel for the casing is reasonable.[47]

• 2.4 Mt of fusion energy corresponds to the burning of about 30 kg of deuterium. Assuming a fusion-burn efficiency of 25%, this corresponds to 840 liters of liquid deuterium at a density of 0.14 g/cm^3. From the photographs of Mike, and in particular from the position of the diagnostic light-pipes [95, Photo 70], the secondary appears to have a length of about 3 m. Hence, the volume of the uncompressed liquid deuterium is equivalent to a 3 m long cylinder of 30 cm radius.

• 8 Mt of fission energy corresponds to the fissioning of about 400 kg of uranium. Most of this fissioning is due to fast-fission splitting of ^{238}U nuclei in the depleted uranium pusher/tamper surrounding the deuterium tank. The weight of this uranium blanket can be derived from the maximum yield expected for Mike, which is estimated to be on the order of 50–90Mt [95, p.493]. At 17 kt/kg fission yield, 90 Mt corresponds to the total fissioning of 5300 kg of ^{238}U. Assuming a pusher/tamper of 5000 kg with an inner radius of 50 cm (i.e., leaving a space of 20 cm for the wall of the liquid deuterium Dewar flask), the uncompressed

[47] Like all exposed high-Z materials, the lead lining is covered by a layer of polyethylene to avoid lead atoms blown off by x-rays to get into the radiation channel. Soon after the explosion of the primary, these plastic layers quickly vaporize and fill the radiation channel with a low-Z plasma essentially transparent to x-rays.

uranium blanket thickness is 2.8 cm. This leaves room for a 20 cm wide radiation channel.

• The minimum compression of the secondary can be estimated by supposing that the time-integrated neutron flux is equal to the fusion neutron flux crossing the compressed deuterium boundary, plus the $(n, 2n)$ and fast-fission neutron fluxes produced by these neutrons in the blanket, assuming that all non-fusion neutrons are produced in a narrow layer at a radius equal to the compressed deuterium radius.[48] Since the number of neutrons is given by the yield, and the flux by reference [230], the compressed deuterium radius is found to be equal to about 2.7 cm. In cylindrical geometry, this corresponds to a geometrical compression factor $(30/2.7)^2 \approx 120$, i.e., a compression of deuterium to a density about 100 times higher than its solid density.

• In the ISRINEX runs, the compression of deuterium is varied between 100 and 500. Since the components of the secondary (i.e., the depleted uranium blanket, the deuterium fuel, and the plutonium sparkplug) are compressed simultaneously, the compression of its various parts can be found from equation of state tables [203], assuming uniform pressure over the secondary. This implies the simplifying assumption that the entire secondary is brought to rest at turnaround [149]. For example, a compression of 300 of the deuterium corresponds to a compression of 8 of the blanket and 16 of the sparkplug.[49]

• The radius of the plutonium sparkplug is determined by the requirement that the sparkplug becomes critical at a time close to the moment when maximum compression is achieved in the secondary. For a compression of 16, the uncompressed radius of a plutonium sparkplug is about 1 cm. This corresponds to 18 kg of plutonium which, because of the intense fusion-neutron bombardment, is totally fissioned in the explosion, contributing 300 kt to the total yield.

• The minimum yield of the primary is determined by the energy required to compress the secondary (i.e., 120 kg of deuterium and 5000 kg of uranium) by a given factor, assuming that no energy is required to heat the fuel. For compression factors of 300 and 16, i.e., $\rho_D = 53$ and $\rho_U = 300$ g/cm^3, the adiabatic compression energies [203] are about 3'000 and 500 MJ/kg, i.e., $0.4 + 2.5 \approx 3$ TJ in total. The typical energy content of a chemical explosive is 5 MJ/kg. Hence, the minimum energy required to compress Mikes's secondary is equivalent to the energy of about 0.6 kt of high explosives. Assuming that the conversion of primary energy into hohlraum plasma energy is 10% and that the efficiency of

[48] This is essentially the method suggested by Lars-Eric de Geer on page 356 of [91].

[49] To approximately take the effect of shock wave convergence into account, we assume that compression is on average a factor of two higher in the sparkplug than in the blanket.

ablative compression is about 25%, a minimum primary yield of $25\ kt$ is required.[50]

The secondary, with deuterium compressed to 300 times its solid density, is shown in Fig. 1.5. The deuterium is squeezed down to a 1.5 cm thick layer surrounding the sparkplug (0.25 cm radius). At this high compression stage, the volume of the thermonuclear fuel is very small in comparison with that of the 12 cm diameter cylinder of depleted uranium surrounding it. The situation is rather similar to that of a compressed boosted primary (Fig. 1.1), except that the geometry here is cylindrical rather than spherical and that the compressions are much higher. As for boosting, it follows that the inertial confinement time is strongly influenced by the tamping effect of the heavy material surrounding the fuel. At a burn temperature of 20 keV, $R/c_s = 3.5$ ns. Thus, with $M/m = 5000/120$, the confinement time calculated with (1.19) is 22 ns. As expression (1.19) is an approximation obtained by ignoring shock compression effects and assuming that the tamper is moving as a whole according to Newton's law, it tends to overestimate the confinement time. However, it is safe to estimate the confinement time to be on the order of 10 ns, in agreement with [229].

The consistency of this model of Mike is checked by looking at the outputs of ISRINEX calculations. These simulations are essential to have a realistic picture of the time evolution of ignition and burn. In Fig. 1.6 we see the Wheeler-mode ignition and burn for deuterium compressions between 100 and 500. The initial temperature is 2 keV for all cases and all three temperatures. The upper part of Fig. 1.6 shows the burnup and the bottom part the ion temperature. In one case, i.e., when compression equals 200, the time evolutions of the ion, electron, and photon temperatures are shown. Unlike the case of deuterium-tritium (Fig. 1.2), there is no significant run-away of the ion temperature after ignition: above 20 keV, T_i is only 2–3 keV higher than T_e, and T_e is higher than T_r by only a very small amount. This is because in comparison to the DT reaction rate, the DD reaction rate is small relative to the inverse-Compton reaction rate. As DD starts burning, most of the energy is transferred to the electrons and photons, so that the ion temperature rise remains slow. To illustrate the crucial importance of inverse-Compton effects, the temperature T_i^* the ions would have in the absence of these effects is shown: as soon as T_i^* reaches 10 keV, it rises to several hundred keV, an unphysical effect that would enable deuterium to burn by simple contact with an atomic bomb...

Figure 1.7 shows the Teller mode ignition and burn of Mike assuming a 6 keV sparkplug temperature. Compared with Fig. 1.6, the various curves have roughly the same slope but ignition, i.e., $T_i = 10$ keV, is reached in less than 10 ns in all cases when the compression is higher than 200. Hence, in Teller mode, 25%

[50] This is 1% of Mike's 2.4 Mt fusion yield. Most likely, the yield of Mike's primary was in the 50 to 200 kt range.

of the fuel can burn in less than 10 ns when the compression is 200, and over 50% of the deuterium can burn in less than 10 ns if the compression is equal to or higher than 300. On the other hand, in the Wheeler mode, self-ignition and burn in less than a confinement time of 10 ns requires $\chi = 500$, a substantially larger compression factor.

Even though the model of Fig. 1.4 and the computer outputs of Figs. 1.6 and 1.7 are sufficient to understand how and why Mike works, they should not be taken as a blue-print or measured results of Mike. This is even more true for Fig. 1.5, as it does not take into account the fact that at the time of maximum compression, the outer surface of the tamper can be severely ablated — unless it is lined by a special pusher material which is blown off when maximum compression is reached. Moreover, several details of the ablation compression process were not taken into account. For instance, the radiation not only ablates the pusher/tamper, but also ablates material from the casing. The inward-moving material expands into the radiation channel and ultimately collides with the ablating material moving outward from the pusher surface. Also, the casing should have sufficient inertia for the radiation to remain trapped long enough in the radiation channel. In other words, in addition to complications arising from numerous engineering constraints, complex processes such as ablation, instabilities, mixing, shock waves, and radiation hydrodynamics should be taken into account in a truly realistic simulation.

Despite all this complexity, a multi-megaton thermonuclear bomb like Mike is a relatively simple device. This is particularly true in comparison with earlier thermonuclear concepts, Teller's "Alarm Clock,"[51] or even the classical "Super". As recalled by Carson Mark in 1974: "The fantastic requirements on calculations imposed by the attempts to explore the question of the classical Super as envisaged in 1946 did not, of course, apply to the same extent with respect to thermonuclear devices in the form considered since early 1951" [80, p.10]. Moreover: "The calculations made in connection with the design of the Mike shot were all made in the year between mid-1951 and mid-1952" [80, p.12].

Similar observations can be made for the Soviet designs. In Sakharov's "layer-cake" ("sloyka" in Russian), like in Teller's "Alarm Clock," the thermonuclear fuel is not burnt under almost static condition as in the center of a Teller-Ulam secondary, but squeezed between an expanding atomic bomb and a moving external tamper. Hence, the fuel is in a very unstable state, surfing on the crest of the disassembly shock wave of an atomic bomb. Compression can thus never become very high, nor be maintained for a long time. Moreover, construction of the layer-cake was very cumbersome. On the other hand, after the discovery of radiation

[51] As in Sakharov's "layer-cake", in Teller's "Alarm Clock," alternating layers of LiD and uranium are wrapped around the core of a fission bomb.

implosion in early 1954 and the completion of the technical specification for building a device in February 1955, computations and theoretical work on a two-stage device were completed by early summer.[52] The experimental thermonuclear charge was successfully tested on November 22 of the same year [97, 98, 99]. As was the case in the United States, "the extraordinary complexity of the physical processes involved did not stand in the way of doing the necessary calculations on the rather simple Mercedes calculating machines in the Soviet Union in 1954. The need for more subtle modeling, unfeasible without computers, did not arise until further improvements had to be made in thermonuclear charges and the characteristics of the structural components had to be refined"[102, p.856].[53]

The relative simplicity which led to the success of Mike and of all subsequent thermonuclear devices can now be explained in rather general terms. It derives from the fact that the Teller-Ulam concept and the sparkplug idea are based on processes that are intrinsically stable: provided some thresholds are crossed, the processes necessarily evolve successfully. This is exactly the case with the atomic bomb: provided a higher than critical mass of fissile material is assembled, the diverging chain-reaction is unavoidable. With the hydrogen bomb, the key threshold is a sufficient compression of the secondary. This is enough to trigger the sparkplug and ignite the fuel. The next threshold is then enough inertia for significant thermonuclear burn to occur. Hence, by simply increasing the yield of the primary and by surrounding the fuel by a sufficiently heavy tamper, one obtains a high yield thermonuclear explosive that works without fail.

1.8 B-28: The first "miniature" multi-purpose H-bomb (Figs. 1.8–1.10)

There are very few technical details publicly available on any stockpiled thermonuclear weapon. While this secrecy might at first seem reasonable if we imagine that such data could be important to a potential enemy or proliferator, it makes

[52] This is remarkable since the 1954 Soviet computers were considerably less powerful than those available to Americans in 1952. This means that while most of the numerical calculations had to be done with the help of simple computing machines, the Soviet scientists had developed a particularly good understanding of the theory of the physical processes involved. That this was the case is demonstrated by the very high quality of the Soviet text-books in plasma physics that were later published, e.g., [187], and which became the world standard reference publications on the subject.

[53] The fact that relatively limited computing resources are enough to design unsophisticated hydrogen bombs is a controversial subject. In the case of the French H-bomb, see references [100] and [101].

much less sense when considering that thermonuclear weapons are in fact based on a small number of simple physical ideas. Moreover, these ideas were all discovered and put into practice between 1940 and 1960. Nothing fundamental has changed since that time: the perfection of thermonuclear weapons has been a slow process of successive improvements in which no real revolutionary concept has been introduced since the mid 1950s. This enables us to discuss in general terms what most likely occurred since then even though we have no access to classified information.

The first stockpiled hydrogen bombs were heavy multi-megaton devices that could only be delivered by bombers. Subsequently, the emphasis shifted to lower yield devices. The American B-28 bomb (of which 1200 were deployed starting in 1958) is an example of a single-megaton strategic and tactical thermonuclear bomb built in numerous versions and carried by a wide variety of aircraft.

Quantitatively, all that is known of the B-28 is that its warhead had a yield between 70 kt and 1.45 Mt, a weight between 975 and 1150 kg, a maximum diameter of 50 cm, and a length of about 90cm [10]. Nevertheless, this information is enough to sketch a plausible design for the B-28.

One can suppose that the B-28 is based, just like Mike, on a very conservative design. The confinement time is thus determined by inertia from a rather heavy tamper, and thermonuclear ignition is assured by a ^{235}U sparkplug.[54] The main qualitative differences with Mike are that the thermonuclear fuel is lithium-6 deuterid instead of liquid deuterium, and that the uranium blanket surrounding the secondary is more than just a tamper and energy multiplier, i.e., it also serves as a neutron reflector/multiplier enabling the Jetter cycle (9) to run. Otherwise, many details of the B-28 derive from those of Mike: the radiation channel is filled with some strong low-density material, the sparkplug boosted by a small amount of tritium, etc.[55]

One can also suppose that most of the yield will come from fission rather than from fusion and (as our first numerical hypothesis) that the fusion yield is 200 kt with a fusion efficiency (burnup) of 50%. For LiD, when burning at temperatures

[54] Although plutonium was the fissile material used in the sparkplug of Mike, it seems that most American thermonuclear weapons use ^{235}U in the secondary, despite the larger critical mass of ^{235}U relative to plutonium. This is due to the relatively lower cost of enriched uranium and to the fact that ^{235}U poses less maintenance problems than plutonium.

[55] While these details are well known for Mike, the corresponding statements for thermonuclear weapons in general were declassified only in 1999: "The fact that materials may be present in channels and the term 'channel filler,' with no elaboration (98–2)" [22, C.2.n]; "The existence of secondary designs containing liquid or gaseous isotopes of hydrogen with no elaboration (98–2)" [22, C.2.o].

sufficient to sustain the Jetter cycle, the maximum yield is about 50 kt/kg. This implies 8 kg of LiD, which corresponds to a volume of about 10 dm^3. Assuming 50 cm for the length of the secondary, this gives a radius of 8 cm for the LiD.

Since the total weight of the warhead is around 1'000 kg and a reasonable maximum weight for the tamper is somewhat less than half of that, one can suppose that the tamper weighs 400 kg. This corresponds to a 6 cm-thick layer of uranium wrapped around the LiD. With a burn temperature of 20 keV, the LiD disassembly time scale is $R/c_s = 2.2$ ns for $R = 8$ cm. Taking the 400 kg tamper into account, formula (1.19) gives a confinement time of about 15 ns.

A fusion yield of 200 kt corresponds to 3×10^{26} DT fusions reactions. Assuming that for each of these reactions about one out of three neutrons escapes into the blanket and provokes a fast fission, the corresponding total fission energy is 800 kt. This means that under these conditions the total yield of the B-28 is approximately 1.2 Mt — including a 200 kt yield from the fissioning of the sparkplug.

It is most interesting to consider ISRINEX's results for the ignition and burn of LiD (shown in Figs. 1.9 and 1.10) and to compare them to those of Mike. Since the effective volume of the LiD molecule is about 2.2 times smaller than the effective volume of the D_2 molecule (or of the DT or H_2 molecules) at solid density, the deuterium number density in LiD is approximately the same as in solid D_2 (in fact it is about 10% larger). Consequently, curves corresponding to the same compression factor, e.g., curves in Figs. 1.6 and 1.9 with the same χ, can be compared directly because they are normalized in that they have about the same voluminal concentrations of hydrogen isotopes.

Comparing ignition and burn of D_2 and LiD (Figs. 1.6 and 1.9), it is readily seen that, as soon as ignition (i.e., $T_i = 10$ keV) is reached, the LiD burn rate is much larger than the DD burn rate. This is because in LiD, the neutrons produced in the reaction (1.4)[56] produce tritium *in situ* by interacting with lithium in the exothermic reaction (1.6). Moreover, since the LiD fuel is surrounded by a thick uranium blanket, those neutrons which escape from the burn zone are multiplied in number by fast-fission of uranium or the $(n, 2n)$ reaction (1.7), and therefore reflected back into the burn zone because the neutron albedo of the blanket is greater than one. Consequently, the tritium concentration in LiD increases exponentially, until it levels off at the time the Jetter cycle (1.9) becomes the dominant process at the peak of the reaction. However, because of losses due to the presence of lithium, the Jetter cycle burn time is never as short as the DT reaction (1.1) burn time. Thus, the LiD burn time has a value between that of DD and DT. To make

[56] Or in the daughter reaction (1.1) in which the tritium produced in (1.3) is burnt.

this statement quantitative, the DT equivalent of expression (1.20) is introduced, i.e., the DT reaction burn time:

$$\tau_{DT} = \frac{2}{N_i < \sigma_{DT} v >}, \tag{1.25}$$

where N_i is again the total hydrogen isotope number density[57]. At $kT = 20$ keV, $< \sigma_{DT} v >= 4 \times 10^{22}$ m^3/s, so that $\tau_{DT} = 100/\chi$ ns. Hence, at 20 keV, the DT burn time is 20 times less than the DD burn time. Turning to ISRINEX results, the effective burn times can be determined from the slopes of the curves in Figs. 1.6 and 1.9. For DD, the ISRINEX results are consistent with expression (1.20), i.e., $\tau_{DD} = 2000/\chi$ ns. For LiD, on average $\tau_{LiD} = 300/\chi$ ns. Thus, in good approximation, LiD is about 8–10 times better than DD and only 2–3 times worse than DT — the best possible thermonuclear fuel. In conclusion LiD is a good substitute for D_2, especially since LiD is solid while D_2 is liquid at ordinary temperatures.

However, compared with D_2, LiD has two disadvantages. First, it is heavier than D_2 and requires more energy to be compressed by a given factor. Second, as found by trial and error with ISRINEX, the Wheeler mode starting temperature has to be 4 keV with LiD instead of 2 keV with D_2. Otherwise, self-ignition fails because low-temperature self-heating is less effective in LiD than in DD. This is because in LiD there are more electrons per deuteron, which implies that LiD has a greater heat capacity as well as a larger energy transfer rate between charged particles and photons, so that the ion temperature rises more slowly with time than in D_2.

The first disadvantage of LiD is compensated by its higher reaction rate and the possibility of raising the yield of the primary. The second disadvantage disappears if a fission sparkplug is used. Hence, LiD remains a good substitute for D_2. This is confirmed by ISRINEX. Figure 1.10, i.e., B-28 burn in Teller mode, shows that 50% of the fuel burns in less than 10 ns when the compression is 150 and that over 75% of it burns in the same time if the compression is equal or higher than 200. This is compatible with the confinement time given by (1.19). The assumptions made in sketching the design presented in Fig. 1.8 are thus consistent with the physics of LiD ignition and burn.

Finally, it is useful to make a comment on *in situ* tritium breeding because it is sometimes suggested that either the primary or the sparkplug are playing an

[57]The factor of 4 difference between expression (1.20) and expression (1.25) comes from the fact that the DT reaction has two distinct particles in the input channel, while the DD reaction had two identical ones, and that each of the DT reactions produces either a T or an ^3He – which are assumed to react with another D as soon as they are produced.

essential role for that purpose. This is, however, not the case: the number of neutrons set free, in either the fission of the primary or of the sparkplug, are orders of magnitude too small to contribute substantially to tritium breeding during LiD burn. On the other hand, just as the neutrons from the primary are needed to start the fission chain reaction in the sparkplug, any amount of tritium bred by neutrons from the primary or the sparkplug will "enrich" the LiD and facilitate ignition.

1.9 1970-1980 thermonuclear designs (Fig. 1.11)

The possibilities of improvement in thermonuclear weapons design are constrained by ultimate limiting factors such as the maximum fission yield (i.e., about 17 kt/kg for either fissile materials such as ^{235}U, or Pu, or fast-fissioning blanket materials such as natural or depleted uranium) and the maximum fusion yield (i.e., about 50 kt/kg for LiD).[58] This leads to the definition of the *yield-to-weight ratio* as the main figure of merit of a thermonuclear weapon. For the B-28, this factor is 1'000 kt/1'000 kg , i.e., about one kt per kg, a factor of fifty smaller than the theoretical maximum.

The second important figure of merit is simply the *weight*: since the typical payload that can be carried by an ICBM (intercontinental ballistic missile) is on the order of a few tons, the lighter the warheads the more weapons can be carried in a MIRV (multiple independent reentry vehicle) configuration. The evolution of the U.S. nuclear arsenal [10], which is certainly representative of what is possible in terms of modernization, reveals strikingly that the yield-to-weight ratio of strategic weapons remained fairly constant since 1960, at about one kt/kg. This reflects the fact that thermonuclear weapons technology has not fundamentally changed since then. Consequently, while the weight of strategic warheads has continuously decreased since 1960, the yield of the weapons decreased in roughly the same proportion, so that the main overall trend has been one of *miniaturization*, i.e., of scaling down a well known design.

However, it is also known that there have been a considerable number of improvements it terms of safety, reliability, serviceability, hardness, etc. [20]. Since all of these features require additional space and weight, there must have been some improvements in the design itself.

Firstly, there has been an increased reliance on fusion energy production (which yields 50 kt/kg) relative to fission energy production (17 kt/kg). However, this is only significant if the total weight is substantially reduced at the same time. This

[58] See Table 1.1.

is illustrated by the largest thermonuclear device ever tested, the Soviet 60 Mt explosion of October 1962. In order to reduce the fallout, the heavy uranium tamper around the fusion fuel was replaced by lead [22, p.97]. This material has good neutron multiplication and reflection properties, allowing the Jetter cycle to run efficiently, but only a small fast-fission cross-section compared with that of depleted uranium. As a result, the explosion was almost "pure-fusion," with only a few megaton fission yield out of a total of sixty [22, p.97].[59] However, the device was certainly very heavy and bulky. Hence, an improvement in the yield-to-weight ratio by increasing the fusion yield requires a significant decrease in weight, and, more specifically, in the weight of the tamper (since it contributes less to the total yield).

Second, sufficient improvement in understanding the physics of the secondary led to the possibility of dispensing of the sparkplug for igniting the thermonuclear fuel. In effect, while the sparkplug gives a simple solution to the problem of ignition, it is at the same time a radioactive component which, just like the fissile material in the primary, leads to maintenance and reliability problems.[60] Moreover, since the sparkplug is boosted by some DT gas, the whole secondary becomes a much simpler and essentially passive device if the sparkplug can be eliminated.

In fact, extensive above- and under-ground testing, and considerable progress in theoretical modeling, led to more efficient implosion of the secondary. This not only allowed higher compressions to be reached so that the fuel could burn faster and the amount of tamping could be reduced, but also to heat the fuel to a higher initial temperature so that the Wheeler mode became sufficient on its own to ignite the fuel (making the sparkplug unnecessary).

Figure 1.11 sketches a plausible, but hypothetical, design for the W78/Mk-12A reentry vehicle (RV) for the Minuteman-III ICBM. The basic assumptions are that there is no sparkplug and that the total yield is about 50% fission and 50% fusion. These characteristics can be met with 6 kg LiD as fuel and a uranium tamper of 100 kg. The yield of the W78 warhead is 330 kt and total weight of the Mk-12A reentry vehicle less than 360 kg [10]. With a mass equal to that of the reentry vehicle, this gives a yield-to-weight ratio of about one. On the other hand, with a warhead mass of 200 kg, as implied by Fig. 1.11, the yield-to-weight ratio is 1.65 .

An important variation of the design sketched in Fig. 1.11 is to apply a concept which was already suggested in the Teller-Ulam document of 1951, namely to use

[59] According to Khariton and Smirnov, two key participants in the Soviet nuclear weapons program, this explosion was "97% pure" fusion [94, p.30]. But the device was by no means a "neutron bomb": most of the fusion neutrons stopped in the lead instead of escaping.

[60] These problems are most serious if Pu is used as the sparkplug material. This is why stockpiled thermonuclear weapons use ^{235}U instead.

enriched uranium rather than depleted or natural uranium for the pusher/tamper surrounding the thermonuclear fuel in the secondary [11, p.315]. Since the cross-section for fission by neutrons with energies above 2 MeV is about twice as large for ^{235}U than for ^{238}U (see, e.g., [69, p.114]), the thermonuclear fusion neutrons will produced about twice as many fissions in a highly enriched uranium tamper than in one made of depleted uranium.[61] Therefore, by simply replacing part or all of the depleted uranium by enriched uranium it is possible to significantly increase the total yield of the warhead without increasing its weight and volume, or to reduce its weight and volume for a given yield.[62]

This concept was first demonstrated in the late 1950s by a team of the Lawrence Livermore laboratory lead by Carl Haussmann[63] and was first used in the W47 warhead for the Polaris submarine launched missile [11, p.315], [27, p.54], [104, 105]. According to reference [11], "virtually all modern thermonuclear weapons of all nuclear powers derive from this advance, including all MIRV explosives" [11, p.315].

A major penalty of using ^{235}U instead of ^{238}U for the tamper is obviously the high cost of enriched uranium.[64] This lead to a fierce competition for this scarce and expensive material during the early 1980's when the warheads under consideration for the Trident II and the MX missiles were designed to use ^{235}U to reach the desired half-megaton yield range, but there was not enough available for both systems [27, p.153].[65]

A significant improvement in the performance of secondaries using *enriched* uranium is obtained if the compression by the primary is sufficiently high to make the pusher/tamper critical and therefore to allow a self-sustaining chain reaction to run in the secondary's fissile material. This can be achieved in two circumstances. First, a highly efficient primary may compress the pusher/tamper so much that it becomes critical before the fusion reactions begin in the LiD. The fissioning pusher/tamper could then heat the LiD and replace the axial "sparkplug" that

[61] Moreover, since ^{235}U is also fissionable by neutrons with energies less than 1 MeV, moderated neutrons and secondary neutrons generated by various fusion-neutron interactions will also produce more fissions in enriched than in depleted uranium.

[62] This concept corresponds to the design code-named "L-3" in [33, p.131-133].

[63] Carl Haussmann arrived at Livermore in 1953 as the Laboratory's second military research associate. He was previously a member of the team that helped Princeton University's John Wheeler calculate the first hydrogen bomb [105].

[64] "If cost were no object, very high yield-to-weight weapons could be developed in small weight classes by extensive use of tritium, ^{235}U and plutonium." Harold Brown to Alfred D. Starbird, 29 January 1958, quoted in [33, p.144].

[65] The yield of the W87 warhead for the MX could be increased from about 300 kt to about 500 kt by adding a sleeve of ^{235}U around the secondary [10, p.126], [12, p.203].

normally starts the thermonuclear reactions. The secondary would then resemble a boosted primary, with x-rays, ^{235}U, and LiD replacing the chemical explosives, plutonium, and DT of the primary. Second, the pusher/tamper may become briefly critical during or after thermonuclear burn. The contribution by fission in the pusher/tamper would then be larger than by the effect of the increased fission cross-section of ^{235}U relative to ^{238}U alone. Either way, high compression of the pusher/tamper results in a design requiring less fissionable and fusionable materials for a given yield, a significant economy that seems to have been realized in going from the 330 kt W78 of the 1970s to the 300 kt W87 of the 1980s [10, p.126], [12, p.203].

1.10 Thermonuclear detonation waves and spark ignition (Fig. 1.12)

As we turn to more recent (or more sophisticated) designs, our considerations become more speculative. One reason is that the emphasis on high yield thermonuclear weapons has steadily decreased between 1950 and the present. Contemporary strategic weapons have yields in the 0.1 Mt range, while similar weapons of the 1960s had yields in the 1 Mt range. This comes in part from the fact that a larger number of lower yield weapons is strategically more effective than a small number of high yield weapons.[66]

Hence, as strategy moved in the direction of requiring large numbers of relatively low-yield low-weight thermonuclear weapons, technological developments came closer to the engineering limits. This is because certain physical phenomena scale differently with changes in size than others, and in the case of thermonuclear weapons this makes low-yield weapons more difficult to build than high-yield weapons. As a consequence, without access to classified information, it is also more difficult to guess what compromise had to be made in order to build modern thermonuclear weapons.

However, starting from conservative designs in which ignition and confinement are achieved by external means such as a sparkplug or a heavy tamper, the obvious route to improvement is to master the technique of thermonuclear detonation waves.[67] In fact, this idea was part of thermonuclear weapons research from

[66] This is especially the case if the lower yield weapons are MIRVed in such a way that a given target is targeted by several warheads carried by different rockets.

[67] A comprehensive review of thermonuclear detonation wave physics, including a number of historical and technical comments related to nuclear weapons, has been recently published in Russia [200].

the beginning [72]. It was probably inspired by what happens in a chemical explosion. In the latter, the detonation wave consists of a shock wave followed by a reaction zone (the Zel'dovich-von Neumann-Doring model). The energy produced by the chemical reaction is such that the detonation front moves at supersonic speed. For this reason, the whole mass of explosive is consumed before it starts flowing apart. Similarly, if a central hot spot (a "spark") is formed in some thermonuclear fuel, which then ignites and initiates a burn wave that propagates outward[68] more rapidly than the "inertially confined" fuel can expand, it is possible to achieve high burn efficiency without using a tamper. Moreover, since ignition of a central spark requires less energy than heating the whole volume of the fuel, thermonuclear detonation waves provide in principle the most efficient method for burning thermonuclear fuel. Similarly, since there is no heavy tamper to compress at the same time as the fuel, and since compression of the fuel can be adiabatic apart from the small amount necessary to heat the spark, the energy required to implode and heat the fuel is minimized.[69]

An important property of thermonuclear detonations, as compared with chemical ones, is the enormous compression of the matter, which is caused by the much higher energy release in nuclear reactions than in chemical reactions. Nuclear detonations lead to compression ratios of several hundreds [200, p.1143].

In practice, the formation of thermonuclear detonation waves is very difficult. The reason is that the thickness of such waves is very large, on the same order as the size of a typical nuclear weapon.[70] This thickness comes from the way the thermonuclear detonation wave front propagates (i.e., from the nature of the processes heating the cold fuel in front of the wave) and from the way thermonuclear energy is released in the reaction zone behind the detonation front.

At least three mechanisms can in principle contribute to the propagation of a thermonuclear burn wave and make it more complicated and thicker than an ordinary shock wave: photons [185, 187, 125], charged fusion products [191, 82, 192], and possibly neutrons if compression is sufficiently large [191, 82, 192]. The minimum thickness of the detonation wave is then on the order of the absorption length of the corresponding radiations, which are measured (at solid densities and thermonuclear temperatures) in centimeters or more.

The maximum thickness of the detonation wave is on the order of the product of

[68] Through the cooler outer regions of the fuel.

[69] This is confirmed by detailed ICF simulations which, however, show that the performance of spark ignition is in fact no more than a factor of two better than that of optimal volume ignition [144].

[70] In comparison, the thickness of an ordinary shock wave is on the order of the molecular mean free path, i.e., totally negligible on the macroscopic scale.

the mean thermonuclear reaction time τ_b times the shock velocity $M_s c_s$ [72, 188]. Hence, in first approximation,

$$\lambda = \tau_b c_s M_s, \tag{1.26}$$

where c_s is the sound velocity and M_s the Mach number. In the strong shock limit[71], $M_s \approx \sqrt{2/\gamma(\gamma-1)}$, i.e., $M_s = 1.3$ to 2.1 depending whether the plasma energy density is matter or radiation dominated ($\gamma = 5/3$ or $4/3$). The difficulty of generating thermonuclear detonation waves in a thermonuclear explosive can now be measured by the ratio, Ω, of the radius R of the fuel to the thickness λ of the thermonuclear wave (1.26):

$$\Omega = \frac{R}{\lambda}\chi_s. \tag{1.27}$$

Here R and λ are calculated at the initial compression of the fuel, and χ_s takes into account the fact that the outgoing detonation wave is compressing the fuel by an extra factor[72] $\chi_s \approx (\gamma+1)/(\gamma-1)$, i.e., $\chi_s = 4$ to 7. If Ω is much larger than one, thermonuclear detonation waves are possible. If Ω is close to or less than one, such waves are marginally possible or impossible. A conservative estimate of the possibility of thermonuclear detonation waves is provided by the optimistic assumption that radiation effects can be neglected in first approximation (i.e., $M_s = 1.3$, $\chi_s = 4$, and c_s given by the matter sound velocity). Using $\tau_{DD} = 2000/\chi$ ns for DD and $\tau_{LiD} = 300/\chi$ ns for LiD as determined by ISRINEX, and calculating c_s at an average burn temperature of 20 keV, thermonuclear detonation waves are found only marginally possible in Mike, the early B-28, or even in the more advanced W78 type hydrogen bombs. In other words, it is likely that none of these bombs were sufficiently large, nor was compression sufficiently high, for a thermonuclear detonation wave to play an important role.

In order to have a high radius to wave-thickness ratio, the best configuration for the secondary is given by spherical symmetry. This is suggested in Fig. 1.12, where the LiD is in the form of a thick hollow shell, with possibly some DT gas in the center to facilitate ignition. For 10 kg of LiD, which corresponds to a maximum yield of 250 kt at 50% burn efficiency, the uncompressed fuel radius is 15 cm and $\Omega \gg 20$ for $\chi = 100$. Spark ignition and thermonuclear detonation waves

[71] The exact shock jump equations giving the post-shock state in terms of the pre-shock state and the Mach number can be found in section 85 of [186]. The special case in which the shock wave propagates into a stationary medium, which applies here, can be found in [190].

[72] See previous footnote.

are then possible and it is likely that the most modern thermonuclear weapons are based on such a design. In this configuration, because of spherical symmetry, the radius of the secondary is larger than the radius of the primary. It is then natural to place the primary towards the front of the RV and the secondary at the rear, what is apparently normal U.S. practice [28, p.14]. This is confirmed by the fact that, in the case of the French submarine launched ballistics missile RV (where the secondary is towards the front and the primary at the rear) the small space around the secondary was a special problem for design [28, p.14].

According to information released by U.S. federal officials in the context of the alleged charge that China had obtain design secrets of the W-88, the U.S. arsenal's most modern warhead, it appears that the W-88 primary is indeed placed in the front and the secondary in the rear, and that the shape of the W-88 thermonuclear fuel is definitely of spherical symmetry [107]. Of the three other "key" attributes of the W-88 listed in an internal Chinese document obtained by CIA, two measurements accurate to within one millimeter (the sizes of the casings containing the primary and the secondary) are not significative because such precision is irrelevant to the construction of a different weapon and because their approximate value can be deduced with sufficient precision from the outside dimensions of the warhead (or estimated by calculations of the kind we made in this report).

The final attribute concerns the shape of the core of the atomic trigger which is described as non spherical.[73] Oval shaped fissile cores have been considered since 1944 as a practical means for making compact fission bombs in which criticality is achieved by deforming the ellipsoid into a sphere by a relatively small amount of high explosives.[74] Development of a boosted device using an oval plutonium pit was part of Lawrence Livermore's laboratory initial research program from 1953 onwards.[75] Such a device, tested in the *Tesla* event, performed as expected on 1 March 1955 [33, p.95]. Its design challenged computational tools available at the time and helped propel Livermore's development of two-

[73] In principle, both the fissile material of the primary and the fusion material of the secondary can be of spherical or non-spherical symmetry. A possible design of the neutron bomb published in 1984 relied on the assumption that the secondary was of oval shape [113].

[74] It is well known that chemical explosives of non spherical shape can be used to form cylindrically or spherically collapsing waves [189, p.238]. (See also, [61, Fig. 8]). More generally, high-explosive systems of non spherical shape can be designed to implode non spherical cores. This leads to fission explosives which are slimmer and therefore easier to fit in the nose cone of strategic weapons than spherical ones. According to David Wise's article *Inside the Chinese spy mystery*, Gentleman's Quarterly (November 1999) 285–300, page 288, "the W-88's primary (is) *two-pont aspherical* (...) meaning that it (is) shaped more like a football or pear than a grapefruit, with implosion points at each end."

[75] Even though this weapons design concept is well-known since many years, this line of research is code named "Manticore" in [33].

dimensional computer codes. A series of tests completed in the 1957 *Plumbob* series resulted in the "Robin" family of primaries [33, p.132]. As Robins were well suited to the narrow confines of strategic missiles reentry vehicles, they soon became a standard feature of the stockpile, deployed in both Livermore and Los Alamos systems for many years [33, p.133].[76] In fact, a non-spherical pit might be an important ingredient in making nuclear weapons that are "inherently safe."[77] Indeed, if boosting is a dramatic contribution to increased safety, boosting *alone* is not enough: an accidental explosion of a spherically symmetric pit might result in some nuclear yield even when there is no deuterium-tritium in the pit. However, if the pit is oval, or more generally aspherical, it can be made to collapse linearly in the absence of boost gas so that the fissile material will just be dispersed instead of becoming critical.

In the reentry vehicle depicted in Fig. 1.12, the warhead itself may weigh as little as 100 kg and have a maximum diameter of 30 cm and a length of about 60 cm. These figures are compatible with the characteristics of the W80 warhead for U.S. cruise missiles, which has a yield-to-weight ratio of about two [10]. Similar characteristics can be deduced for the "physics pack" of the B61 nuclear bomb, using published photographs [46] and the information that the basic W80 warhead design is a modification of the B61 bomb [10].

In conclusion, while sophisticated designs of the kind depicted in Fig. 1.12 have certainly been studied,[78] and may even be used in some recent warheads, it is likely that the majority of stockpiled thermonuclear weapons are still of the type sketched in Fig. 1.11, i.e., of a relatively simple design with highly enriched uranium used in the "third stage" of the fission-fusion-fission yield generation mechanism. This leads to the 50% fission, 50% fusion, type of thermonuclear devices that are characteristic of the current arsenals and implies that no truly significant new idea has been incorporate in stockpiled thermonuclear weapons since the late 1950s.[79] One reason for this, at least in the case of the United States, is that all warheads used or contemplated for use by the military have been

[76]Edward Teller gives credit for the design of this small and efficient primary fission bomb to John Foster [104, p.16].

[77]In 1972, the U.S. Department of Energy declassified the statement that "some of our nuclear weapons are inherently safe" [22, B.2.j].

[78]According to Wood and Nuckolls: "The '60s saw a remarkable flowering of quite novel thermonuclear explosives concepts and successful experimental demonstrations of many of them" [11, p.316].

[79]Using information published by David Wise in the Gentleman's Quarterly (November 1999) 285–300, Bill Broad in the New York Times [107], and previously Dan Stober in the San Jose Mercury News (8 April 1999), this statement will be made more precise in the eighth edition of this report. In particular, there is now sufficient information to make a "reverse engineering analysis" of the W-88 and to run simulations with ISRINEX the way we did for Mike in section 1.7.

tested *at their full yield before the imposition of the 150 kt TTBT*[80] [27, note 50, p.234]. However, the main reason may simply be technical: Namely that the fission-fusion-fission design is the most straightforward "quick and dirty" path to compact, high-efficiency, high-yield thermonuclear explosives. This can be seen by looking at Table 1.1: In terms of yield-to-weight, LiD fusion is three times more efficient than fission [1]. However, in terms of yield-to-*volume*, fission is eight times better than LiD fusion. Therefore, as the throw-weight of missiles increased over the years, it became less important to emphasize warhead weight reduction, and the use of enriched uranium in secondaries enabled to increase the yield while keeping the warhead volume roughly the same.[81] Only the use of antimatter may significantly alter this picture by enabling an improvement by a factor of about five in yield-to-volume over fission, and of about three hundred in yield-to-weight over fusion.[82]

[80] Threshold Test Ban Treaty which stopped tests over 150 kt after March 1976.

[81] This is illustrated by the W78 and W87/W88 warheads which have virtually the same dimensions.

[82] This assumes that the full annihilation energy (about 1877 MeV) of each $H\overline{H}$ pair contributes to the explosive yield of the device. In reality, only a fraction of this enegy can be used in a practical device. See section 4.4 and reference [292].

Nuclear fuel:	$H\overline{H}$	DD	DT	^6LiD	$Pu/^{235}U$
M	2	4	5	8	239/235
Density [kg/ℓ]	0.08	0.17	0.22	0.80	19
Yield-to-weight [kt/kg]	21400	80	80	50	17
Yield-to-volume [kt/ℓ]	1700	13	18	40	320

Table 1.1: Normalized maximum energy contents of nuclear fuels

Thermonuclear explosion timing [nanoseconds]

Primary:	
Compression by chemical high explosives (HE)	10’000 - 50’000
Rayleigh-Taylor instability (HE/Pu boundary)	5’000 - 10’000
Rayleigh-Taylor instability (Pu/DT boundary)	100 - 400
Chain reaction	150 - 300
Rayleigh-Taylor instability (Pu/DT mixing)	2 - 8
Boosting (DT burn)	1 - 4
X-ray pulse	10 - 50
Fission core disassembly	10 - 50
Full disassembly	500 - 2’000
Primary/Secondary:	
X-ray arrival time	1
Neutron arrival time	20
Shock wave arrival time	1’000
X-ray thermalization within hohlraum	10
Secondary:	
Ablative compression	100 - 500
Chain reaction (sparkplug)	10 - 30
Thermonuclear burn	3 - 20
Fusion fuel disassembly	3 - 20

Table 1.2: Sequence of events and timing of a thermonuclear explosion

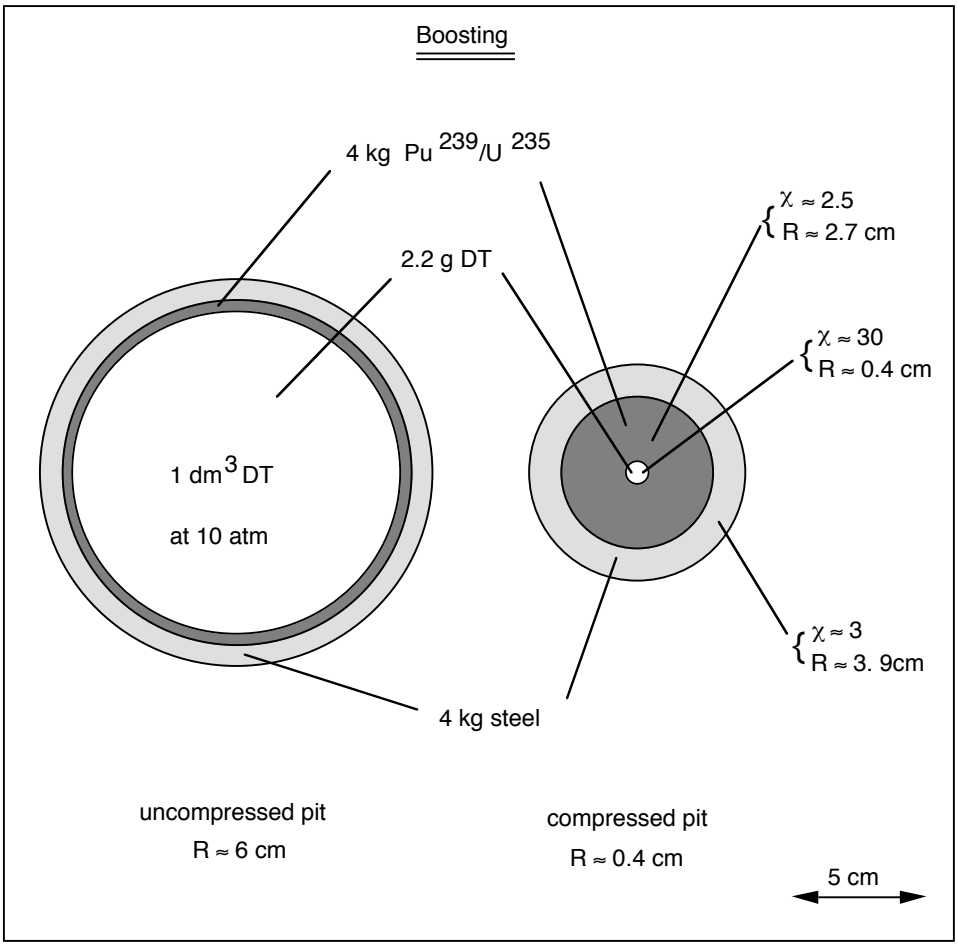

Figure 1 Fissile material pit containing 2.2 g of deuterium tritium fusion fuel shown before and after compression by the shock waves generated by about 10 kg of high explosives.

Figure 1.1: Figure 1

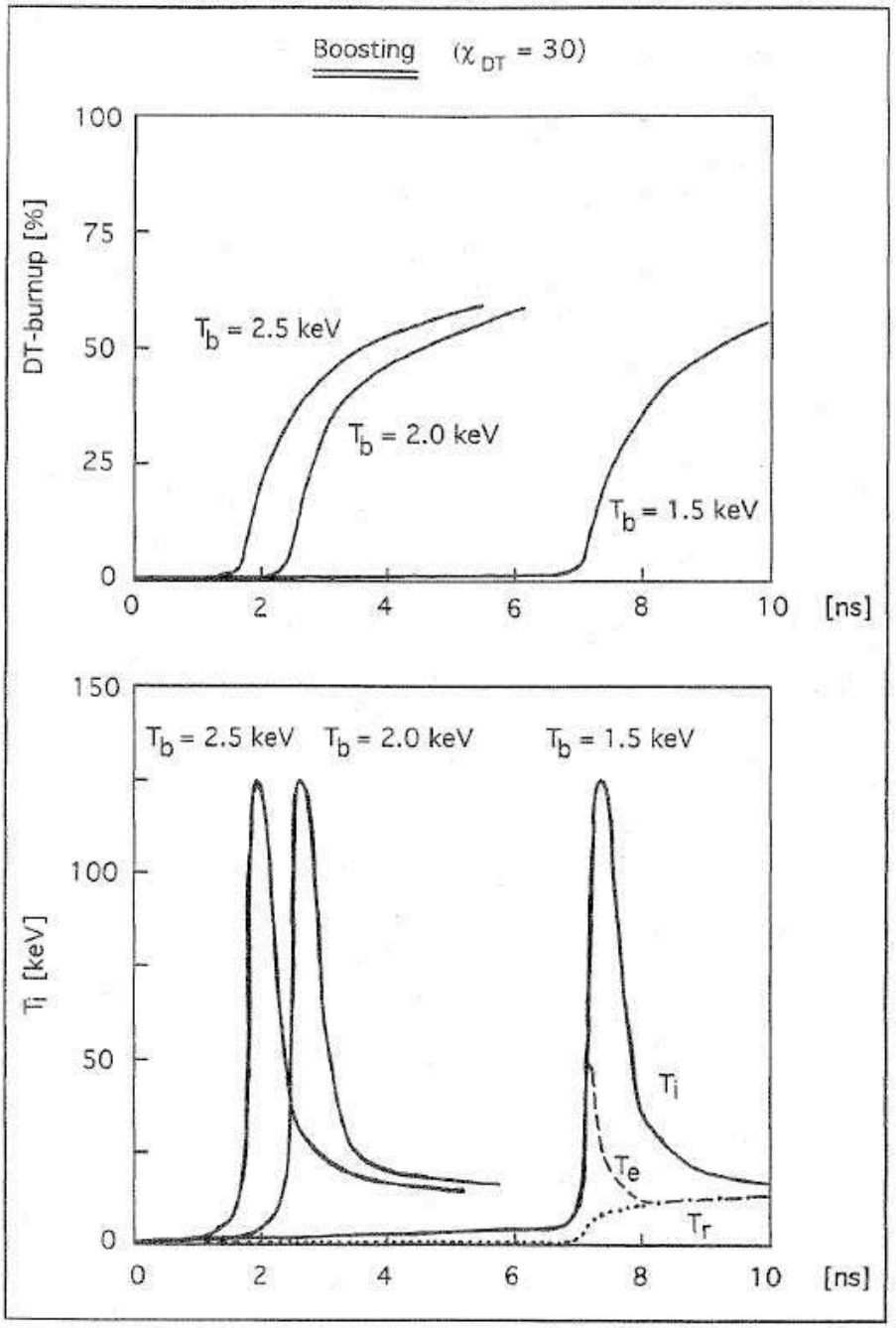

Figure 2. Time evolution of DT burn efficiency and plasma ion temperature as a function of the fissile material temperature T_b. For T_b = 1.5 keV, all three plasma temperatures are indicated, showing significant runaway of T_i relative to T_e and T_r. The compression of DT is $\chi = 30$ in all cases.

Figure 1.2: Figure 2

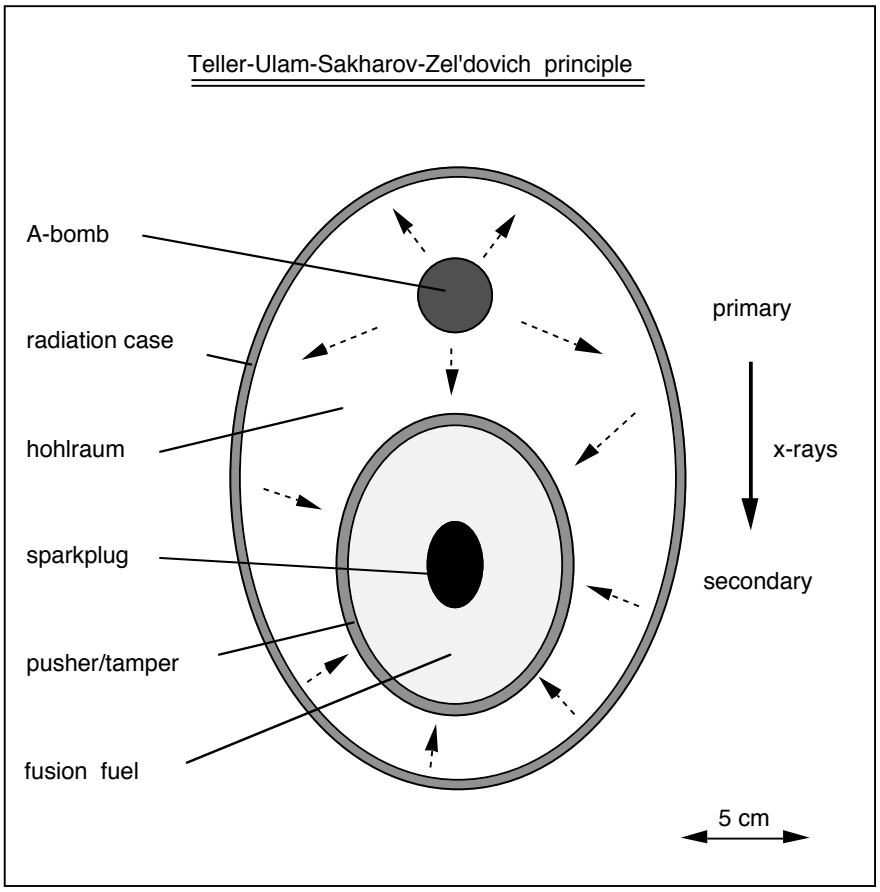

Figure 3 "*In thermonuclear weapons, radiation from a fission explosive can be contained and used to transfer energy to compress and ignite a physically separate component containing thermonuclear fuel. (February 1979)*".

Reference: U.S. Department of Energy, Office of Declassification, "*Drawing back the curtain of secrecy - Restricted data declassification policy, 1946 to present*", RDD-1, (June 1, 1994) page 94.

Figure 1.3: Figure 3

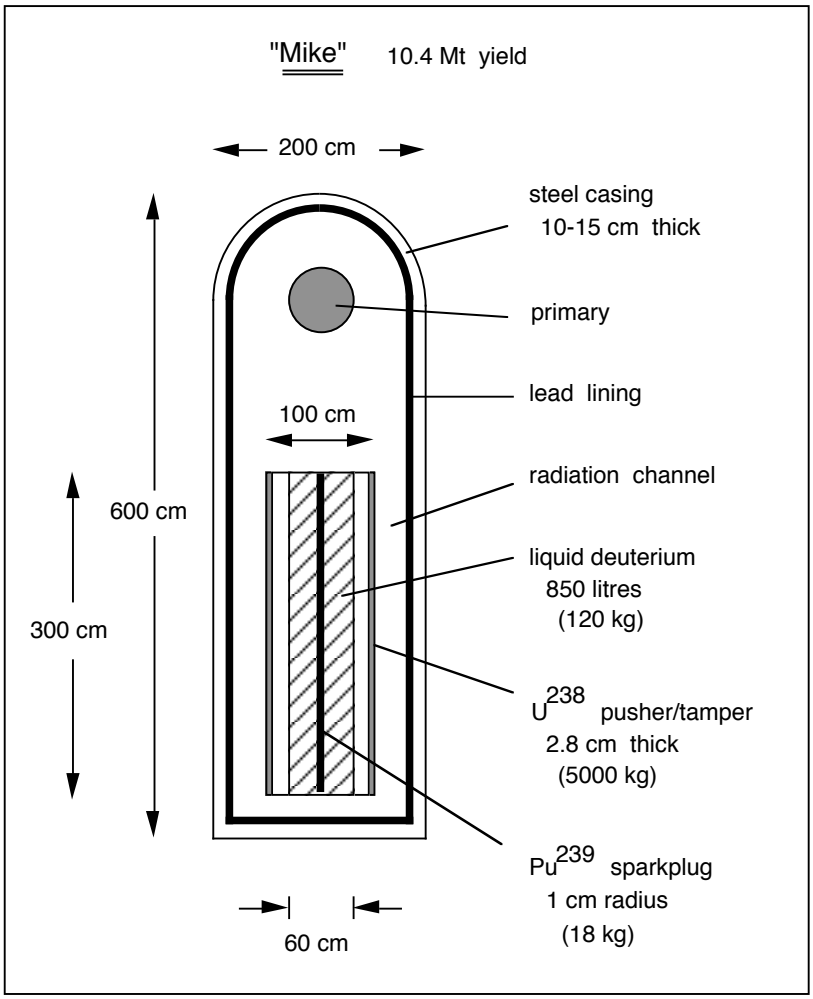

Figure 4 Main components of "Mike", the first hydrogen bomb, schematically drawn using plausible estimates for their dimensions and weights.

Figure 1.4: Figure 4

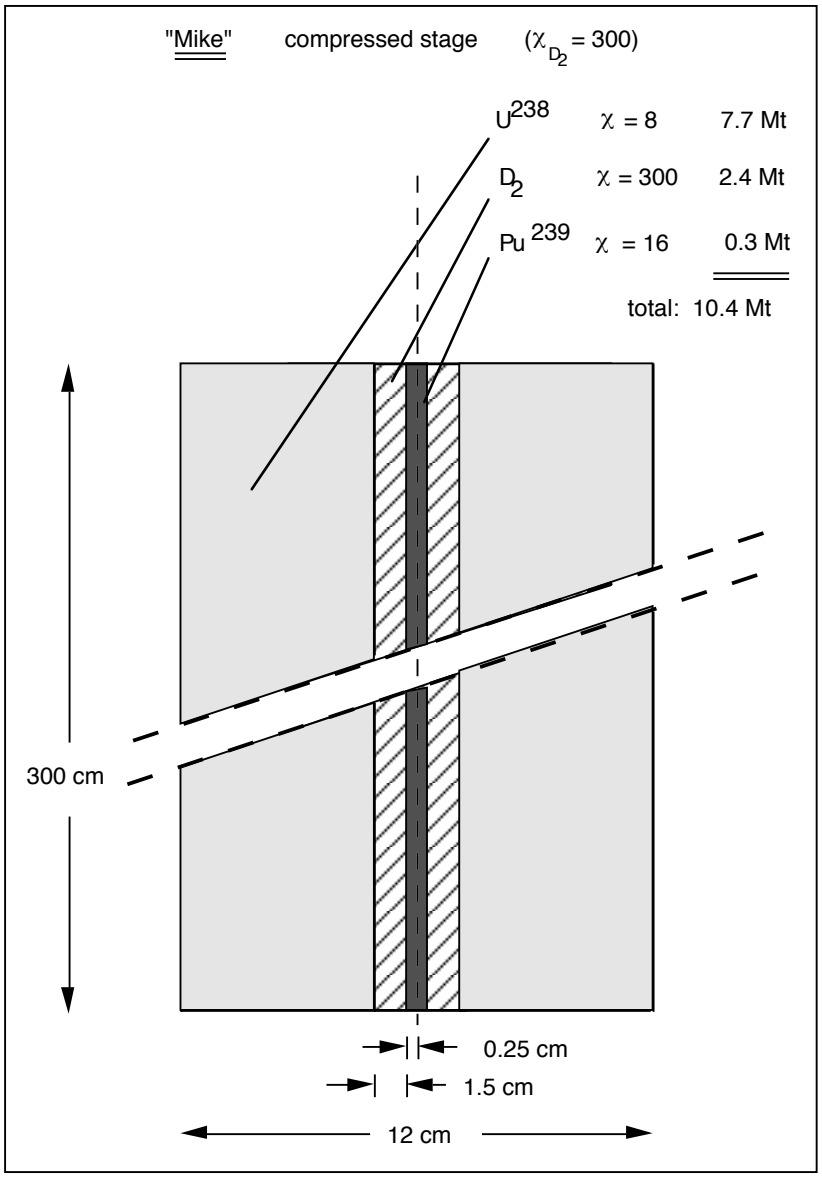

Figure 5 At maximum compression the 100 cm diameter, 2.8 cm thick, uranium blancket is squeezed down to a 12 cm diameter hollow uranium bar, compressing the liquid deuterium to 300 times its solid density.

Figure 1.5: Figure 5

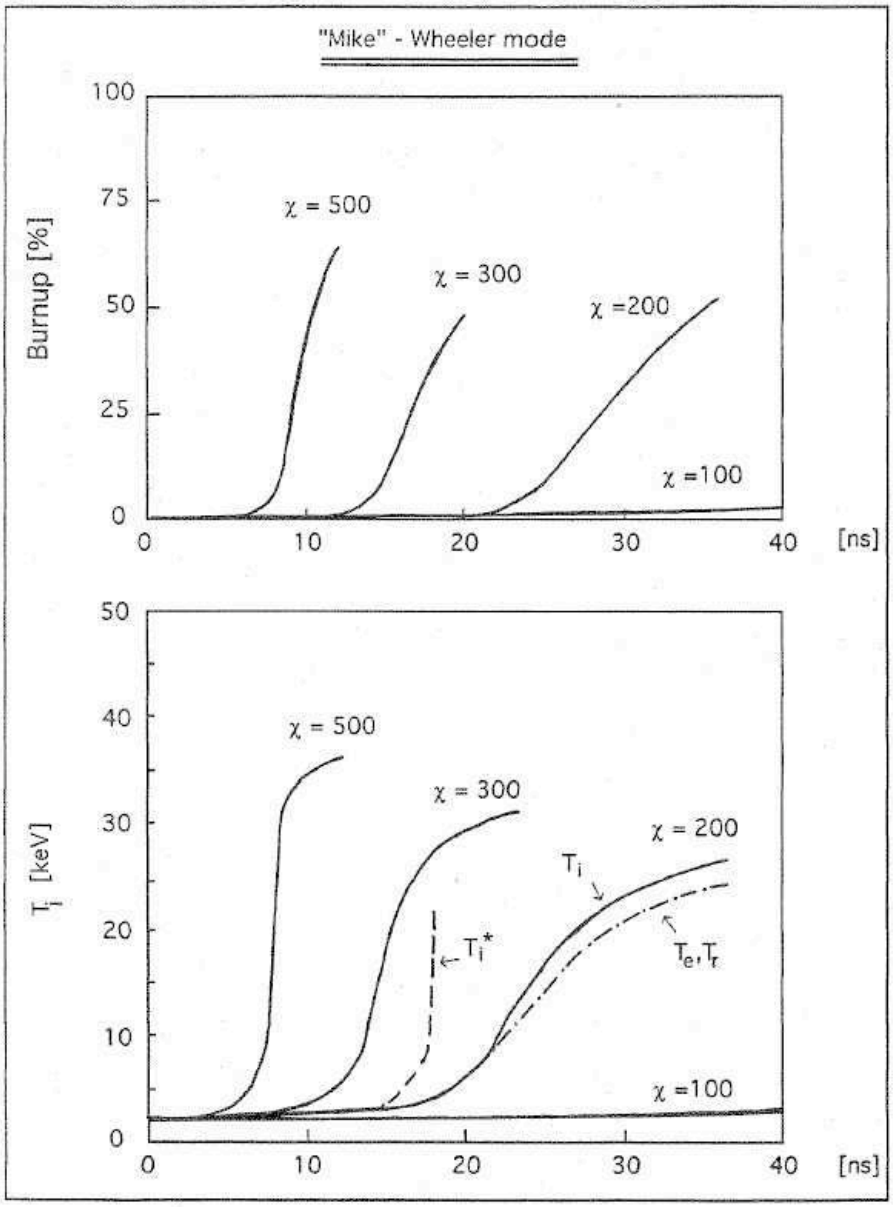

Figure 6. Time evolution of D_2 burn efficiency and plasma ion temperature in Wheeler mode (ignition by self-heating) as a function of the compression factor χ. For $\chi = 200$, all three plasma temperatures are depicted, showing little runaway of T_i relative to T_e and T_r. T_i^* is the temperature the ions would have in the absence of inverse Compton scattering effects.

Figure 1.6: Figure 6

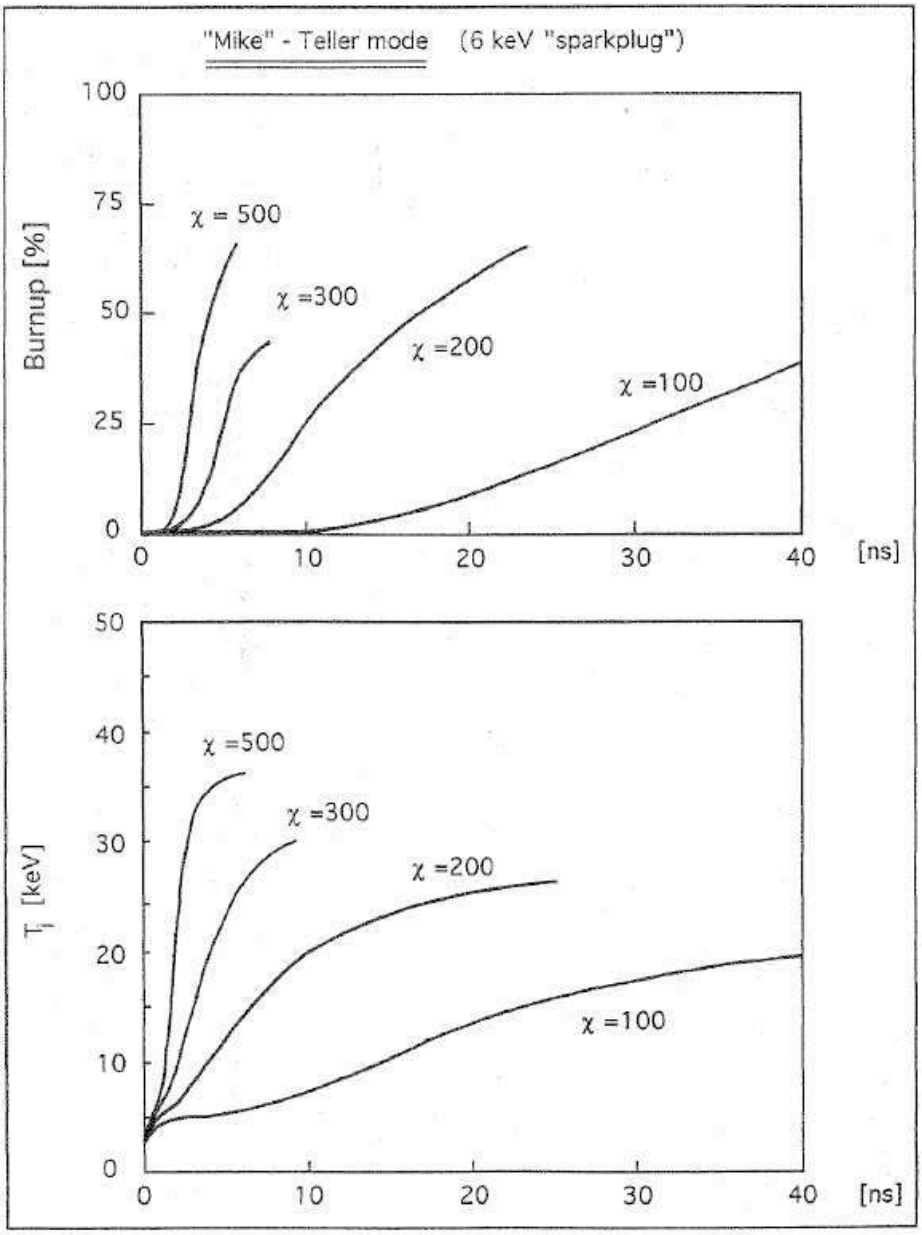

Figure 7. Time evolution of D_2 burn efficiency and plasma ion temperature in Teller mode (sparkplug assisted ignition) as a function of the compression factor χ. The maximum sparkplug temperature is assumed to be 6 keV.

Figure 1.7: Figure 7

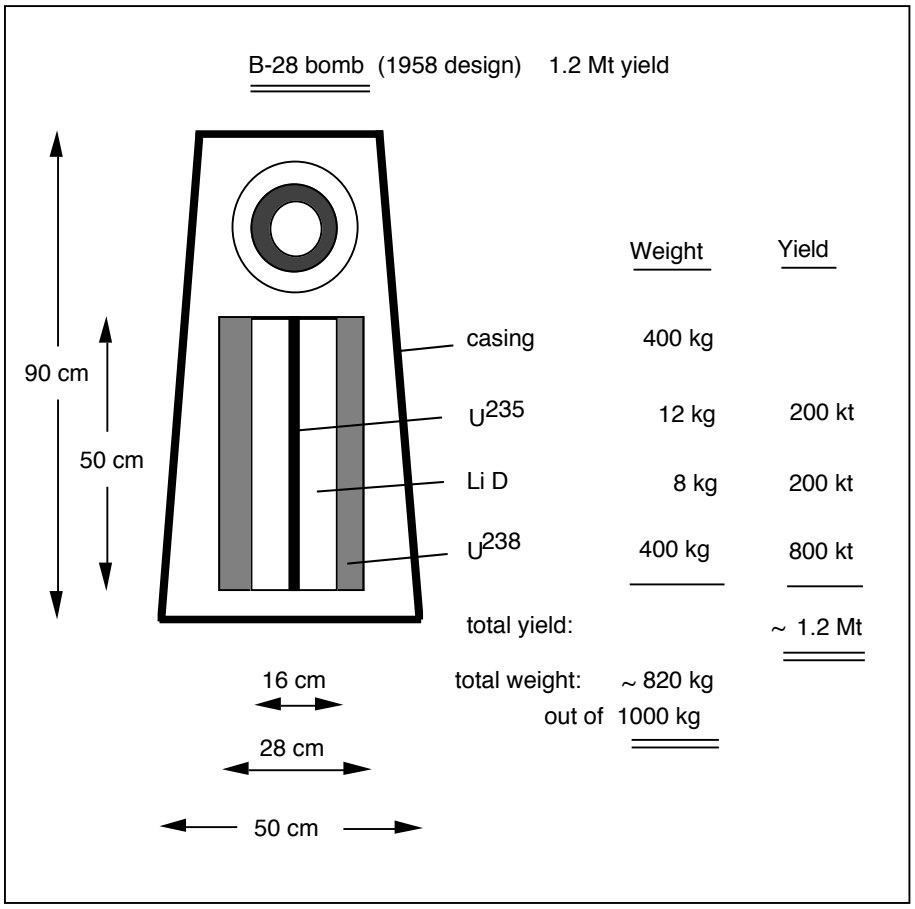

Figure 8 Using realistic estimates for the amount of thermonuclear fuel, the weight of the uranium tamper, and the size of the primary, there is sufficient space to fit everything within the volume of the B-28.

Figure 1.8: Figure 8

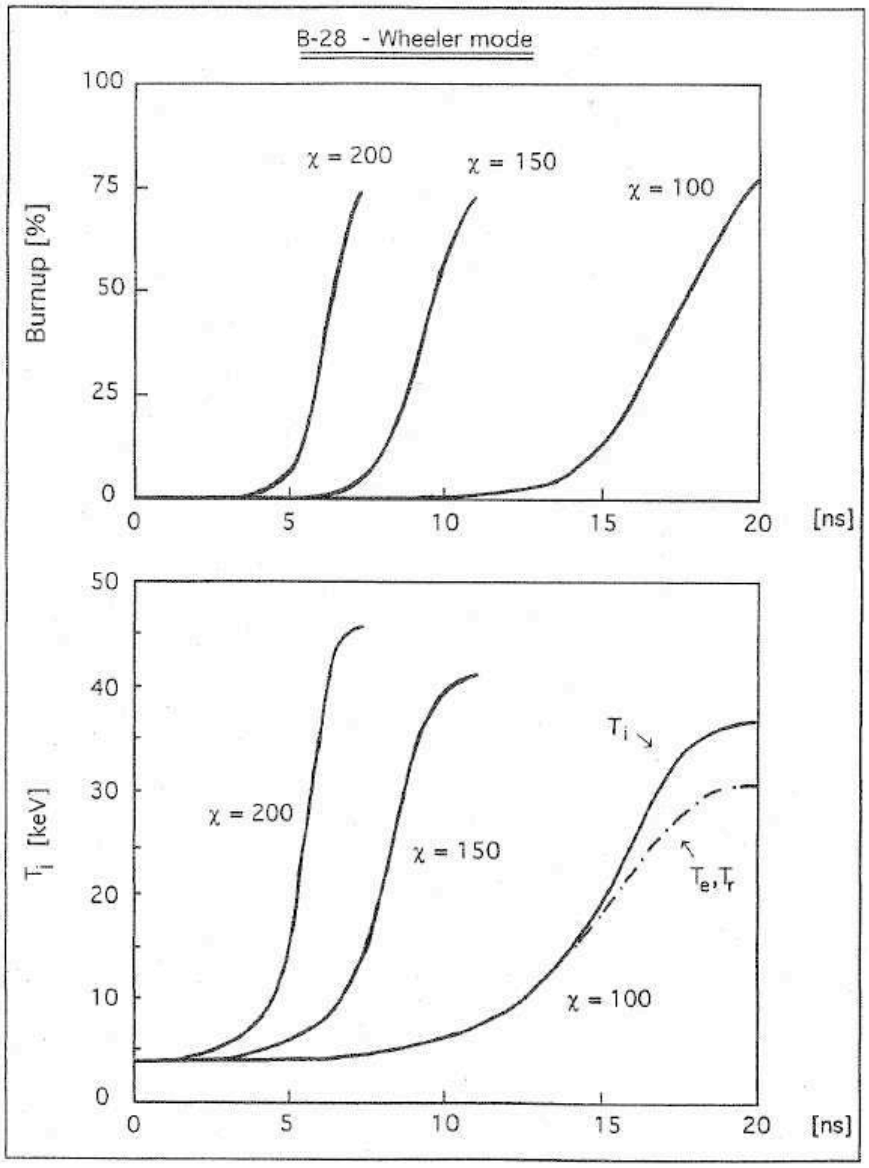

Figure 9. Time evolution of LiD burn efficiency and plasma ion temperature in Wheeler mode (ignition by self-heating) as a function of the compression factor χ. For $\chi = 100$, all three plasma temperatures are depicted, showing slight runaway of T_i relative to T_e and T_r for $T_i > 25$ keV.

Figure 1.9: Figure 9

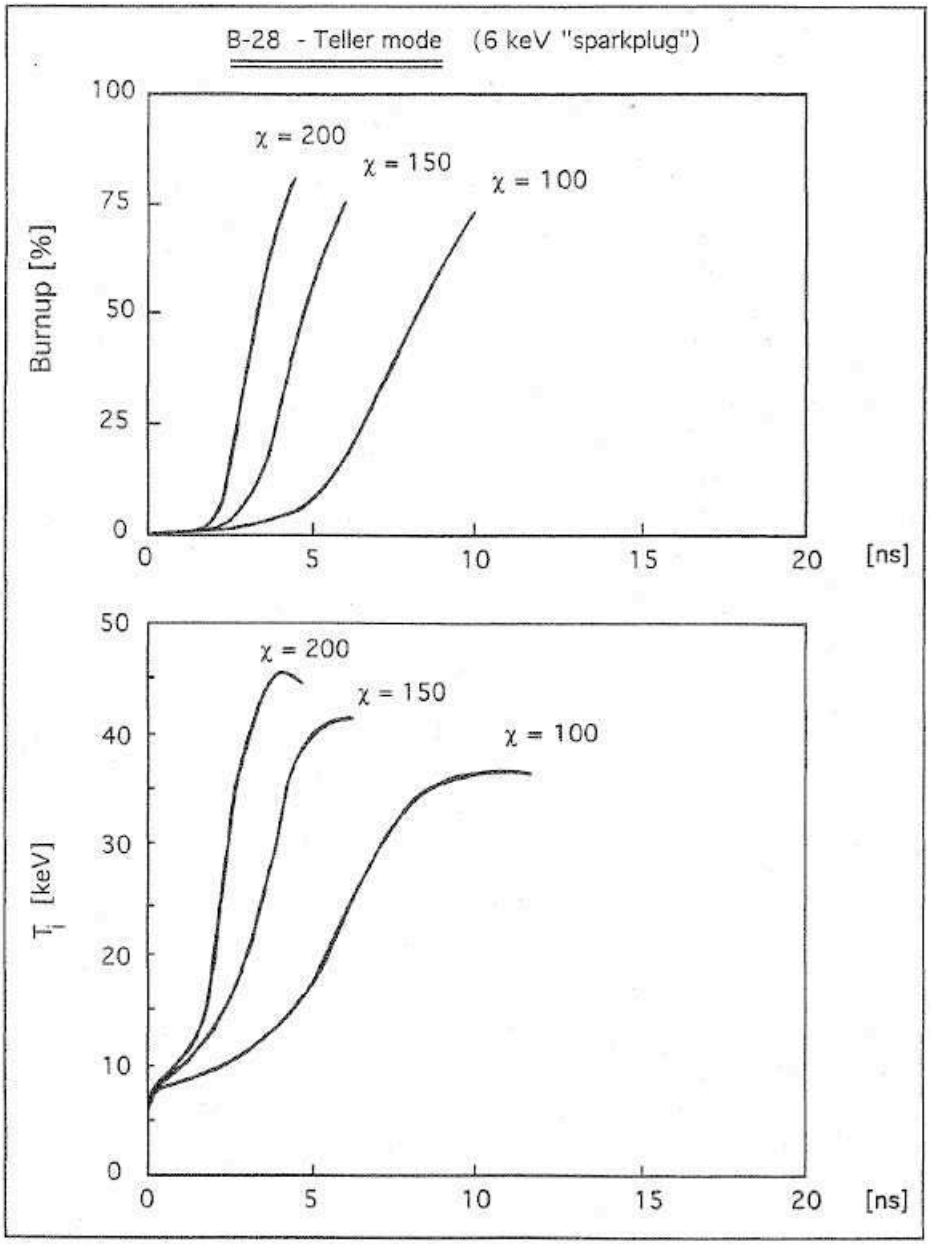

Figure 10. Time evolution of LiD burn efficiency and plasma ion temperature in Teller mode (sparkplug assisted ignition) as a function of the compression factor χ. The maximum sparkplug temperature is assumed to be 6 keV.

Figure 1.10: Figure 10

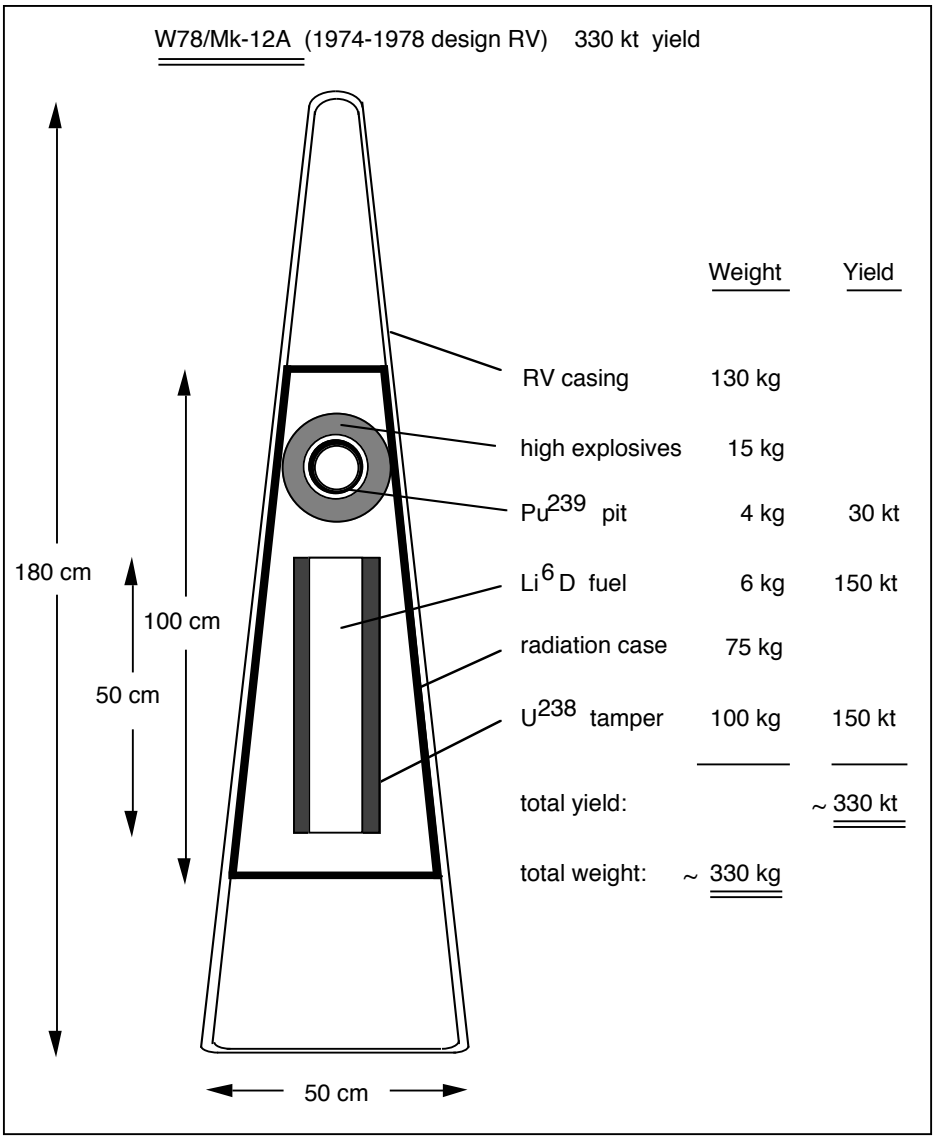

Figure 11 The weight of the W78 warhead is about 200 kg for a total MK-12A reentry vehicle weight of 330 kg. This corresponds to a yield-to-weight ratio of 1.65 *kt* /kg. To increase yield, the U-238 tamper may be enriched in U-235.

Figure 1.11: Figure 11

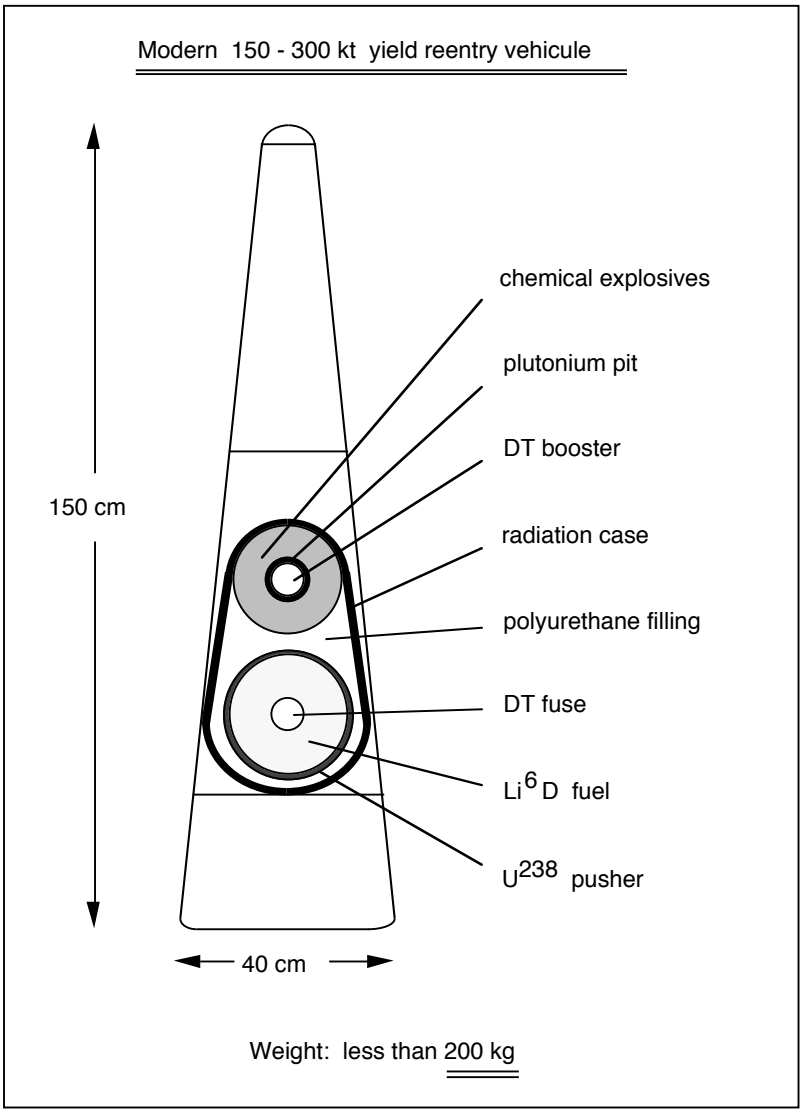

Figure 12 Spherical symmetry of the secondary enables to reach the highest thermonuclear burn efficiency. A reentry vehicle weight of 200 kg for a yield of 200 kt is almost the engineering limit. The warhead itself may weigh as little as 100 kg, implying a yield-to-weight ratio of about 2 *kt* / kg.

Figure 1.12: Figure 12

Chapter 2

Nuclear Weapons Development under the CTBT

2.1 The Comprehensive Test Ban Treaty

The so-called *Comprehensive* Test Ban Treaty (CTBT), which was adopted by the General Assembly of the United Nations on 10 September 1996, has put an end to *explosive testing* of nuclear weapons. However, since laboratory testing is not covered by the CTBT, the development of nuclear weapons will continue using a number of techniques perfected during the last forty years, which today can effectively replace field testing.

Laboratory techniques have the potential of orders of magnitude improvement over traditional methods because they enable the study of many nuclear weapons processes that are still poorly understood. With a complete description of nuclear weapons physics from first principles, producing a new weapon becomes a pure engineering enterprise — deprived of the kind of scientific uncertainties which made design of nuclear weapons a kind of a black art.

In fact, the absence of explosive testing, combined with vastly enlarged laboratory capabilities, creates new opportunities for producing extremely safe and robust new nuclear weapons, whether they are based on old or new principles. Science Based Stockpile Stewardship (SBSS) [21] — the euphemistic concept that in the absence of full scale testing, laboratory techniques merely help maintain the minimum competence necessary for "keeping the nuclear weapons stockpile safe, secure and reliable" [38][1] — has therefore the potential to revolutionize nuclear

[1]For some complementary points of view, see references [35, 37, 46].

weapons technology.[2]

There are two major classes of nuclear tests allowed by the CTBT: *subcritical experiments* and *microexplosions*.

Subcritical experiments — and the conditions for use of fissile material targets in laser and other pulsed power simulation facilities — are addressed in section 2.2. Microexplosions — and the question of their legality under the Comprehensive Test Ban Treaty (CTBT) and the Nuclear Non-Proliferation Treaty (NPT) — are discussed in section 2.3.

2.2 Subcritical tests and treaty limitations

During the CTBT negotiations, the five nuclear-weapon States met confidentially several times, either bilaterally or multilaterally, in order to clarify their interpretations of the words of the treaty, which only stipulates "not to carry out any nuclear weapon test explosion or any other nuclear explosion" (Article I of the treaty). In particular, they exchanged information on what they wanted to be allowed or forbidden by the CTBT, and negotiated a common understanding among themselves regarding "activities not treaty prohibited."

Although the exact terms of this understanding are confidential, it is known that an important issue was that of the so-called *hydronuclear tests*,[3] i.e., nuclear weapon tests, or high-explosive-driven experiments, limited to subcritical, or slightly supercritical, neutron multiplication.[4] In order for the treaty to be qualified as "fully comprehensive," i.e., "truly zero-yield," and therefore politically acceptable to the majority of the United Nations member States, the nuclear-weapon States agreed to ban hydronuclear tests in which fissile materials are driven to criticality.

In other words, any nuclear tests in which fissile material remains in the subcritical state is allowed by the CTBT. In particular, this allows the study of properties of

[2]The concept of "Science Based Stockpile Stewardship" is primarily the brain-child of JASON, an elite group of scientists who advise the U.S. Government. This group of consultants was formed in 1960 on the initiative of a number of senior scientists and advisors to the U.S. government, with the purpose of involving highly capable younger people, largely physicists, in national security affairs [34, Note 1], [2]. For a collection of documents relating to JASON and its influence during the Vietnam war see [2, 5, 6]. While JASON traditionally kept a rather low profile, its activities have become much more visible since the collapse of the Soviet Union.

[3]For a technical discussion of hydronuclear tests in the context of the CTBT see in particular [179].

[4]A precise definition of these terms will be given in section 4.2.

fissile materials at any pressure or density, using any kind experimental technique, provided the sample is kept small enough to never become critical.

The fact that subcritical experiments are not forbidden by the CTBT was made definitely clear in Spring 1997. This came after a controversy was started by the announcement of the U.S. Department of Energy to conduct a series of high-explosive-driven experiments with plutonium[5] at the Nevada test site [180]. A first statement appeared in a JASON review of these subcritical experiments:

> "The CTBT, in accord with its negotiating record, forbids explosions that produce any nuclear yield. The U.S. interprets this to mean that experiments in which conventional explosives assemble a critical mass of fissionable material are prohibited" [181, p.10].

This statement implies that the mere fact that criticality (and *a fortiori* supercriticality) is not reached is sufficient for consistency with the provisions of the CTBT. In other words, for the United States, "nuclear yield" is associated with energy released during a diverging chain reaction, suggesting that the kind of explosion forbidden by the Treaty is that in which the energy release is "uncontrolled". This is confirmed by a U.S. Department of Energy statement on subcritical experiments released shortly after the publication of the JASON review:

> "Subcritical experiments are fully consistent with the terms of the Comprehensive Test Ban Treaty (CTBT), signed by President Clinton last September at the United Nations. The treaty bans 'any nuclear weapon test explosion or any other nuclear explosion.' Subcritical experiments, on the other hand, are configured such that no self-sustaining nuclear chain reaction can occur even though special nuclear materials will be present. In other words, the configuration of each experiments guarantees that no nuclear explosion prohibited by the treaty can result" [182].[6]

This official statement suggests that there can be nuclear *explosions* which are *not* forbidden by the CTBT: the only explicit restriction is that "no self-sustaining nuclear chain reaction" should occur. This leaves open the possibility of designing

[5] It should be stressed that important parts of the data that can be gathered in these subcritical experiments (e.g., "equation of state, constitutive relations, surface properties, ejecta, spall effects, and phase changes of plutonium" [181, p.2]) can also be obtained using laser techniques [193, 210].

[6] Note 1 in reference [55] confirms that CTBT does only ban "explosions producing any self-sustaining nuclear fission reaction."

devices in which nuclear fission energy is released in a semi-controlled fashion, i.e., in a subcritical fission burn. The characteristics of these new types of fission explosives will be discussed in section 4.2.

The first subcritical test of the post-CTBT era was conducted by the United States on 2 July 1997. The first three official reactions to this test were reprobative statements by the governments of China on 3 July, India on 5 July, and Indonesia on 19 July 1997.[7] On 19 February 1998, after 15 countries had publicly expressed their concern about or opposition to these tests, the European Parliament passed a resolution calling on all governments to refrain from carrying out such tests. The European Parliament also asked the "U.S. Government to issue an official declaration stating that these tests in no way form part of a new weapons design program and that new nuclear weapons design does not form part of U.S. policy" [183].

2.3 Microexplosions and treaty limitations

The legality of microexplosions, i.e., the detonation of millimeter-sized pellets of fissionable and/or fusionable materials,[8] is an obvious and major loophole of both the NPT and the CTBT. Despite of this, however, there have been only limited efforts during the CTBT negotiations — except from the part of India[9] — to include ICF and other kinds of microexplosions into the scope of the treaty.

The reason for not including microexplosions into the scope of the NPT or CTBT comes largely form the unwillingness of the nuclear-weapon States to accept restrictions in this area of research, and from the intent of the majority of United Nations member States to secure a treaty regime aimed at banning, in priority, weapons of *mass* destruction.

In fact, the absence of reference to nuclear microexplosions is not the only omission of the current nonproliferation treaty regime. *Thermonuclear fusion*, for example, is never explicitly mentioned in any international arms control treaty,[10]

[7] The total population of these three countries corresponds to 41% of the world population.

[8] Such *micro*explosions correspond to yields in the range of 0.1 to 10 *tons*!

[9] India proposed "to prohibit and to prevent, and not to carry out, any nuclear weapon explosion, or any other nuclear test explosion, or any release of nuclear energy caused by the (rapid) assembly or compression of fissile or fusion materials by chemical explosives or other means" [39]. Since this proposal was not accepted, and no compromise made by the nuclear-weapon States in order to enlarge the scope of the treaty, India finally refused to join the CTBT.

[10] A technical and legal assessment of the scope of the existing arms control treaties (and of the various nuclear export control arrangements which are in force) with regards to fusion and other

and the notion of "special nuclear materials" refers only to highly fissionable materials such as plutonium or enriched uranium. These ambiguities have prompted a number of reactions. For instance, at the 1975 review conference of the Non-Proliferation Treaty (NPT), the Swiss delegation raised the matter of laser fusion research.[11] The United States declared:

> "Such contained explosions are not 'other nuclear explosive devices' in the sense of the NPT and research in this area is allowed under Article IV.1" [3].

This declaration was followed by a more substantial statement by the U.S. delegation, which addressed the general question of micro-fission and micro-fusion explosions:

> "A question has been raised with respect to energy sources, of a kind on which research has been reported, involving nuclear reactions initiated in millimeter-sized pellets of fissionable and/or fusion material by lasers or by energetic beams of particles, in which the energy releases, while extremely rapid, are designed to be, and will be, non-destructively contained within a suitable vessel. On the basis of our present understanding of this type of energy source, which is still at an early stage of research, we have concluded that is does not constitute a nuclear explosive device within the meaning of the NPT or undertakings in IAEA Safeguards Agreements against diversion of any nuclear explosive device" [4].

This interpretation was supported by the United Kingdom and Denmark [4]. The Soviet Union did not object.

In 1996, during the final negotiations of the CTBT, the question of microexplosions was again a major issue, especially for the nuclear weapon laboratories. This is illustrated by a statement by C. Paul Robinson, Director of the Sandia National Laboratory (SNL), the third of the three research laboratories of the U.S. Department of Energy nuclear weapon R&D complex (LANL, LLNL and SNL):

> "I am concerned that some recent policy discussions regarding the content of a comprehensive test ban treaty could restrict the laboratories' ability to conduct an adequate stockpile stewardship program

non-fission nuclear technologies can be found in [45].

[11] At the time Switzerland was still debating its accession to the NPT and working on various aspects of fission [214, 63] and fusion explosives [133, 136, 202, 71].

> in the absence of testing. If the Arms Control and Disarmament Agency decides to seek provisions in a test ban treaty that restrict inertial confinement fusion (ICF) to *only* [sic] laser and particle beam drivers, based on the negotiating record of the 1975 Nonproliferation Treaty, then other methods of driving ICF, some of which are being aggressively developed here and abroad, would be treaty violations.
>
> Some would have the United States take the extreme position that inertial confinement fusion is incompatible with a zero-yield policy. This contention has been thoroughly studied in the past and found to be without merit. The yields of ICF are so small that they fall well within the intent of a zero-yield policy, and they certainly do not present a proliferation threat. Further restrictions on ICF are not at all necessary for the purpose of the testing treaty. Moreover, inertial confinement fusion is recognized worldwide as an important experimental tool for the study of high-energy-density physics.
>
> If the ICF language of the 1975 Nonproliferation Treaty were to be carried over to a comprehensive test ban treaty, some of the high-energy accelerators the laboratories use today to simulate a variation of radiation condition, and some that will be needed in the future, would have to be abandoned. Such restrictions were not part of the laboratory director's understanding when we told the President we could perform our missions without underground nuclear testing. Our clear expectation was that further limitations would not be placed on our ability to employ the various approaches to inertial confinement fusion in support of the stockpile stewardship efforts. In my view, it is essential that inertial confinement fusion be permitted under a CTBT without such restrictions" [159, p.9–10].

An answer to the these concerns was given by President Clinton in a report of the Department of State appended to his letter of 23 September 1997, transmitting the CTBT to the Senate for advice and consent to ratification. This report includes an article-by-article analysis of the CTBT [49]. In this analysis, "inertial confinement fusion (ICF) and other similar experiments" are explicitly mentioned as *examples* of CTBT-permitted activities "which, while not involving a nuclear explosion, may result in the release of nuclear energy." Therefore, it follows that all possible approaches to microexplosion are legal under the CTBT.

Moreover, the Department of State analysis of the CTBT recalls the U.S. statement made at the 1975 NPT Review Conference which (by defining the size of "fissionable and/or fusionable" pellets) gave an upper limit to the yields of

acceptable laboratory explosions. These maximum yields, which are on the order of 0.1 to 10 *tons* of high-explosive equivalent, have obvious military significance. They are also in the range of the microexplosion yields required for the efficient operation of the hoped-for future commercial ICF power plants. This is probably why, upon signing the CTBT on 24th of September 1996, Germany made the following declaration:

> "It is the understanding of the German Government that nothing in this Treaty shall ever be interpreted or applied in such a way as to prejudice or prevent research into and development of controlled thermonuclear fusion and its economic use" [41].

Therefore, neither the NPT or the CTBT are putting any restriction on ICF research and development, including the possibility of using drivers different from the huge laser or particle beam facilities that are currently used for this purpose. Moreover, even though the concept of "zero-yield" applies to "any nuclear weapon test explosion or any other nuclear explosion," the yield of microexplosions is not restricted by the NPT or the CTBT.

While this absence of restriction is clear for micro-*fusion* explosions, the situation is not as clear for micro-*fission* explosions. This is because — as we have seen in the previous section devoted to subcritical tests — the interpretation of the CTBT (i.e., by the U.S.) is such that only those experiments in which a self-sustaining nuclear fission chain reaction occurs are prohibited. It seems therefore that one will have to wait for the official justifications that might be given when the first micro-fission-explosion will be performed at the NIF or any other facility. However, since all information on ICF targets in which "fissile material [is] driven to criticality" [22, p.121] is classified, and since micro-fission and micro-fusion experiments can be made virtually indistinguishable, it is possible that such experiments will be made in secrecy.[12] In any case, it is known since a long time that ICF facilities are designed to "accommodate target pellets that incorporate fissionable materials," e.g., [132, p.7-50].

2.4 Nuclear explosions and the "zero-yield" CTBT

According to the US Department of State, "the U.S. decided at the outset of the negotiations that it was unnecessary, and probably would be problematic, to seek

[12] One of the reasons given for not including microexplosions into the scope of the CTBT is that their prohibition creates a very difficult verification problem.

to include a definition in the Treaty of a *nuclear weapon test explosion or any other nuclear explosion* for the purpose of specifying in technical terms what is prohibited by the Treaty" [49, p.6]. By doing so, the U.S. remained consistent with the policy of "not defining precisely what constitutes a nuclear explosion," a policy going back to the 1966–68 negotiations of the NPT [18].

However, on 8 June 1967, at the Geneva Conference on Disarmament, the U.S. Delegation gave a broad definition of nuclear weapons:

> "All nuclear weapons have one characteristic in common ... that upon activation of a prearranged trigger mechanism they can release *large quantities* of energy in a very short period of time from sources of relatively small volume and light weight" [18, p.17–18] (emphasis added).

Therefore, the apparent contradiction between a treaty which, on the one hand, "permits *no yield* from nuclear (fission and fusion) explosions — not 1 kiloton, not 1 kilogram, not 1 milligram of yield, but zero yield" [50, p.3] and, on the other hand, allows *micro*explosions with yields of the order of 10 *tons*, may be solved by considering that, in the eyes of the nuclear-weapons States, the "nuclear weapons" concerned by the "zero-yield" CTBT are only those which potentially or actually release *large quantities* of energy — *large* meaning more than 10–100 *tons*.

If such is the case, the yield of a hydrodynamic or subcritical test related to the primary of a contemporary 100 kt warhead would indeed have to be zero. On the other hand, the yield of any new type of non-conventional nuclear-explosive is not restricted to be zero, even though it could be 100 or 1000 times more effective than a conventional chemical-explosive.[13] Considering that the official interpretation of the language of the CTBT "does not imply that the Treaty prohibits the development of new types of nuclear weapons or the improvement of existing weapons" [49, p.2],[14] the CTBT will only constrain the development and testing

[13] In 1971, a technical definition of a nuclear explosion was offered by J. Carson Mark [1]: "an explosion giving at least three orders of magnitude more energy per unit weight than would be available from high explosives; this is, a specific yield of at least 10^3 kilocalories per gram" [13, p.47]. If inforcement of the CTBT would use this definition, all types of nuclear weapons (including fourth generation nuclear weapons) would by clearly banned.

[14] According to R.L. Garwin, "activities that would be permitted under the CTB Treaty could include stockpile maintenance and refabrication; product improvement of existing weapons (for example, increased yield-to-weight ratio, safety and reliability or maintenance or remanufacture); or even the introduction of entirely new types of weapons, such as nuclear explosion-pumped x-ray lasers or other nuclear weapon-powered, directed-energy weapons which were under development as part of the Strategic Defense Initiative (SDI) in the 1980s" [50, p.4].

of new types of nuclear weapons to a yield range that would ensure that they could not be considered as weapons of *mass* destruction.

However, this interpretation might be too narrow in the perspective of what is *explicitely* banned by the CTBT. As already mentioned in section 2.2, only explosions in which a *self-sustaining nuclear fission reaction* is produced are strictly forbidden. That this is the case was confirmed in a brief JASON publication intended to encourage the members of the U.S. Senate to ratify CTBT:

> "The CTBT is a true zero-yield treaty, banning all explosions producing any self-sustaining nuclear fission reactions" [55, Note 1].

In other words, to take a specific example, a non-zero-yield pure-fusion explosion of any size is not forbiden by the CTBT.

2.5 Nuclear activities not prohibited by the CTBT and advanced nuclear processes

The US Department of State article-by-article analysis of the CTBT includes a "not all-inclusive but illustrative" list of activities allowed by the Treaty:

> "computer modeling; experiments using fast burst or pulsed reactors; experiments using pulsed power supplies; inertial confinement fusion (ICF) and similar experiments; property research of materials, including high explosives and fissile materials, and hydrodynamic experiments, including subcritical experiments involving fissile material." [49, p.6].

None of these activities constitute a "nuclear explosion." Similarly "activities related to the operation of nuclear power and research reactors and the operation of accelerators" [49, p.6] are not prohibited by the Treaty. However, in performing these activities, a number of militarily significant non-nuclear and nuclear processes and techniques are used. In the context of their applications to weapons technology, as well as for their use in military explosives, these physical processes can be classified according to the nature of the energy release, which is either of *atomic* or *nuclear* origin.

In Table 2.1, the most important *standard* physical processes that are currently used in existing military explosives (as well as for their development) are compared

to the more *advanced* processes that may become part of new types of military explosives within a decade or two, as well as to more *exotic* processes that may become relevant in the more distant future.

In this table, when considering standard processes, devices such as lasers and particle accelerators are presented on a level similar to apparently more fundamental processes such as chemical detonation or fission. The reasons are that laser beams can be used very effectively to compress fission or fusion materials (something that before the invention of the laser could only be done by means of chemical explosives) and that high energy particle accelerators can be used in a variety of ways to induce nuclear fission or fusion reactions [8].

Similarly, when compared to standard processes, the advanced or exotic processes consist of more difficult technologies (such as magnetic compression or subcritical fission), rare materials (such as isomers or superheavy nuclei), or more energetic processes (such as superlasers or antimatter).

In this classification, "lasers" correspond to lasers with maximum intensities on the order of 10^{14} W/cm^2, and "superlasers" to lasers with intensities on the order of 10^{20} W/cm^2 or more. This distinction is important because standard "lasers" are not powerful enough to produce nuclear reactions, whereas the much more powerful "superlasers" are able to induce *nuclear* reactions such as nuclear fission, nuclear fusion, transition between bound nuclear states, pion production, proton-antiproton pairs production, etc. [542, Fig. 4].

Not all of these processes are studied in this report. Nevertheless, as will be seen, substantial progress has been made on all of them in the past few years. Similarly, it will be shown that many links exist among those processes. For example, the same accelerator technique that can be used to produce tritium for thermonuclear weapons can also be used to produce antimatter; superlasers can serve as fast-igniters for ICF pellets as well as neutron-triggers for microfission pellets; etc. Moreover, while some of the advanced or exotic processes do not on their own present a realistic option for any significant military application, various combinations of them may result in very effective new weapons. This is because rare materials (such as antimatter, special isomers, or superheavy nuclei) are too expensive to be used as main explosives in cost-effective weapons. However, very small amounts of these materials can be used to trigger large scale explosions in which the main charges are more conventional explosives such as DT or LiD.

An example of how new technology and a strictly literal interpretation of international treaties allow a non-nuclear-weapon State to carry out military research at the forefront of nuclear weapons technology is given by the present involvement of Germany in superlaser research and development. As will be discussed in more

details in section 4.8, the atomic and plasma physics departments of *GSI Darmstadt* have started a petawatt high-energy laser project — PHELIX — as a joint venture together with the *Lawrence Livermore National Laboratory* (LLNL) and the *Max Born Institute* in Berlin. Offering pulse energies up to 5 kJ in nanosecond pulses or alternatively petawatt peak power in pulses of less than 500 femtoseconds PHELIX will be among the world leading superlaser facilities. Since Germany is a non-nuclear-weapon State, it is politically very disturbing that PHELIX is built in collaboration with a U.S. nuclear weapons laboratory, and that there is a "cooperation agreement" between GSI and LLNL that is similar to those LLNL has with the French and British nuclear weapons laboratories [564, p.60]. Moreover, it is troublesome to see that in two recent issues of the LLNL magazine *Science and Technology Review* Germany is listed as the *prime* foreign partner of LLNL for the development of superlaser technology.[15]

In conclusion, we see that there is a relatively large number of physical processes available for the design of new types of military explosives — a confirmation that atomic and nuclear physics are relatively new sciences. Many surprising discoveries are still possible, with many implications for new types of nuclear explosives. The fact that international treaties such as the NPT and CTBT only take into account the more standard of these processes, without any provision constraining the potential military application of the more advanced ones, is therefore a serious reason for concern.

[15]The cover story of the March 2000 issue of *Science and Technology Review* is dedicated to the LLNL superlaser named "Petawatt" that has been between 1996 and 1999 the most powerful laser in the world [575]. In the abstract (back cover page), the commentary by the Associate Director for National Security (page 3), and the main article [575, p.12], the word "Germany" appears three times, and each time at the beginning of a list of country names ("Germany, France, etc." and "Germany, England, etc.") with which LLNL is collaborating on superlaser science and technology. "Petawatt" was closed down in May 1999 but superlaser research at LLNL continues with JanUSP, a facility described in the May 2000 issue of *Science and Technology Review*. Although JanUSP has only a fraction of the power and energy of "Petawatt," it enables research begun on "Petawatt" to continue in a different regime of laser matter interaction. JanUSP is open to researcher from other nations. However, Germany is the only country cited as an example [576, p.27].

	atomic processes	**nuclear processes**
standard processes	chemical detonation lasers	fission fusion acceleration
advanced processes	magnetic compression atomic isomerism x-ray lasers superlasers	subcritical fission nuclear isomerism γ-ray lasers muon catalysis antimatter
exotic processes	metallic hydrogen atomic clusters etc.	superheavy nuclei bubble nuclei halo nuclei etc.

Table 2.1: Major atomic and nuclear processes of importance to present and future military explosives

Chapter 3

Nuclear Weapons Applications of Inertial Confinement Fusion

3.1 Introduction

Today, the most significant modern laboratory tool available to weapons designers, is Inertial Confinement Fusion (ICF). This simulation technology enables thermonuclear fusion explosions — with yields equivalent to a few kg of TNT — to be performed in the laboratory.

Various ICF facilities are operating and are under construction in several countries (See Tables 3.1 and 3.2). The two largest ones currently being built, are the National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory (LLNL) in California [514] and the Laser Mégajoule (LMJ) near Bordeaux in France [515]. These facilities will be roughly twenty times more powerful than the largest exiting one, the NOVA laser facility of LLNL.

In order to demonstrate the potential of NIF and other above-ground experimental facilities (mentioned later in this chapter), scientists from LLNL circulated a series of impressive graphs comparing the capabilities of NIF with those of explosive testing [21, 37, 155]. With captions such as "Weapons physics scaling: highest energy density works best" [21, p.53], "If you want to achieve weapons conditions you need a large laser" [37, p.34] or "NIF energy densities will overlap those of nuclear weapons" [155, p.26], these graphs have been reproduced in a number of documents. Four of them, in simplified form, have been discussed in *Energy and Technology Review* [155], a monthly journal published by LLNL.

Section 3.2 reviews the basic features of ICF and addresses its military impli-

cations in general terms. In sections 3.3 to 3.9, nine of the above mentioned graphs will be referred to and used to illustrate the significance of ICF and other simulation techniques for nuclear weapons development.[1] In particular, by comparing the capabilities of these above-ground experimental facilities to those of actual full-scale nuclear explosions, i.e., explosive weapons tests, it is possible to gain further insight into modern thermonuclear weapons physics and to demonstrate the considerable impact of ICF on both horizontal and vertical proliferations of nuclear weapons.

In the conclusion of this chapter, section 3.10, the nuclear weapon proliferation impact of ICF will be assessed. However, in making this assessment, the proliferation impact of the use of *superlasers* in the context of ICF will not be addressed. This will be done in section 4.8, together with a systematic review of the potential applications of superlasers to fourth generation nuclear weapons. Similarly, the application of ICF to the study of advanced nuclear processes, and to the production of metallic hydrogen, superheavy elements, isomer or antimatter, will be done in the corresponding sections of chapter 4.

3.2 Inertial Confinement Fusion (Fig. 3.1)

Inertial confinement fusion — i.e., contained thermonuclear explosions — is potentially an "energy option, but weapons simulation is first" [130]. This has been officially recognized since the very beginning [130, 444, 8], which in the United States goes back to the well known paper of John Nuckolls *et al*. [126], the first significant unclassified American paper on the subject [141], that was preceded by a number of articles published in several countries since about 1958 [142]. Today, the military importance of ICF is confirmed by the emphasis on "stockpile stewardship" and by the fact that the possibility ICF might become the basis for a thermonuclear power reactor is still as remote as for magnetic confinement fusion.[2]

The concept of *inertial fusion energy* (IFE, i.e., energy production by an inertial confinement fusion reactor) is that a sequence of tiny fuel pellets containing deuterium and tritium are projected towards the center of a reaction chamber where high-power laser or particle beam pulses strike each pellet, compressing and heating its fuel, and releasing thermonuclear energy by the reaction: $D+T \longrightarrow {}^4He + n + (2.8 \times 10^{-12}\text{J})$. This energy is converted in an absorbing blanket into

[1] Seven of these graphs have been reproduced and discussed in the *INESAP Information Bulletin* [42].

[2] The major limitations for the construction of thermonuclear reactors, which are mostly of an engineering type, are independent of the method of plasma confinement employed [164].

thermal energy which is coupled to a turbine to make electricity through a normal thermal cycle. Since 1 g of DT produces about 340 GJ of energy, a nominal 1 GW (electric) fusion power plant with a thermal efficient of 30% would consume 10 mg of DT per second.[3] If we assume that one pellet is detonated each second, the explosive yield of each pellet would be 3.4 GJ, i.e., equivalent to about 810 kg of TNT.

From a military perspective, success with *inertial fusion energy* will open the way to the development of radically new types of nuclear weapons. This is because IFE is basically a continuous salvo of contained thermonuclear explosions with yields, dependent on the firing rate, in the range of a few 100 *kg* to a few *tons* of TNT equivalent. The military significance of these yields derives from the fact that the amount of conventional high-explosives carried by typical delivery systems is quite limited. For example, a Tomahawk long-range cruise-missile carries a conventional or thermonuclear warhead weighting about 120 kg, and a typical big air-dropped bomb weighs between 500 and 2000 kg. Since an ICF pellet weighs only a fraction of a gram, ICF based military explosives would revolutionize warfare. Combined with precision guidance, earth and concrete penetration, and other existing techniques, small and lightweight ICF based warheads would destroy virtually all possible targets, and render existing types of very-high yield nuclear weapons obsolete. The challenge, of course, will be to replace the huge laser- or particle-beam driver by some sufficiently miniaturized device. This problem will be discussed in chapter 4, where a number of potential drivers will be described. Nevertheless, it can already be said that a single-use device is usually much more compact and simple than a multi-purpose re-usable experimental facility, and that very-high energy-density technologies such as antimatter and superlasers are ripe to meet the challenge.[4]

At present, and independently of its possible future impact on the *design of radically new types of nuclear weapons*, inertial confinement fusion has already the capability of orders of magnitude improvement over traditional methods of nuclear weapon simulation for at least two related purposes: studying basic *weapons physics* and developing new *warhead designs*. Many aspects concerning these and other military implications of ICF have already been addressed [8, 15, 21, 38, 37, 155]. These comprise the use of ICF facilities for *weapons effects* research which previously required full-scale nuclear testing, and the *measurement of basic*

[3]This corresponds to a consumption of 0.5 kg of tritium per day. The large scale development of IFE is therefore equivalent to a world of extreme tritium abundance — which implies finding adequate solutions to the nuclear weapons proliferation problems, and to the environmental safety risks, associated with tritium abundance. *Note added in 2009:* See, in this context, reference [593].

[4]These considerations about radically new types of nuclear weapons should not minimize the potential of using ICF facilities for improving existing types of nuclear weapons [48].

physical data necessary for thermonuclear weapons design. These data include the temperature- and pressure-dependent x-ray opacity functions for high-Z elements, as well as high-pressure, high-temperature equations of states which previously could only be measured in underground nuclear explosions (see sections 3.4 and 3.5). Let us now introduce the subjects of nuclear weapons-effects and nuclear weapons-physics research:

• *Nuclear weapon-effects research* [132, 135].

ICF systems enable both nuclear and non-nuclear effects to be studied. The latter consists of the effects of low and high altitude single and multiburst detonation in the atmosphere. Such studies enable (a) prediction of the effects of subsequent bursts in a multiburst environment; (b) evaluation of the spatial extent and duration of satellite communication interference; and (c) evaluation of radar shielding effects which hinder detection of secondary missions. Since 1964, because of the Partial Test Ban Treaty (PTBT), such problems cannot be studied with real nuclear explosions in the atmosphere.

The total radiation field of a nuclear explosion is composed of x-ray, gamma-ray, neutron and electromagnetic pulse (EMP) components. The intensity of each of these is strongly dependent upon the specific design and the yield of the weapon. Also, the presence or absence of some of these radiations depend on the environment in which the nuclear detonation occurs. For example, in an underground explosion some of the radiation (e.g., EMP) will be absent compared to an atmospheric or high altitude explosion.

Until the conclusion of the CTBT, synergistic testing was done through underground explosions, but ICF provides now an alternative method for carrying out such tests in the laboratory; an ICF exposure is expected to cost less than one percent of an underground experiment.[5] Furthermore, experiments with an ICF facility are much more convenient and reproducible. For example, meter-sized costly equipments such as reentry vehicles, missiles, satellites, can be exposed to neutron fluxes of 10^{13} to 10^{14} n/cm^2/s, or 3 to 30 cal/cm^2 x-rays, without completely destroying them. ICF systems can also be used for "nuclear hardening," and to "burn in" ready-to-field equipments by exposing them to radiations and replacing the weakest components that may have failed.

• *Nuclear weapons-physics research.*

A comprehensive and thorough independent assessment of the full implications of ICF for *weapons physics* and new *warhead design* would require a considerable

[5]However, for countries such as India, because of the complexity and hugh cost of large ICF facilities, underground tests would be much less expensive than ICF simulations.

amount of research. As a prerequisite, such research would have to push the understanding of the principles of existing nuclear weapons beyond what is readily available in the open literature. Our simulation program ISRINEX was written as a first step in this direction and will have to be further developed in order to include what is necessary to assess the full vertical proliferation implications of ICF. Nevertheless, the insight into thermonuclear weapons physics already gained by developing ISRINEX is sufficient to highlight the main weapons physics implications of ICF.

Figure 3.1 is a simplified diagram of an advanced indirect-drive ICF target of the kind that is extensively studied for future ICF reactors [157]. Such a target consists of a hohlraum containing a 5 mg deuterium tritium fuel pellet. Typical targets for the large weapons simulation facilities currently under construction (NIF and LMJ) will contain between 1 μg and 1 mg of DT. The concept of *indirect drive* refers to the fact that in this type of target the driver energy is not directly deposited onto an outer layer of the fuel but is first converted into thermal x-rays confined in a hohlraum [145, 153, 156]. In the U.S., this concept was declassified in 1979 at the same time as the Teller-Ulam principle (Fig. 1.3), using a wording that is almost identical:

> "In some ICF targets, radiation from the conversion of the focused energy (e.g., laser or particle beam) can be contained and used to compress and ignite a physically separate component containing thermonuclear fuel" [22, p.103].[6]

It is therefore not surprising that Figs. 3.1 and 1.3 are very similar, except for the technique used to generate the soft x-rays filling the hohlraum. In laser driven ICF, the hohlraum is generally a cylinder with openings at both ends to allow the laser beams to heat the inner surface of the hohlraum, causing emission of x-rays. In heavy-ion driven ICF, the heavy-ions are stopped in converters (i.e., small pieces of high-Z materials placed within the hohlraum) which are strongly heated. With other drivers, e.g., light-ion beams or antiprotons, the details would be different, but the result the same: strong heating of the radiation case or of the converters leading to x-ray emission into the hohlraum. Hence, any type of indirect drive ICF system will enable the simulation of H-bomb physics in the laboratory.

At any given driver energy (which for NIF and LMJ is on the order of one megajoule delivered to the target) it is possible to use various techniques to multiply

[6]However, the technical details of indirect drive were not declassified until December 1993 [23]. At that time, many of these details had already been published by scientists from other countries[23].

the x-ray energy production far beyond what is obtained by direct conversion of the beam energy into thermal x-rays by heating the radiation case or a converter. One such technique is the use of a small amount of fissile material driven to criticality by the beams [174]. Placing this pellet of plutonium or uranium at the position of the primary in Fig. 1.3 and letting the laser or particle beams pass through the radiation case to implode the fissile material, leads to a highly miniaturized hydrogen bomb! For this reason, all information on "fissile material driven to criticality" [22, p.106], "capsules containing fissile materials" [22, p.107], and "capsules intended to mockup specific nuclear weapon designs, simulate nuclear weapon outputs, or address specific weapon physics issues" [22, p.107] are classified.

Having shown that ICF physics is qualitatively the same as thermonuclear weapons physics, it is now important to show that this similarity persists on the quantitative level. Fig. 3.1 shows that the typical size of a large ICF target is on the order of 1 cm. This must be compared with the diameter of the smallest hydrogen bomb, namely the 155 mm artillery shell (W82). Hence, the external size of a large ICF target is only 1/16 of the diameter of the smallest fully developed and engineered thermonuclear weapon! The same difference arises when comparing the masses of the fuels. For instance, at 100% burn efficiency and 50/50 fission/fusion contributions to the yield, the amount of fusion fuel in a 100 kt hydrogen bomb and in a 1 kt neutron bomb are 1 kg of LiD and 0.01 kg of Li_2DT, respectively. Compared with a range of 10 mg to 1 mg of DT fuel in an ICF pellet, this corresponds to a scaling factor of 10^6 for the fuel mass, and of only 10^2 for the fuel size.

But this comparison takes only size into account: proper scaling must also take compression into consideration. To do this, the physics of thermonuclear burn has to be included. A good way to do this is to calculate Ω, i.e., the ratio of the pellet radius to the thickness of a thermonuclear detonation wave at the optimum compression for ignition and burn propagation, which is defined by (1.27). In doing so, while $\Omega \approx 1$ is found for today's 1 μg pellets, $\Omega \approx 10$ is found for the larger 1 mg NIF/LMJ pellets.[7] Hence, with the type of pellets that will be available on the large simulation facilities which are currently under construction, it will be possible to study thermonuclear detonation physics under conditions which are equivalent to those of large scale thermonuclear explosions. In other words, the physics of a 1–5 mg DT pellet is the same as that of a 100–500 kt hydrogen bomb!

Of course, it may be objected that not all physical phenomena scale in a way that enables them to be simulated in an ICF facility. This applies for example to some instability effects which cannot be simulated unless the ICF target is

[7] This simple qualitative argument is confirmed by the results of elaborate computer simulations which have recently been published [166, p.10–11].

sufficiently large. It turns out that facilities such as NIF and LMJ will be of just the right size for these effects to become accessible to laboratory investigation (see section 3.6).

It is therefore clear that ICF experiments will contribute very significantly to progress in *weapons physics*. This is particularly true as ICF microexplosion experiments can be performed at a frequency of about one implosion per day, while underground explosions were limited to about one per month. Moreover, ICF physics is also considerably more complicated than hydrogen bomb physics. Indeed, "radiation transport and hydrodynamic calculations will have to be perfected to a high level to achieve ignition" [21, p.49]. Thus, ICF simulation will not only replicate on a small scale what would otherwise have been done with high yield explosions, it will raise the understanding of weapons physics to a level which could not have been achieved by means of underground nuclear tests. This fact is highlighted in a review article entitled *The evolution of high-energy-density physics: From nuclear testing to the superlasers*, which is co-authored by several prominent experts from the Lawrence Livermore National Laboratory and by Edward Teller [213]. This authoritative article was submitted for publication after the conclusion of the CTBT. It is worthwhile quoting from its conclusion:

> "Nuclear detonation experiments offer the unique possibility of bringing very large volumes of material into high-energy-density conditions. However, such experiments are expensive, difficult to diagnose with high precision, and currently prohibited under a comprehensive test-ban treaty. In contrast, the megajoule-class superlasers such as the NIF will be able to conduct multiple-shot experimental campaigns over time frames of days or weeks. Therefore, the laser experiments offer the possibility of extensive parameter variation, control and diagnostic development. [...] The routine quantitative examination of matter with these enormously capable and flexible facilities will invigorate and firmly establish the field of high-energy-density physics. With the cessation of nuclear testing, some regimes of high-energy-density physics will be lost, but a considerable subset will be accessible with much greater control and reproducibility with the superlasers" [213, p.623].[8]

A last aspect of ICF which is of importance in weapons physics is that of rate-dependent processes. An ICF system can easily expose a recoverable target

[8] In this quote, "superlasers" refer to conventional laser facilities such as NIF in the United States and LMJ in France. The impacts on high-energy-density and weapons physics of advanced superlasers, such as Livermore's 'Petawatt' [547, 550, 575], are not addressed in this article.

to neutron and x-ray fluxes comparable to those of a full size nuclear explosion.

Concerning *weapons design*, the situation is similar, except that the principles of the *new* weapons will be more than just simple improvements of existing ones. The new types of weapons that will result from extensive ICF research will therefore be *fourth generation nuclear weapons*. These new kinds of explosive devices based on atomic and nuclear processes that are not restricted by the CTBT are the subject of chapter 4.

We now expand on the weapons-physics applications of ICF and other laboratory pulsed-power simulation techniques.

3.3 Total energy versus energy density (Fig. 3.2)

The most obvious difference between a laboratory microexplosion and a weapons test is the *total energy* of the explosion, i.e., the yield, which differs by a factor 10^4 to 10^8. In order to put this difference into the right perspective it is necessary to take into account the *specific energy density*, i.e., the amount of energy per unit of weight. This is done in Fig. 3.2 where the two axes are the total energy in a test and the specific energy density. For both quantities the energy is measured in kiloton equivalents of TNT ($1\ kt = 4.18 \times 10^6$ MJ). For weapons tests, the total energy is on the order of kilotons, whereas for experiments on NIF it is equivalent to only a few kg of high explosives.[9] However, the specific energy densities achieved in NIF operations show significant overlap with the energy density regime available from weapons tests. NIF can therefore provide the high energy densities that are needed for thermonuclear reactions to occur. The two main advantages of NIF over weapons tests are that experiments on NIF can be performed much more frequently, and without destroying most or all of the diagnostic and measuring instruments.

Two regions are shown for NIF — with ignition and without ignition. This distinction reflects the two alternative modes in which NIF will be used for experiments in physics related to weapons. NIF without ignition is characterized by the type of experiments described in Ref. [155] and in the first half of this chapter (Figs. 3.3, 3.4, 3.5, 3.6, and 3.7). These experiments — which are among the most fundamental in the sense of probing phenomena which are virtually irreducible — do not use thermonuclear-fuel-filled capsules. Instead, the targets are foils and

[9] The baseline NIF and LMJ laser energies are 1.8 MJ, i.e., equivalent to 0.43 kg of TNT. Several documents (e.g., [36]) however, refer to a High Yield Facility (HYF) that will have a much higher yield than NIF, i.e., 40–200 *kg* [154].

other materials that enable the study of the behavior of materials and media at the high energy densities obtained when heated by x-rays to extreme conditions. The fundamental phenomena investigated are equations of state, opacities, and compressible turbulence.

NIF with ignition characterizes experiments in which the target is indeed a capsule filled with deuterium-tritium (DT). In Fig. 3.2 the calculated energy densities are those predicted to be achievable in the different regions of a burning capsule. Because the energy densities achieved in both modes of NIF operations show significant overlap with the energy density regime available from weapons tests, NIF can be used to investigate the high-energy-density subprocesses that occur in that regime. Among the more complex areas of investigation are phenomena which arise from combinations or interactions of several different processes. These include the dominant energy coupling processes involved in the operation of nuclear weapons — the high-energy-density hydrodynamics and radiation transport phenomena illustrated in Figs. 3.8, 3.9 and 3.10 — radiation-driven hydrodynamics, pure hydrodynamics and radiative transport.

It is clear that with ignition, the maximum achievable energy density is the same for NIF as for weapons test: about 20 kt/kg, slightly more than the fission energy content of plutonium, and about a quarter of the theoretical maximum yield-to-weight ratio of a thermonuclear weapon — the energy released in the total fusion of a DT mixture.

The shaded area in Fig. 3.2 represents the region of high energy density. The dividing line with the low energy density region corresponds to a specific energy of 2 t/kg, i.e., about 8 MJ/g, the energy required to compress DT to 1'000 times its solid density. This specific energy also corresponds to the energy in the fissile material of a fission fizzle: a fission bomb with an efficiency of 0.01%, therefore producing a temperature of only about 100 eV, insufficient to initiate boosting (see section 1.4).

The lower limit of the energy density scale is 1 kg/kg, the energy content of high explosives. It corresponds to "hydrodynamic experiments" for which full-scale assemblies using mock nuclear materials are used to study experimentally the hydrodynamics of the implosion process at the beginning of a weapon's operation. "Subcritical experiments" and "Hydronuclear tests," in which fissile nuclear materials are used and in which a limited amount of nuclear energy is released, would lie on the line joining "Primary hydro" with "Weapons test."

The advanced hydrodynamics facilities under construction for the SBSS program include powerful x-ray machines such as DARHT. Just as American and French scientists collaborate on the design and construction of LMJ, they also col-

laborate on AIRIX [512], the next generation French hydrotest facility. Other facilities indicated on Fig. 3.2 are pulsed power machines based on electromagnetic energy cumulation (Pegasus, Atlas, Saturn, and Jupiter).[10] Compared to laser-beam pulsed-power systems, particle-beam (and magnetic compression) pulsed-power technology has the advantage of having target volumes that approach sizes larger than a cubic centimeter, whereas NIF targets are a few millimeter in size. Moreover, in some of the parameter spaces shown in Figs. 3.2 to 3.10, the particle-beam pulsed-power machines are complementary to laser facilities.[11] However, as will be seen in the following figures, "it is evident that NIF will be dominant in all the parameter spaces shown when it comes to reproduce bomb conditions" [21, p.80].

3.4 Equation of state (Fig. 3.3)

A material's equation of state (EOS) is the thermodynamic relationship between the energy content of a given mass of the material and its pressure, temperature, and volume.

Accurate high-pressure data for various materials can be obtained up to a few Mbar using static and dynamic methods (i.e., high-explosive driven devices [209]), and above a few hundred Mbar of pressure the statistical Thomas-Fermi-Dirac theories can be used reliably for generating EOS of materials. However, in the recent past, access to the region of pressure from 10 to 100 Mbar (commonly known as the "intermediate region") required the use of nuclear explosive drivers [211, 213].

ICF facilities can be used to measure high-pressure, high-temperature equations of state in a regime which was previously achievable only in underground nuclear explosions [21, 208, 211]. Lasers of relatively modest size, such as those existing in Israel [193], India [143, 198, 199] or Korea [518], for example, already provide very significant data of this type [193, 210]. However, the development of high power ICF facilities enables improvement of the quality of these data *beyond* [213] what could previously be done with relatively small lasers [208] or underground nuclear explosions [201, 205, 207, 198].[12]

[10] For an overview of the U.S. pulsed power facilities, see [21, p.71–88], [516].

[11] Such a complementarity already exists between the Saturn pulsed-power-driven Z–pinch at SNL and the Nova laser at LLNL [165].

[12] According to reference [207, p.1124], reference [201] is the "the first open publication of the measurements of the compressibility (of condensed materials) under the conditions of underground nuclear tests."

In an operating weapon, pressures may reach hundreds of Gbar and temperatures several tens of keV in LiD. As can be seen in Fig. 3.3, equation of state experiments on NIF do not extend to this regime. They are limited to a few Gbar and to less than one keV. But this is not really a problem: in the very-high-pressure/temperature limit there are good theories based on the Thomas-Fermi model.[13] In fact, it is in the 10 Mbar to 5 Gbar regime where NIF is operating that precise data is most necessary. In this region, NIF has the advantage of enabling very clean measurements. In contrast to lower energy laser systems, it can produce planar shocks that are much easier to analyse than spherical shocks [208], and it avoids the "preheat" problem which tends to destroy the sample before it is shocked.

Recently, the extraordinary potential of laser technology for equation of state studies has been highlighted by the results of the first precise measurements of density and shock speed in deuterium at pressures up to 200 GPa (2 Mbar). These measurements were made on the NOVA facility at LLNL [212] and showed a discrepancy of a factor of two with a widely used equation of state model on which standard tables are based (e.g., [203, 206].[14]

3.5 Opacity (Figs. 3.4–3.5)

Opacity is the degree to which a medium absorbs radiation of a given wavelength. This fundamental quantity is very difficult to calculate because there are many transitions and competing ionization stages that can contribute to the opacity of a given element. Knowledge of the opacity of a medium is crucial to understanding how the medium absorbs energy and transmits it from one place to another. In a nuclear weapon, opacities at x-ray wavelengths are particularly important, because this is the energy range in which much of the energy is transported. This is particularly the case in the Teller-Ulam configuration, where x-rays from a primary fission explosion are used to compress and ignite a secondary assembly containing fusion materials.

The temperature- and pressure-dependent x-ray opacity functions for high-Z elements were until recently classified[15] and are now openly discussed in inter-

[13] For a review, see, in particular, the articles by Shalom Eliezer in [204].

[14] A large subset of "SESAME," the Los Alamos National Laboratory equation of state data-base, has been declassified between 1984 and 1994 [206].

[15] x-ray opacities for temperatures below 0.35 keV have been declassified in 1993 [22, p.104] as a consequence of a U.S. Department of Energy "openness initiative" [23]. The JASON study [21, p.55] suggests that opacities for temperatures up to 0.6 keV could be declassified.

national meetings [216]. These high-Z opacities are of little interest for astrophysics.[16] But they are of crucial importance for ICF targets and nuclear weapon design.

In Fig. 3.4 the abscissa is the temperature of the material. A sample is placed in a hohlraum heated by the NIF laser, creating a bath of x-rays which uniformly drives it to the desired temperature and density. The measurement is performed by passing x-rays, generated by a backlighter laser, through the hohlraum to probe the sample. Backlighter x-rays may have energies from a few tens of eV to a few keV (the maximum x-ray energy produced by a fission primary). NIF hohlraum temperatures of 600-700 eV should be accessible, which would enable opacity measurements to be performed under close-to-secondary conditions [21, p.49].

The ordinate in Fig. 3.5 is the atomic number of the sample. The lower and upper boundaries of the shaded area correspond to the minimum hohlraum temperature necessary to open the L or M shell of the atom under investigation (the intercepts at Z=10 and Z=29 are the respective atomic numbers for which the corresponding shell are completed). Clearly, experiments on NIF can reach ionization levels sufficient to measure M-shell-dominated opacities in materials as heavy as uranium (Z=92).

In modeling radiant energy transfer, a considerable simplification occurs when the material is sufficiently opaque to radiation that the medium is locally in thermodynamic equilibrium (LTE). In this limit the so-called Rosseland approximation (or radiative conductivity model) is valid [187]. Radiation transfer is governed by a non-linear diffusion equation, and the medium is characterized by a single parameter: the Rosseland mean free path λ, which is related to the Rosseland average opacity σ by the relation $\lambda\sigma\rho = 1$ where ρ is the density. Figure 3.4 shows that on NOVA, LTE is driven by collisions between the electrons and the ions of the plasma, whereas on NIF it is possible to reach the radiatively driven LTE which is characteristic of nuclear weapons.

Figure 3.4 is taken from Ref. [37]. In Fig. 3.5, taken from Ref. [21], opacity measurements are represented in a different parameter space: the temperature is replaced by the ratio of the target lifetime to the thermal equilibration time (the time for the electron, ion, and radiation temperatures to become equal). This ratio is between 1 and 100 for NIF, as for weapons-tests, which means that M-shell-dominated Rosseland opacities of heavy elements can definitely be measured under conditions of LTE on NIF.

[16] Starting in 1986, a group made up of 30 experts drawn from 13 leading laboratories and observatories in atomic physics and astrophysics in the U.S., Europe and South America has selected key research papers, computer simulations and data on elements up to iron, which reveal the most interesting information for stellar opacities [217].

3.6 Compressible turbulence (Figs. 3.6–3.7)

A major issue in the operation of nuclear weapons is the question of stability of implosion in both the primary and the secondary. In inertial confinement fusion the fuel must be compressed to densities on the order of 1'000 to 10'000 times solid density with a temperature in the central hot spot of about 5 keV. Success in achieving such high compression and temperature requires very symmetrical energy deposition, as well as the avoidance of the well-known hydrodynamic instabilities (Rayleigh-Taylor, Kelvin-Helmholtz, and Richtmyer-Meshkov), whose understanding is also critical to weapons design [21, p.39].

Since targets made of fissile material can be used on NIF, it is possible to use this facility to advance the materials science of plutonium in areas such as equations of state, opacities, or spalling. However, another class of uncertainties relates to generation of mix at the various interfaces and its effect on booster burn [21, p.49]. Here the experience gained on NIF with plutonium targets filled with a deuterium-tritium mixture can be transferred to the understanding of the behavior of boosted nuclear weapons and of the primaries of thermonuclear weapons.

Rayleigh-Taylor instabilities [218, 219, 220] develop when the interface between two fluids of different densities is accelerated, and Kelvin-Helmholtz instabilities occur when one fluid acquires a tangential velocity relative to the other. Both types can lead to laminar or turbulent mixing of the materials, for example, plutonium and DT in a high-explosive driven implosion of a boosted primary, or depleted uranium and LiD in x-ray ablation-driven implosion of a thermonuclear secondary. Avoidance of such mixing is obviously essential for proper operation of nuclear weapons.

While Rayleigh-Taylor and Kelvin-Helmoltz instabilities can to a large extent be controlled by careful design, Richtmyer-Meshkov induced compressible turbulence [221] is more difficult to avoid. This instability produces a mixing layer when a strong shock passes through the interface between two materials.

The program of work in instability research on NIF involves the study of shocked mixing layer growth and the evolution of compressible turbulence from the small-amplitude, linear growth regime (which is pertinent to ICF implosion) to the full evolution of turbulence (which is pertinent to weapons). In the case of turbulent mixing layers, universal rules that control the width of such mixing layers as a function of time have been discovered in 1983 in England at the British Atomic Weapons Research Establishment.[17] It would be of great importance to weapons designers to pin down these rules [155].

[17] For a review, see [221].

In Fig. 3.6 it is clear that whereas the moderate compression on NOVA allows one to follow the transition from linear instability to weak turbulence, the high compression and larger scale volumes accessible on NIF allow one to follow this all the way to turbulent mix [155]. Moreover, since the sample size is smaller and the perturbation wavelength readily adjustable on NIF, laboratory experiments should be easier than weapons tests. On the right side of the graph, the ordinate gives the shock pressure, p. On the left side, the approximate value of the corresponding compression factor is given. Theoretically, for an infinitely strong single shock, the maximum compression is equal to 4 for a matter-dominated plasma ($\gamma = 5/3$) and to 7 for a radiation-dominated plasma ($\gamma = 4/3$).

Figure 3.6 is taken from Ref. [37]. In Fig. 3.7, taken from Ref. [21], the left hand side ordinate is not the compression factor χ but M, the Mach number of the unshocked medium. At $\chi = 1$, M is obviously equal to one, and at $\chi = 5$, M is approximately equal to six.[18]

By using large facilities such as NIF or LMJ, it is possible to study compressible turbulent mixing under the extreme condition found in the explosion of ICF pellets or the secondary of thermonuclear weapons. However, as is the case for equation-of-state data [210], the nonlinear and transitional stage of compressible turbulent mixing that is relevant to the operation of boosted nuclear weapons, or the secondary of non-sophisticated thermonuclear weapons, can be studied with much less powerful facilities. For this purpose, shock tube devices [222] and 50–100 J lasers [193, 223] are powerful enough.

3.7 Radiation-driven hydrodynamics (Fig. 3.8)

An essential feature of nuclear weapons physics is the importance of radiation dominated plasma effects. This has no analogy within other realms of science except for some parts of astrophysics.

In Fig. 3.8 the parameter space of radiation-driven hydrodynamics is illustrated in terms of the relative radiant flux and the Rosseland mean free path λ in uranium at normal density. This mean free path (about 2 mm at 10 keV, and about 0.1 mm at 2 keV [214]) gives a measure of the thickness to x-rays of a fission bomb, or of the penetration depth of x-rays into the surface of the radiation case of an H bomb.

From the value of their respective λ, one can infer that the typical radiative temperatures of NOVA, NIF, and weapons tests are about 1.8, 5, and 10 keV. If we

[18] The equations giving χ and p as a function of M are given by equations (85.7) and (85.8) of Ref. [186]. Similar equations in spherical symmetry are given in [195].

take the T^4 temperature dependence of the Planck law, the corresponding radiant energy fluxes have the relative values indicated on the horizontal axis, with NIF relatively close to weapons tests and NOVA approximately a factor 1'000 below.

3.8 Pure hydrodynamics (Fig. 3.9)

Shock compression and heating of imploding materials is described by scalable hydrodynamics, provided radiation effects are negligible (pure hydrodynamics) and the various ionic components of the plasma are in local thermal equilibrium (two-fluids hydrodynamics). Such conditions are likely to prevail within a secondary during implosion, before ignition of thermonuclear reactions.

Figure 3.9 shows the corresponding parameter space. Consistent with Fig. 3.3, it can be noted that NIF is capable of producing single shock dynamic pressures of several Gbar. This allows the simulation of implosion conditions equivalent to those of nuclear weapons operation.

In a plasma, the temperatures of the different species of particles are determined by energy transfer processes, which depend on their respective electric charges and relative masses. Electrons and ions of various kinds may thus have quite different temperatures. Figure 3.9 shows that the LTE conditions reached on NIF are similar to those of weapons tests, with a ratio of heavy to light ion temperatures of about 0.5 .

3.9 Radiative transport (Fig. 3.10)

Figure 3.10 illustrates the similarities of radiative transport conditions in NIF and weapons tests. $E_{rad} \propto T^4$ and $E_{mat} \propto T$ are the radiation and matter energy densities. Consistent with Fig. 3.8, there is a ratio of about 20 in the mean free path between NOVA and weapons test or NIF, and a factor of about 100–200 in $E_{rad}/E_{mat} \propto T^3$. NIF operation is clearly in the radiation-dominated domain, and the diffusive approximation is applicable since NIF targets are larger than the radiation mean free path.

3.10 ICF and nuclear weapons proliferation

In the JASON assessment of SBSS [21], the following statement is made:

> "The NIF technology is not a nuclear weapon, cannot be adapted to become a nuclear weapon, and demands a technological sophistication far more advanced and difficult than required for nuclear weapons. NIF will contribute to strengthening the science based understanding of secondaries of thermonuclear weapons, but without high-yield underground tests ($\approx 150\,kt$ as under the current Threshold Test Ban Treaty), it is not practical to envision any significant (if indeed any at all) performance improvements emanating from NIF experiments" [21, p.54].

This statement[19] is essentially correct because the high-yield nuclear weapons currently in the stockpile are based on principles discovered in the 1940s and 1950s. After more than fifty years of research and development, even though the scientific understanding of many details is still incomplete, the existing types of thermonuclear weapons have reached such a degree of perfection that little can be done to improve them significantly. Moreover, they already have all the necessary qualities that make them suitable for military use: they are simple, rugged, safe, reliable, highly lethal, and relatively inexpensive. It is therefore unlikely that thermonuclear weapons of the existing type will disappear, unless they are banned by international law.

The new types of weapons that will result from extensive ICF research will be *fourth generation nuclear weapons*, i.e., explosive devices based on atomic and nuclear processes that are not restricted by the CTBT. These physical processes — which have been under consideration for military uses for decades — are discussed in the next chapter.

The development of these new weapons will stem from the thorough understanding of the physics of thermonuclear explosions that will result from the use of ICF facilities such as NIF and LMJ. The fact that the total energy in these facilities is equivalent to only a few kg of TNT will be no limitation: producing higher yields is just a matter of scaling. The main problem, for which a number of solutions are already under investigation (see sections 4.7 to 4.9), will be to build a compact (but single use) primary to replace the huge laser that is necessary for laboratory implosion of fusion pellets. This is why the "CTBT-allowed" physical processes reviewed in the next chapter are so important: they will provide means for designing extremely compact primaries, i.e., primaries making use of exotic materials such as antimatter, nuclear isomers, super-heavy elements, or metallic

[19] A similar statement is made in a the 1996 JASON review of ICF: "Openness is needed to inspire confidence in the world community that SBSS is not hiding the development of a new generation of nuclear weapons, enabled somehow by the connection between ICF and the physics of secondaries" [36, p.12].

hydrogen, or of relatively ordinary processes such as magnetic compression, subcritical fission burn, or chemical-explosive-driven lasers. With the availability of such compact primaries, the knowledge and skills gained in ICF research will be used to make compact secondaries, which will use the relatively inexpensive thermonuclear fuels (e.g., deuterium, tritium, lithium, etc.) as the main explosive charge.

However, as was shown in the previous sections, without even referring to fourth generation nuclear weapons, laser and other high-energy-density facilities can be used to investigate numerous aspects of the physics of present day nuclear weapons. These capabilities are summarized by Shalom Eliezer, of the Soreq Nuclear Research Center, Yavne, Israel, in the preface [197] to a special issue of the journal *Laser and Particle Beams* devoted to laser and particle beam induced shockwaves [196], with contributions from China, France, Japan, Israel, Italy, United Kingdom and Russia.[20] Moreover, the considerable value of ICF technology to potential nuclear weapon proliferators is explicitly recognized in the study entitled "The National Ignition facility (NIF) and the issue of nonproliferation" [158], prepared by the Office of Arms Control and Nonproliferation for the Secretary of the U.S. Department of Energy:

> "The thermonuclear warheads developed by the U.S. and USSR in the 1950s were huge, heavy and designed for delivery by large aircraft rather than missiles. It was through an extensive nuclear testing program that thermonuclear warheads were made lighter and more deliverable. Without nuclear testing, it is probable that a proliferator would not be able to develop a highly deliverable thermonuclear weapon, but depending upon its motivations for developing the weapon, the proliferator may not require long-range deliverability. A modern, sophisticated proliferator with access to ICF computer codes and today's computer workstations would have far more tools for designing a secondary than the U.S., U.K. or USSR had in the 1950s or France and China in the 1960s. Furthermore, many of the basic concepts have been declassified"[21] [158, p.27].

[20] Eliezer lists six main areas of laser- and particle-beam induced shock-wave research: equations of state, phase transitions, dynamic behavior of materials, electrical conductivity, atomic physics and hydrodynamic instabilities [197, p.109].

[21] The main argument of the Office of Arms Control and Nonproliferation to discount the proliferation impact of NIF and ICF (and therefore to support the construction of NIF) is that: "Regardless of access to the NIF or any other ICF facility, one cannot rule out that a technologically advanced country would be able to field a very conservatively designed thermonuclear weapon that would present a credible threat without nuclear testing" [158, p.27].

Indeed, the complexity of ICF target experiments requires that they be analysed by simulating the experiment with two- and three-dimensional hydrocodes. Thus verification and improvement of weapon design code is an intrinsic part of ICF experiments. Since ICF research is done in non-nuclear weapons States, very sophisticated computer codes have been developed and published by scientists in such States. For instance, the two-dimensional hydrocode MULTI2D [147] developed at the *Max-Planck-Institut für Quantenoptik*, in Garching, Germany, is considered to be in several respects better and faster than LASNEX, the currently standard (and partially classified) U.S. two-dimensional hydrocode. These codes allow, in particular, the simulation of the dynamics and stability of implosion (of either passive or nuclear materials) driven by ICF or other types of drivers: chemical high-explosives, magnetic fields, electromagnetic guns, etc.

Tables 3.1 and 3.2 are compilations of the main characteristics of the major operating or planned ICF-related facilities in the world. In the last column, "C" means that the facility is under construction, and "D" that it is in the design stage. The laser beam wavelength is in μm.

In these tables, the tabulated energy of the facility is the *nominal* maximum energy. This is because the beam-target coupling is a function of the nature of the beam (i.e., laser- or particle-beam) and of its energy, e.g., of the photon's wavelength in the case of a laser beam.[22] Hence, a comparison of the relative capabilities of ICF-related facilities is not trivial. Some convention is required. For example, the power of microexplosion fusion installations can be expressed as the total energy that the laser system is capable of delivering to the target at a given wavelength. At present, applying this convention to the shortest possible wavelength, the most powerful laser energy attains approximately 30 kJ for the United States, 10 kJ for Japan, 6 kJ for France, 2 kJ for Russia and China, 1.5 kJ for the U.K. and about 0.5 kJ for Germany.

Much more powerful facilities are under construction in the United States and France. They are the *National Ignition Facility* (NIF) and the *Laser Mégajoule* (LMJ). They will have similar nominal energies (i.e., 1'800 kJ) corresponding to a maximum energy on the order of 600 kJ at the shortest wavelength. But Japan and Germany have also projects of a similar magnitude, i.e., *Koyo* and *Hiball*, with planned energies of about 4 MJ. Moreover, like those other countries (especially India and Israel) the quality of their ICF and other thermonuclear fusion facilities are more and more comparable to those of the United States and France.

[22] This wavelength can be shortened by an optical frequency multiplier, what has the effect of improving beam-target coupling, but at the cost of a lower beam energy.

A graph showing the predicted nominal ICF target yield as a function of the beam energy incident on the NIF point design target appeared in a 1977 review of the U.S. inertial confinement fusion program by the National Research Council [166, Fig. 1, p.10]. This graph indicates that a driver's energy of about 0.9 MJ is needed in order to reach an ion temperature of 15–18 keV in the ICF capsule, which enables ignition and leads to a target gain greater than unity. The nominal energy of 1.8 MJ corresponds therefore to a factor of two safety-margin, which should enable to observe a plateau of approximately constant gain (≈ 6) for driver's energies between 0.9 and 1.8 MJ.

Consequently, it is clear that ICF facilities with nominal energies in the range of 0.1–1 MJ will not be powerful enough to reach ignition. This is why Japan will probably not build the Kongoh facility, but a larger one, Koyo. A similar conclusion applies to the German HIBALL project [140]: once the heavy-ion beam interactions with the target are well understood — using low-energy facilities such as KALIF — the construction of a full-size heavy-ion-driven facility can start at once. In effect, contrary to high-energy laser technology, the heavy-ion-driver technology is well known [134] and routinely used in several major fundamental research laboratories, especially in Europe at the Gesellschaft für Schwerionenforschung (GSI, Darmstadt) and the Centre Européen de Recherches Nucléaires (CERN, Geneva). Under the leadership of Germany, a collaboration of European laboratories and university groups, now known as the HIDIF Collaboration, has started in 1991 to study the design of a Heavy Ion Ignition Facility (HIDIF) that is today the most advanced design for such a facility [169].

During the year 2000 the construction of the NIF laser at the Lawrence Livermore National Laboratory ran into serious problems: assembling the laser in a clean environment proved much more difficult and costly then expected, optical damage was found to limit the laser energy to about half of the 1.8 MJ design energy, and it became unclear whether any NIF-scale target could reach ignition, even if the laser operates perfectly [170, 171]. While it is understood that the NIF laser is basically a research and development project, not merely a construction project, these problems may prove to be fatal to the laser facility because alternative technologies are available (or on the design horizon). For example, if NIF fails because of practical problems with laser-beam technology, the less exacting particle-beam technology could provide a back-up [134]. Similarly, if the "pure fusion" targets that are usually discussed in the context of NIF do not work, various hybrid types of targets containing fissile or exotic materials such as antimatter may do the job. Under such conditions, the 50 GeV particle accelerator that is projected to be constructed at Los Alamos as a replacement of the nearly 40 years old linear accelerator LAMPF, and the 18 beams *Advanced hydrotest facility* [523] that is expected to be driven by this accelerator, could also be used as a heavy-ion beam

driver for inertial confinement fusion.[23]

In conclusion, the construction of large ICF microexplosion facilities such as NIF and LMJ will give the arms race a fresh boost. It must be understood that, as a result, there will be considerable follow-on effects within other countries. Japan[24] and, to a lesser extent, Germany[25] already possess ICF and other thermonuclear fusion facilities of comparable quality to those of the United States and France. These countries will certainly increase the power of their laser- and particle-beam ICF-drivers. India[26], Israel[27] and Korea [518] are close behind. The world runs the risk that certain countries will equip themselves directly with fourth generation nuclear weapons, bypassing the acquisition of the preceding generations of thermonuclear weapons.

[23] A new accelerator facility for Los Alamos has been under consideration since about twenty years [505, 506]. Such a facility, which could also be used for the large scale production of antimatter [292], would be a "revenge" for Los Alamos that did not recently get a new facility of a size comparable to Livermore's NIF.

[24] Japan has found itself in the position of the world leader in ICF research at several occasions. In 1986, for example, a record thermonuclear yield of 10^{12} neutrons was achieved with the Gekko XII laser — a performance that the U.S. and French nuclear scientists took several years to surpass. Today, Japan is still leading the world with a pellet compression of 600 times its initial solid density, a record achieved in 1989–90. Finally, in August 2001, when the petawatt superlaser under construction at the Institute of Laser Engineering at Osaka University will be terminated, Japan will operate the most powerful superlaser in the world [573, p.I].

[25] Germany is the world leader in the heavy-ion beam approach to ICF. It has experimental facilities at the *Gesellschaft für Schwerionenforschung* (GSI) in Darmstadt [163] and at the *Forschungszentrum Karlsruhe* (FZK). Furthermore, there are significant ICF-related laser facilities at Garching and a project for a 1 kJ laser at GSI. Germany has also an ambitious superlaser research and development program.

[26] Since a number of years India is operating a 20–50 J Nd:glass laser at the *Bombay Atomic Research Center* [198]. We are indebted to Dr. D.D. Bhawalkar, Director of the *Center for Advanced Technology* at Indore, for providing us the current characteristics of the four-beams laser system (see Table 3.2) that is operating at CAT [Private communication, January 11, 2000]. The fact that India is developing this technology indigenously is illustrated by a contribution entitled *High power glass laser development for ICF studies in India* by A.S. Joshi to the IAEA Technical Committee Meeting on Drivers and Ignition Facilities for Inertial Fusion at Osaka University, Osaka, Japan, on March 10-14, 1997.

[27] According to Prof. Shalom Eliezer [private communication, March 21, 2000] the ALADIN laser energy has not been increased beyond its 1985 level, i.e., 100 J [193]. It should be stressed, however, that Israeli scientists are working in close collaboration with American scientists and that they are at the forefront of several difficult problems, e.g., opacity calculations [215].

Particle beam driven ICF facilities					
Country	System name	Location	Energy [kJ]/[ns]	No. beams	
USA	Saturn	SNL	400/5	36	
	PBFA-II-Z	SNL	1500/20	36	
	ILSE	LBL	6400/10	16	D
Germany	KALIF	Karlsruhe	40/40	1	
	HIBALL		5000/20	20	D
Europe	HIDIF		3000/6	48	D

Table 3.1: Major operating or planned particle-beam driven ICF facilities. In the last column D means that the facility is in the design stage.

Laser beam driven ICF facilities						
Country	System name	Location	Energy [kJ]/[ns]	No. beams	Wave length	
Glass lasers						
USA	Omega	LLE	3/0.6	24	0.35	
	Omega-UG	LLE	40/3	60	0.35	C
	Nova	LLNL	50/1	10	0.35	
	NIF	LLNL	1800/5	192	0.35	C
Japan	Gekko-XII	Osaka	20/1	12	1.06	
	Kongoh	Osaka	300/3	92	0.35	D
	Koyo	Osaka	4000/6	400	0.35	D
France	LULI	Palaiseau	0.5/0.6	6	1.06	
	Octal	Limeil	0.9/1	8	1.06	
	Phébus	Limeil	14/2.5	2	0.53	
	Mégajoule	Bordeaux	1800/15	288	0.35	C
China	Shen-Guang-I	Shanghai	1.8/1	2	1.06	
	Shen-Guang-II	Shanghai	6.4/1	8	1.06	
	Shen-Guang-III	Shanghai	60/1	60	0.35	D
UK	Helen	AWE	1/1	3	0.53	
	Vulcan	RAL	3/1	6	0.53	
Russia	Delfin	Moscow	3/1	108	1.06	
India		Indore	0.4/3	4	1.06	
Italy	ABC	Frascati	0.2/2	2	0.53	
Israel	ALADIN	Soreq	0.1/3	1	1.06	
	Continuum	Soreq	0.07/7	1	1.06	
Germany		GSI	0.1/15	1		
	PHELIX booster	GSI	4/10	1		C
Korea	Sinmyung-I	Taejon	0.08/0.5	1	1.06	
KrF lasers						
USA	Mercury	LANL	1/5	1	0.25	
	Nike	NRL	5/4	56	0.25	C
Japan	Ashura	Ibaraki	0.7/15	6	0.25	
	Super-Ashura	Ibaraki	7/22	12	0.25	C
UK	Sprite	RAL	0.09/60	6	0.25	
	Titania	RAL	0.85/0.5	1	0.27	
China	Tin-Guang	Shanghai	0.4/	1		
Iodine lasers						
Russia	Iskra-5	VNIIEP	15/0.25	12	1.30	
Germany	Asterix IV	Garching	2/5	1	1.30	
	Asterix IV	Garching	1/0.3	1	1.30	

Table 3.2: Major operating or planned laser driven ICF facilities. In the last column C means that the facility is under construction and D that it is in the design stage. The wave length is in μm.

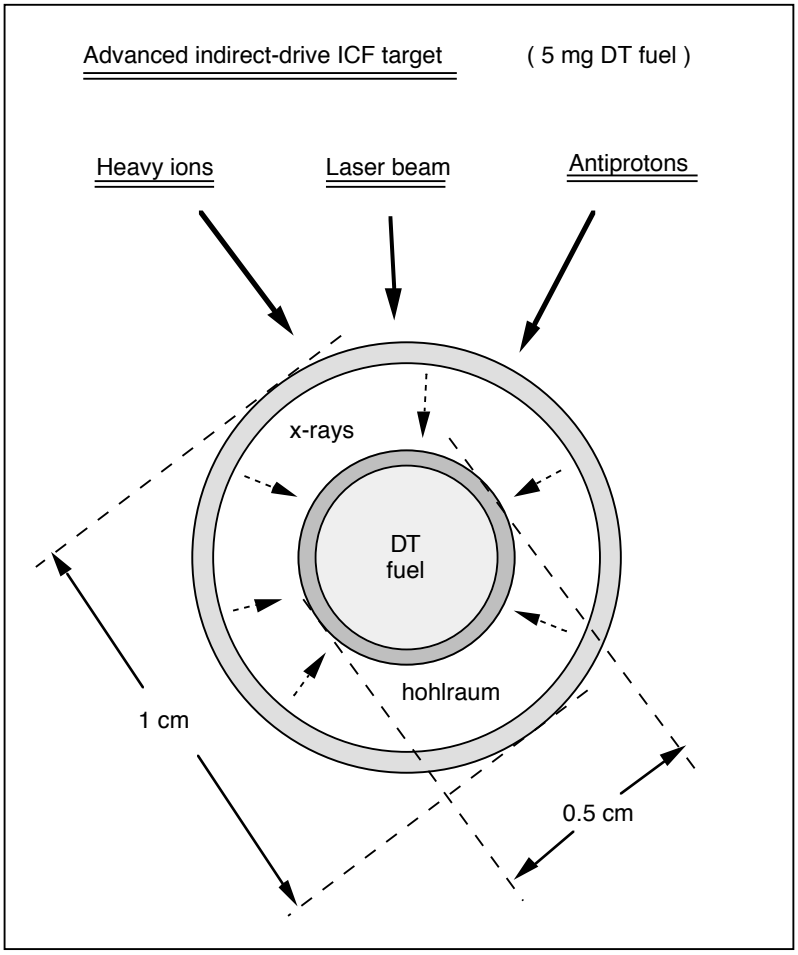

Figure 13 *"In some ICF targets, radiation from the conversion of the focussed energy (e.g laser or particle beam) can be contained and used to transfer energy to compress and ignite a physically separate component containing thermonuclear fuel. (February 1979)".*

Reference: U.S. Department of Energy, Office of Declassification, "*Drawing back the curtain of secrecy - Restricted data declassification policy, 1946 to present*", RDD-1, (June 1, 1994) page 103.

Figure 3.1: Figure 13

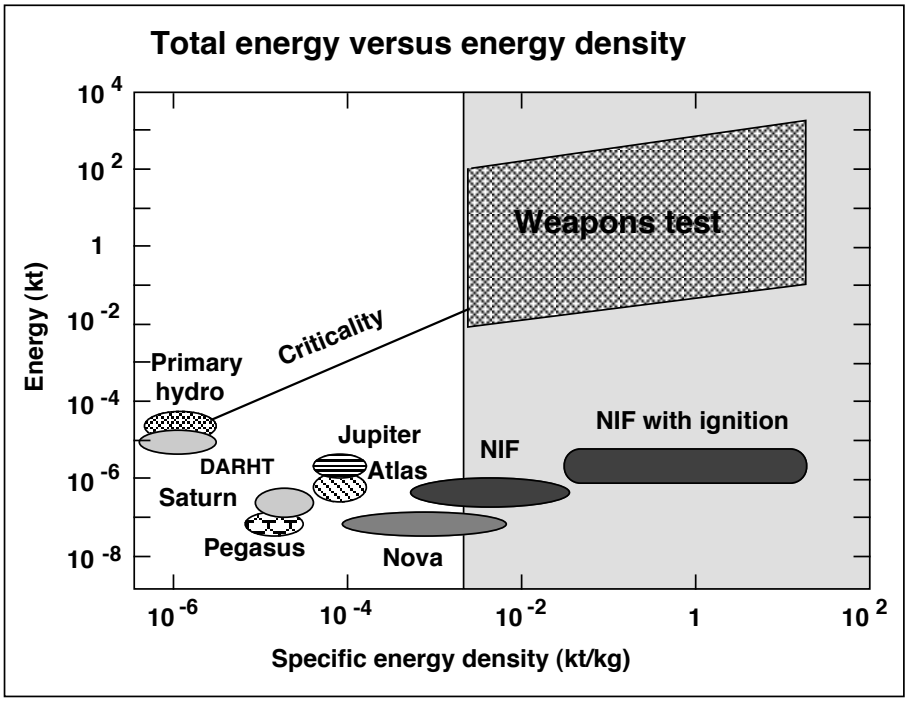

Figure 14 Total energy versus energy density for primary hydrodynamic tests (DARHT), pulsed power facilities (Saturn, Pegasus, Atlas and Jupiter), inertial confinement fusion facilities (NOVA and NIF, and weapons tests.

Figure 3.2: Figure 14

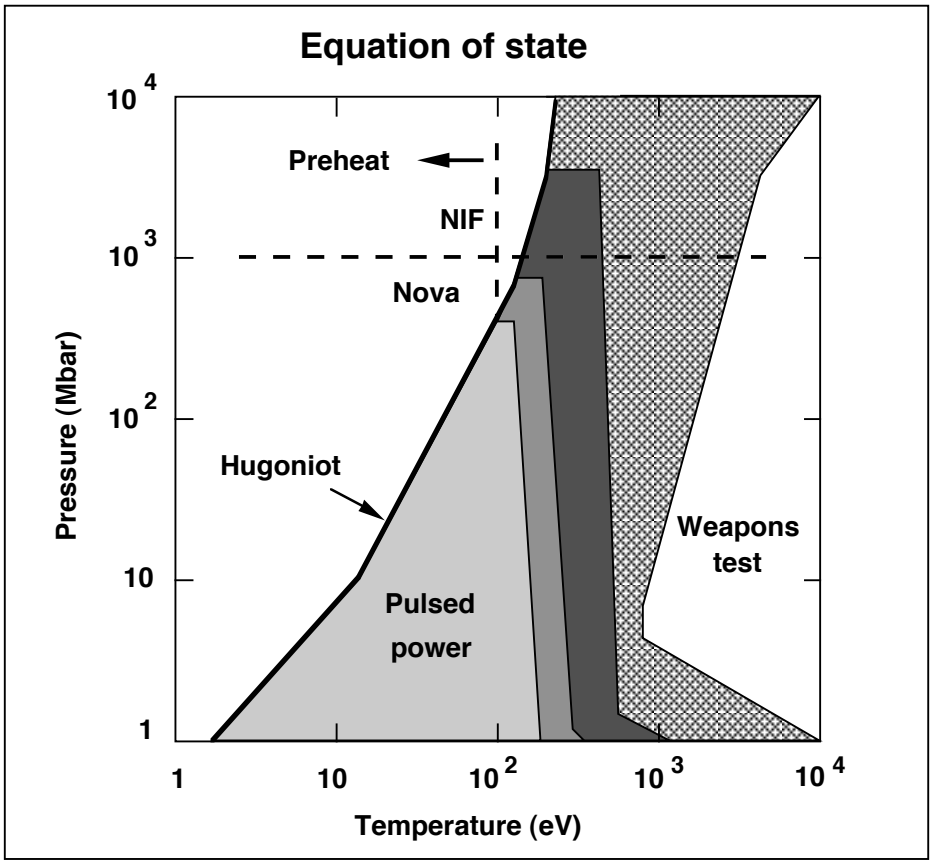

Figure 15 Equation of state measurements achievable on megajoule-scale facilities like NIF or LMJ overlap significantly the weapons-test regime.

Figure 3.3: Figure 15

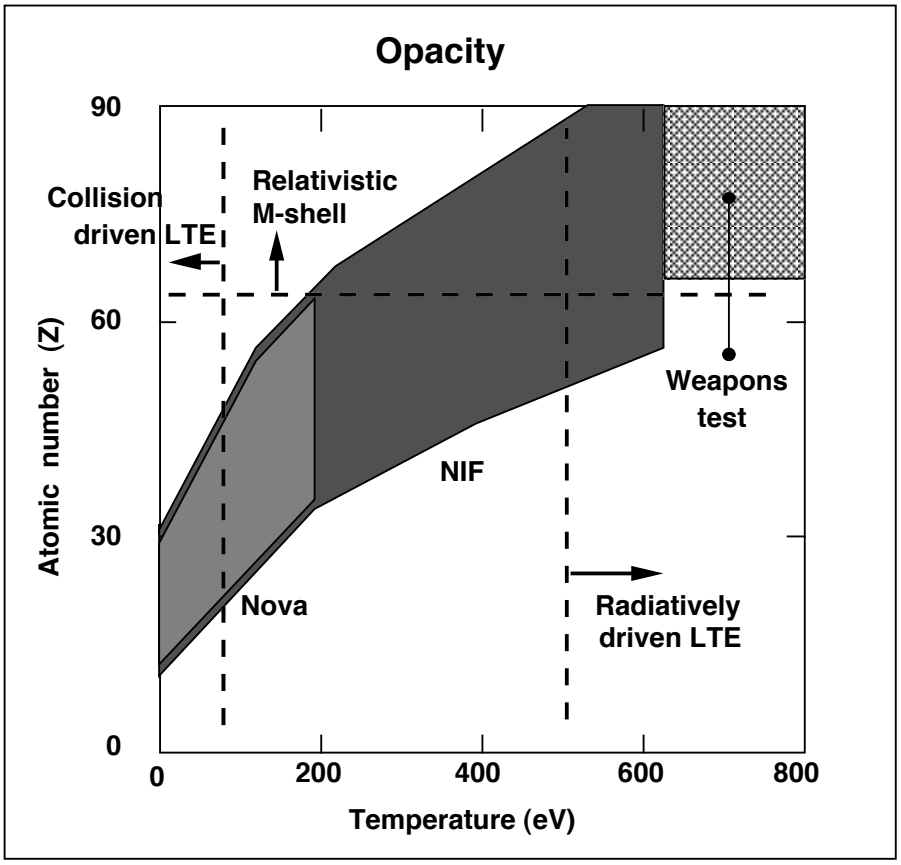

Figure 16a M-shell dominated opacity measurements on NIF are possible in the radiatively driven local thermal equilibrium typical of the weapons-test regime.

Figure 3.4: Figure 16a

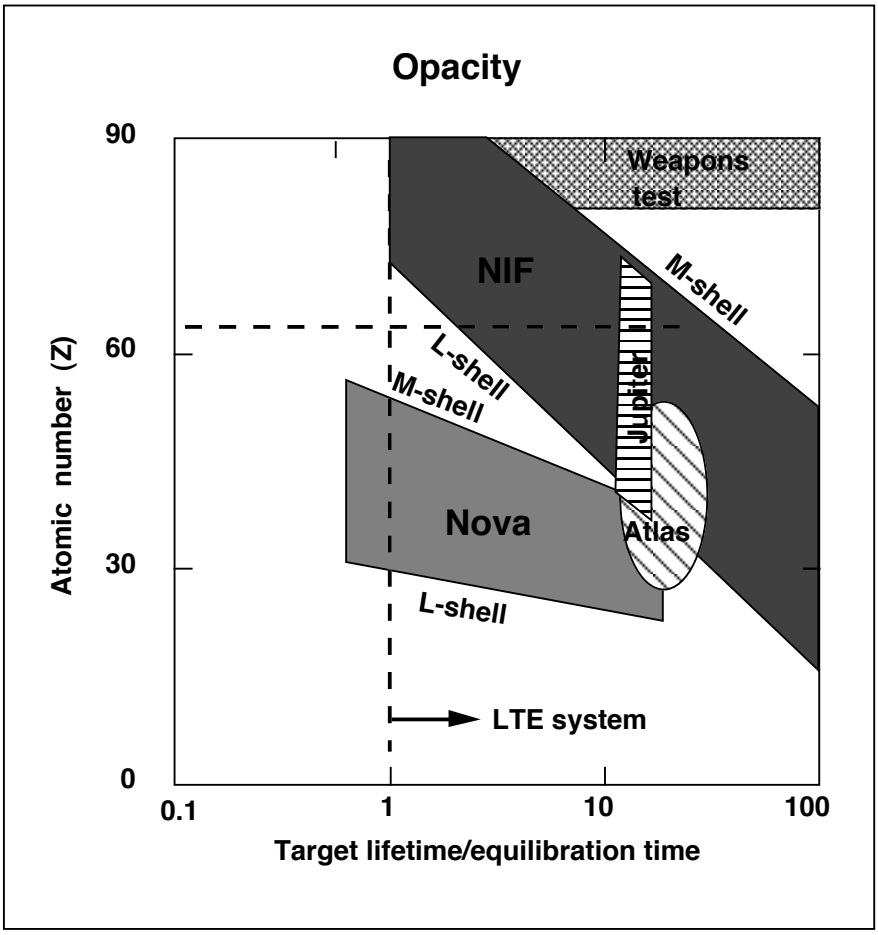

Figure 16b Local thermal equilibrium opacity measurements are possible on NIF, Atlas and Jupiter because the target size is sufficient for its inertial lifetime to be larger than the thermal equilibration time.

Figure 3.5: Figure 16b

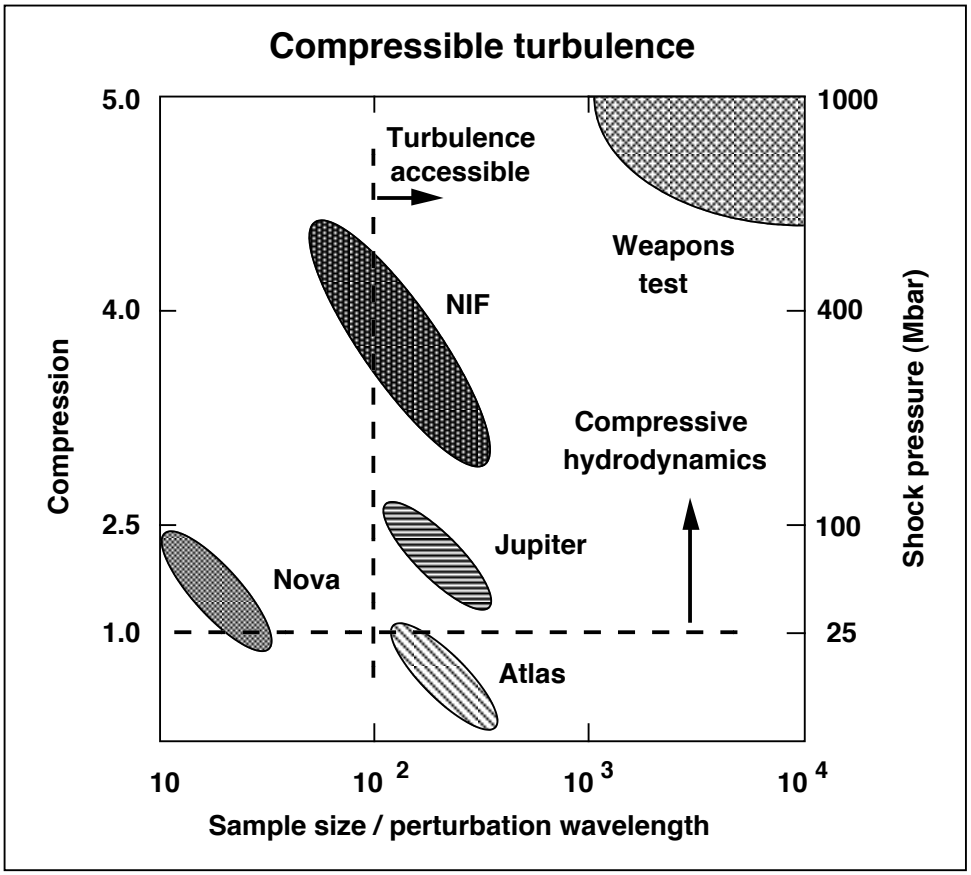

Figure 17a Whereas the moderate compression on NOVA allows to follow the transition from linear instability to weak turbulence, the high compression and larger scale volumes on NIF allows to follow this all the way to turbulent mix.

Figure 3.6: Figure 17a

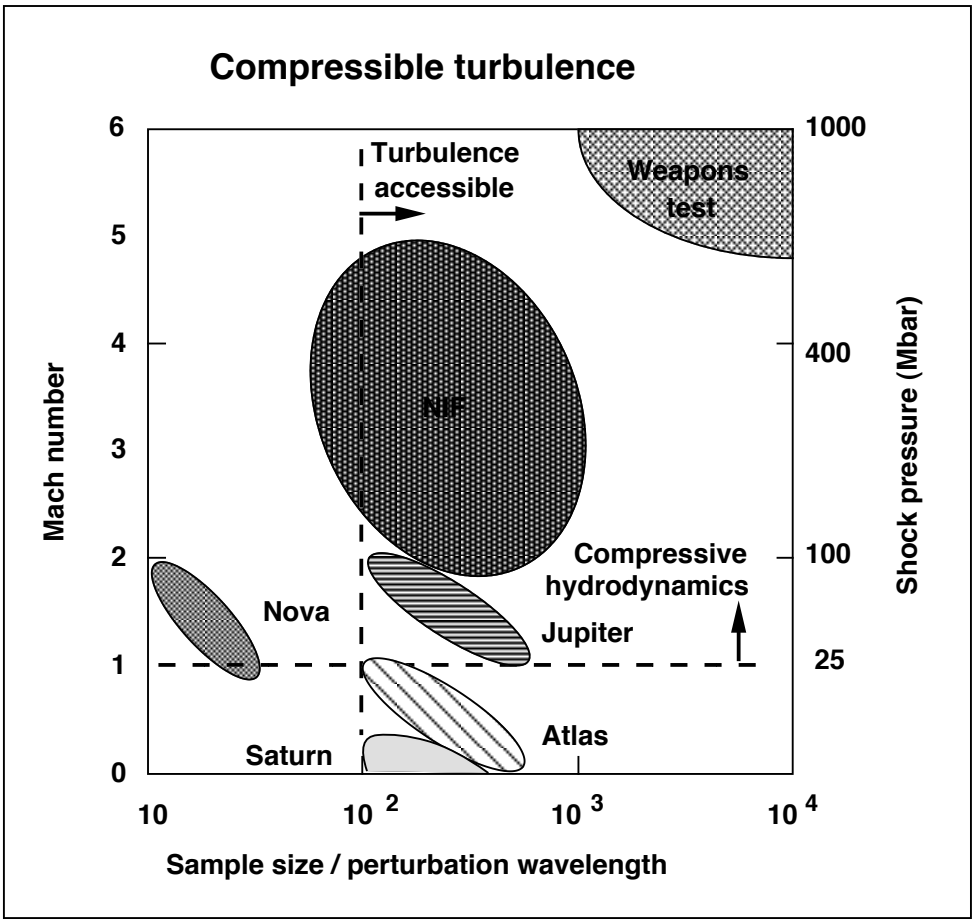

Figure 17b The secondary of a nuclear weapon operates under conditions of strong turbulent mix. Whereas the moderate compression on Nova corresponds to only slightly supersonic shock waves (Mach number 1 to 2), the strong compression of NIF (and the large sample size of Saturn, Atlas and Jupiter) allows to reach the weapons-test regime.

Figure 3.7: Figure 17b

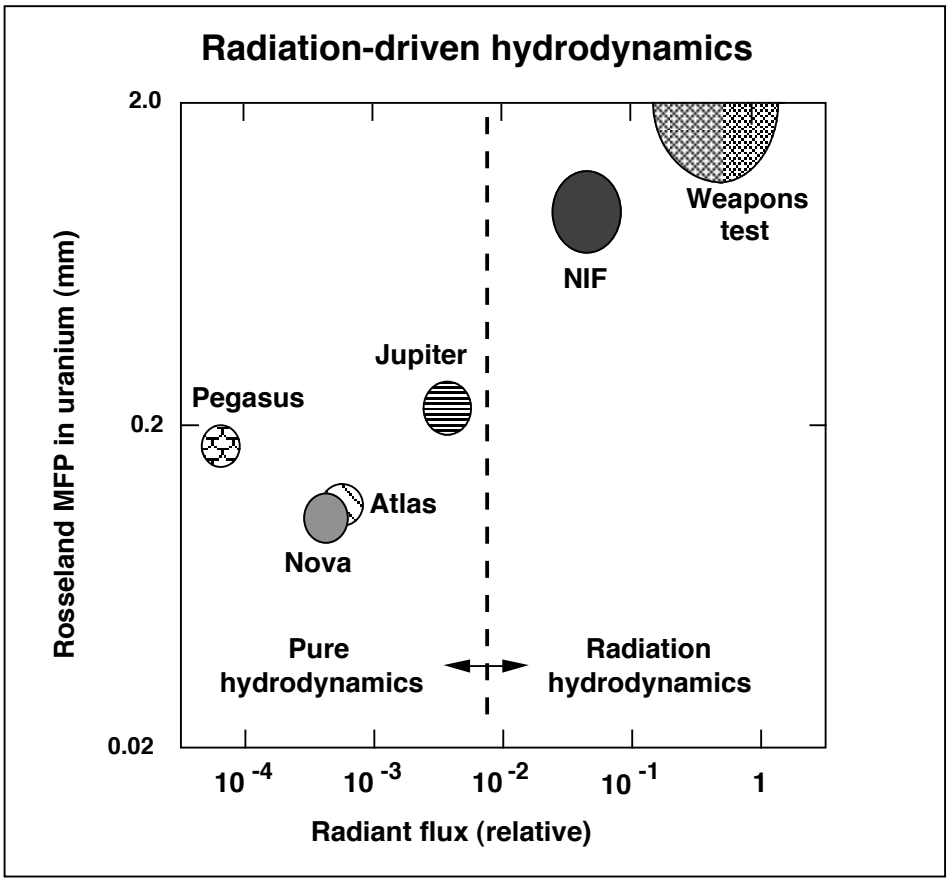

Figure 18 Radiation-driven hydrodynamics is a unique feature of nuclear weapons operation. NIF allows to study radiation hydrodynamics close to weapons-test conditions.

Figure 3.8: Figure 18

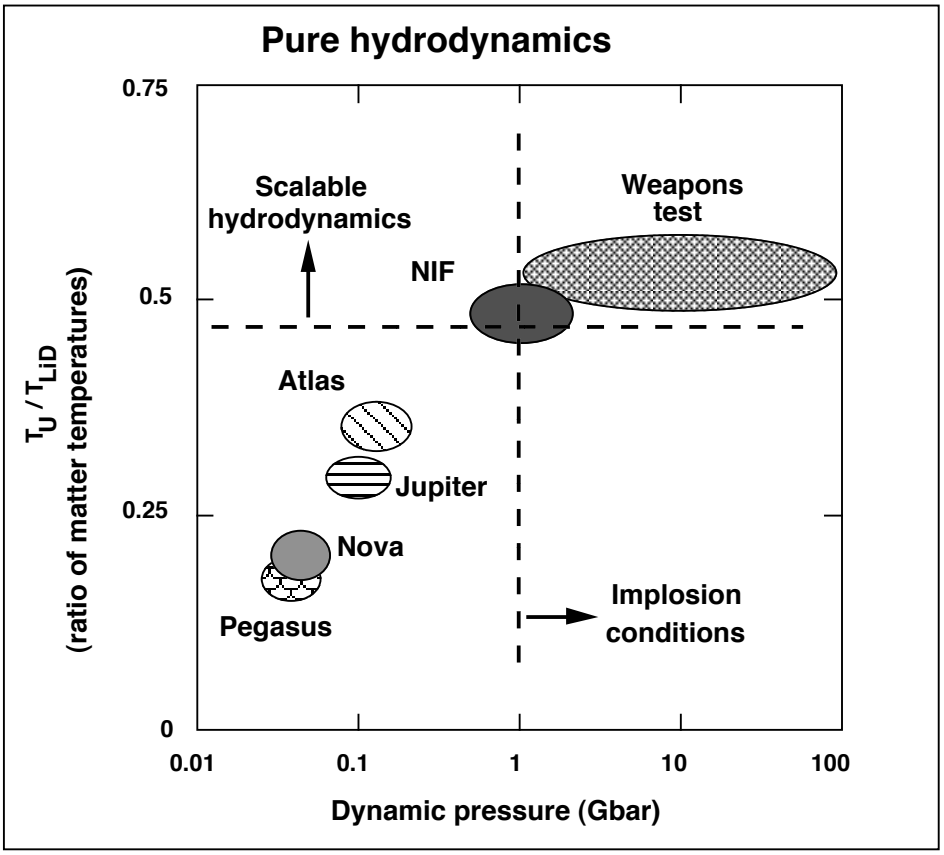

Figure 19 The implosion of a secondary prior to ignition of the thermonuclear fuel (*LiD*) is a problem of pure hydrodynamics which can be studied on NIF.

Figure 3.9: Figure 19

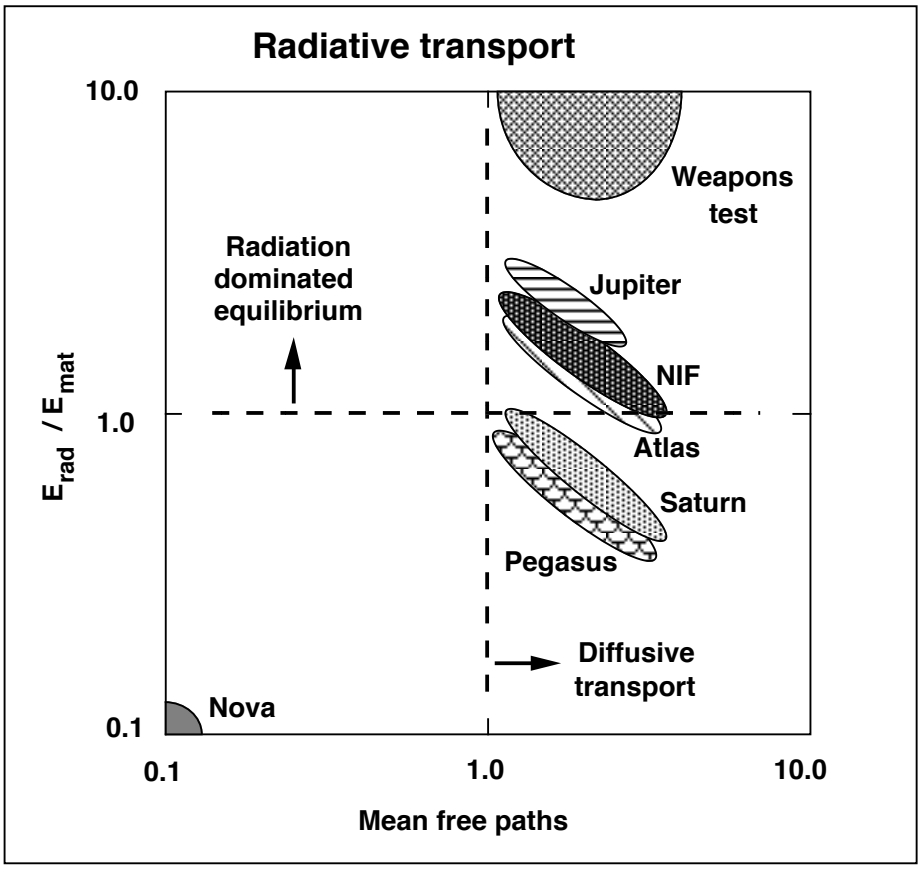

Figure 20 Radiative energy transport is typical of the operation of nuclear weapons. The diffusive approximation applies because of the large size of the NIF targets and because the radiation temperature on NIF is sufficient for the samples to operate in the radiation dominated thermal equilibrium regime.

Figure 3.10: Figure 20

Chapter 4

Fourth Generation Nuclear Weapons

4.1 Introduction

As science and technology advances, new weapons are conceived and developed all the time. However, since the advancement of science is a rather slow process, new types of weapons can be under consideration for quite a long time and come to public attention only after they reach the development or deployment stage. This is what happened with President Reagan's Strategic Defense Initiative, when, in March 1983 many people heard for the first time about high-energy beam weapons, for example, even though they had been under serious consideration since at least World War Two.

In the case of nuclear weapons, many different types — some of which are based on physical processes which differ from those used in current thermonuclear weapons — have been studied over a very long time. This is the case for pure-fusion bombs, antimatter bombs, laser-triggered bombs, thermonuclear shaped-charges, new explosives based on nuclear isomers, superheavy elements, metallic hydrogen, etc.[1] So far, none of these concepts has led to an actual weapon. But this may be only a question of time, especially since considerable progress has recently been made on some of them.

In this chapter we describe the best documented of these concepts and analyse

[1] Some of these concepts have already been considered in the open literature, in particular, by Friedwardt Winterberg [173, 82] and P.K. Iyengar [119, 122]. See also [121].

their potential for becoming part of a new generation of nuclear weapons.[2] We shall restrict ourselves to those which may lead to new types of nuclear *explosives*. For instance, we leave aside developments such as high-energy beam weapons, x-ray or gamma-ray lasers, ICF-driven EMP weapons [31], and thermonuclear shaped-charges [82]. Moreover, we shall focus primarily on their scientific feasibility, leaving the question of technological feasibility to section 4.9. We begin with an overview of the main characteristics of the previous generations of nuclear weapons:

First generation nuclear weapons are all uranium or all plutonium atomic bombs. The science and technology of these weapons is widespread, and their intrinsic simplicity is such that their successful development does not require nuclear testing. Today, these weapons constitute one of the main horizontal proliferation threats. A major military quality of these weapons is that they can be very reliable, rugged and compact. An example is the W33 artillery-fired atomic projectile (first deployed in 1956) which has a yield of 5–10 kt for a weight of about 100 kg.

Second generation nuclear weapons are fusion-boosted fission-explosives ("boosted atomic bombs") and two-stage thermonuclear devices ("hydrogen bombs"). In hydrogen bombs, a tritium-boosted atomic bomb is used to implode and ignite a secondary system in which fusion reactions produce most of the yield. The development of these weapons required extensive testing and resulted in high-yield (100–500 kt) weapons with yield-to-weight ratios about twenty times larger than those of the best first generation nuclear weapons. Progress on these weapons has been slow, and the scientific understanding of the details of the secondary system is still incomplete.[3] Nevertheless, after more than 50 years of research and development, and after almost two thousand test explosions, no significant progress is expected for this generation of weapons. The continuation of full-scale testing would probably never have changed this situation, given the great number of complex phenomena that occur simultaneously within the fraction of a microsecond of the explosion of an H bomb. This is possibly the main technical reason why the comprehensive test ban treaty (CTBT) is, in fact, militarily acceptable.

From a strategic point of view, it is important to realize that modern second-generation nuclear weapons have all the necessary qualities to make them suitable

[2] A short description of some fourth generation nuclear weapons concepts has previously appeared in *INESAP Information Bulletin* [120].

[3] "We do not completely understand the physical processes involved in the operation of a nuclear weapon" [155, p.24]; "We do not understand nuclear weapon processes well enough to calculate precisely the transfer of energy within a weapon" [155, p.30]; "You certainly can't do the calculations from first principles, basic physics principles. [...] That's a very frustrating thing" [29, p.59].

for military use: they are simple, rugged, safe, reliable, relatively inexpensive, and highly lethal. It is therefore unlikely that they will disappear, unless they are banned by international law. For instance, the reduction, by almost half, of the number of arms in the American and Russian nuclear arsenals is mainly the result of the decommissioning of obsolete weapons, the elimination of weapons designed for outdated or doubtful military objectives, and the enormous problems associated with the aging of production facilities and the upkeep of large stockpiles of nuclear weapons.

Third generation nuclear weapons [116] are "tailored" or "enhanced" effects warheads — such as the Enhanced, Suppressed, and Induced Radiation Warheads (ERW, SRW,IRW) [109], the Reduced Residual Radioactivity (RRR) [110, 111] or Electromagnetic Pulse (EMP) [108] bombs, hot x-ray devices for antiballistic missile (ABM) systems, "clean" explosives for possible use in peaceful activities — or nuclear-driven "directed energy" [82, 112, 118] weapons producing beams or jets of x-rays, electromagnetic waves, particles, plasmas, etc. Like many tactical nuclear weapons, these devices have never found any truly convincing military use.[4] Moreover, none of them has provided any decisive advantage (such as significantly reduced collateral damage, absence of radioactivity, etc.), and their development would have required a large number of nuclear test explosions. For these reasons, the development of this third generation of nuclear weapons is the most directly affected by the CTBT [118].

Fourth generation nuclear weapons are based on atomic or nuclear processes that are not restricted by the CTBT [120, 123]. In contrast with second generation nuclear weapons, their development will be essentially science based, making use of many recent advances in fundamental or applied research and of very sophisticated computer simulation techniques that will allow deployment after only limited field testing. In common with first and second generation nuclear weapons, they could allow for rather simple and rugged designs, although the special materials they will use might be much more difficult to manufacture than plutonium or enriched uranium. Fourth generation nuclear weapons may provide significant military advantages (especially for tactical uses, since most of them will produce minimum residual radioactivity) and considerable political advantages, since their development will be restricted to the most technologically advanced countries.

Considering that existing high-yield thermonuclear weapons will remain the principal component of strategic arsenals for quite a long time, it is likely that the first fourth-generation nuclear weapons to be developed by the nuclear-weapon

[4] A typical example is the so-called neutron bomb (ERW), which has not proved to be an effective anti-tank weapon [113, 114, 115].

States will be highly miniaturized explosives with yields in the 1 t to 1 kt range, i.e., within the gap that today separates conventional from nuclear weapons. These "low-yield" nuclear weapons will not be considered as "weapons of *mass* destruction" and their construction will be possible for all countries, including the non-nuclear-weapon States. In the following sections we examine a number of concepts which are under active scientific investigation and which have a strong potential to be developed into such new weapons.

4.2 Subcritical and microfission explosives (Figs. 4.1–4.2)

To address the question of subcritical explosives, it is useful to recall some elements of neutronics.

If k_∞ is the average number of neutrons produced by fission (and possibly by other processes) per neutron absorbed in an infinite medium, and l the number of escaping neutrons leaking out of a finite assembly, the effective neutron multiplication factor, or criticality factor, is:

$$k = k_\infty - l \quad . \tag{4.1}$$

The average lifetime of a neutron in an absorbing medium, i.e., the time τ_a between its production and absorption, is:

$$\tau_a = \frac{\lambda_a}{v} \quad , \tag{4.2}$$

where λ_a is the absorption mean free path and v the average neutron velocity. For each generation of neutrons, that is, for each interval τ_a, the number n of neutrons in the assembly is incremented by $n(k-1)$. The time rate of change of the number of neutrons is therefore

$$\frac{dn}{dt} = \frac{k-1}{\tau_a} n = \alpha\, n \quad , \tag{4.3}$$

where α is called "Rossi α".[5] For k and τ_a constant, and with $n(0)$ the initial number of neutrons, the solution of this equation is an exponential:

[5] In a nuclear explosion, α is a function of time because all parameters, such as the geometry, the density and the nuclear properties of the fissile material, change with time during the chain

$$n(t) = n(0)\, exp\,(\frac{k-1}{\tau_a}t) \quad . \tag{4.4}$$

When the criticality factor $k = 1$, the number of neutrons remains constant, and the assembly is called "critical." This is the normal operation mode of a nuclear reactor in which one has a stable chain reaction. When $k > 1$, the assembly is "supercritical," and the number of neutrons increases exponentially with time. The chain reaction is divergent and leads to the explosion of the assembly. Finally, when $k < 1$, the assembly is "subcritical," and the number of neutrons decreases exponentially with time, which implies that there is no self-sustaining chain reaction. This does not mean, however, that a subcritical assembly cannot be used to produce nuclear energy or to make a nuclear explosion. In effect, since at each generation of neutrons, the number n of neutrons in the assembly is multiplied by k, the total number neutrons produced by an initial number $n(0)$ is

$$n(\infty) = n(0)(1 + k + k^2 + k^3 + ...) = \frac{n(0)}{1-k} \quad . \tag{4.5}$$

This series converges for $k < 1$. Thus, for a subcritical assembly, the initial number of neutrons is multiplied by a factor $G = 1/(1-k)$. For k close to 1, this *gain* factor can become very large. Hence, by injecting a sufficient number of initial neutrons into a subcritical assembly, it is possible to generate a large number of fissions, and thus to release a considerable amount of nuclear energy. This technique is called *subcritical burn*.

To understand the potential advantage of this method for making a fission explosive it is important to recall that in a normal fission bomb the plutonium has to be made highly supercritical so that the divergent chain reaction can fully develop. This means that the plutonium has to be compressed much more than would be required to just reach criticality. For example, a 1 gram plutonium pellet becomes critical at a density equal to about 100 times its normal density. However, to produce significant yield [174], it is necessary to further compress the pellet to increase its density by an additional factor of about 10.

On the other hand, in a subcritical device, it is sufficient to reach $k \approx 1$, an advantage that is especially significant for microfission explosives containing less than a few grams of fissile materials. However, compared to a normal nuclear explosive (in which a few neutrons are in principle enough to start the chain

reaction. In first approximation, $\alpha \approx v\chi N_0 \sigma_f(\nu - 1)$, where σ_f is the fission cross-section, ν the number of neutrons per fission and χN_0 the fissile nuclei number density, with χ the compression factor.

reaction) the disadvantage of a subcritical device is that it needs a very powerful neutron generator to supply the relatively large number of initial neutrons n(0).

Figures 4.1 and 4.2, which are adapted from Ref. [178], are the results of detailed computer simulations of the subcritical burn of small pellets of plutonium. These pellets have weights of 14, 70 and 700 milligrams, and the goal of the simulation was to determine (as a function of compression) the number of initial neutrons required for 100% burn, which corresponds to the release of 240, 1'200 or 12'000 kg of fission energy. Obviously, yields of between 0.24 and 12 tons of TNT are of considerable military interest. Moreover, in subcritical burn, the quality of the fissile material is of little importance: reactor-grade plutonium is just as good as weapons-grade plutonium.[6]

Figure 4.1 shows that with a fissile material density on the order of 10^3 to 10^4 g/cm^3, i.e., for compression factors on the order of 100 to 1'000, the number of initial neutrons required for complete burn is about 10^{18}. In that same range, the compression work to reach the necessary plutonium density is equivalent to the energy content of about 100 g of chemical explosives, as can be seen on Fig. 4.2. Assuming a 10% conversion efficiency of the chemical energy into compression work, this means that with 1 kg of high explosives and less than a gram of plutonium, it is possible (in theory[7]) to produce a very compact fourth generation fission explosive with a yield of several *tons*.[8]

Looking at Fig. 4.1 again, it can be seen that at a sufficient compression the number of initial neutrons decreases dramatically. This is because when $k \to 1$, the gain increases as the assembly approaches criticality where, in principle, a single neutron is enough to start a chain reaction. This leads to the idea of *microfission explosives* in which a small pellet of fissile material is driven to criticality by laser or other means [172, 173, 174]. At first, it was thought that this method could be used to ignite fusion materials [173], and thus to provide an easy route to ICF and almost pure-fusion explosives for military purposes. But it was soon discovered that a major difficulty with microfission was the problem of the initiation of the chain reaction [176]. Indeed, in microfission, the stagnation time of a highly compressed pellet is so short that the probability of a spontaneous fission releasing an initial neutron is negligible. Moreover, the use of an external source of neutrons is almost impossible because it is very difficult to deliver and focus a stream of

[6] All isotopes of plutonium are fissile for fast neutrons, e.g., see [69], and the problem of preinitiation is absent in subcritical burn.

[7] To turn this concept into practice, two major problems are the compression method and the initial source of neutrons.

[8] The yield of non-nuclear warheads of modern missiles and gravity bombs is limited by weight to a maximum of about 0.1 to a few tons of TNT.

neutrons onto a very small target at just the right time.

Hence, it was suggested that the initial neutrons could come from DT fusion reactions produced in the center [175] (or in the reflector [177]) of the fissile pellet. However, as with ICF pellets surrounded by a heavy tamper to increase the confinement time [129], it is always better to work with a pure fusion target than with a hybrid fusion-fission target. This is because DT is easier to compress than any heavier material, and because the specific energy content of DT is higher than that of fissile materials. Therefore, it is much more attractive to develop micro*fusion* rather than micro*fission* devices. Nevertheless, a micro*fission* device would in principle be an extremely compact source of x-rays that could be used to implode a more powerful fusion device.

Compared to microfission, the practical problems of subcritical burn are less acute. For one thing, as can be seen on Fig. 4.2, the compression work can be ten to a hundred times less than the energy necessary to reach criticality. Moreover, since subcritical burn does not depend on a self-sustaining chain reaction, but on an external supply of neutrons, 100% fission burn efficiency can be achieved in principle. Finally, contrary to microfission, subcritical burn is not restricted by the CTBT.

In summary, a critical or subcritical microfission device can in principle serve as a low yield explosive or as a primary to compress a higher yield fission or fusion pellet. To do that, it is necessary to find a means to achieve the required compression, as well as a suitable source of neutrons to initiate the fission reactions, two things for which there was no practical solution in sight until recently.

The problem with compression is that the maximum pressure and the detonation velocity of existing chemical explosives are not high enough to compress fissile materials to the required densities [50, p.9–10]. Using a very sophisticated implosion technology, the maximum compression factor achievable is about 10.[9] To increase the density of uranium, or plutonium, by another factor of 10 would require a "super-explosive" at least 45 times more powerful than any existing high-explosive. Compression to about 100 times normal metal density would therefore require a system of laser or particle beams — or the use of magnetic compression [304] (see section 4.7). Both techniques are under development since a long time and currently available systems are powerful enough to make decisive experiments. However, standard lasers and particle accelerators would probably be too large to make a transportable weapon. But the use of a superlaser to compress the fissile material, or to generate the particle beam, might result in a sufficiently compact device (see section 4.8). In the magnetic compression approach, the

[9]The smallest amount of plutonium that can be made critical in a fast assembly is about 100 g.

problem would be to miniaturize the system converting the energy content of high explosives into the energy of electrical currents and magnetic fields.

To generate the number of neutrons required by the subcritical burn, or by the initiation of the chain reaction, an external neutron source is not practical. However, by focusing a beam of charged particles (electrons, protons, antiprotons, etc.) on the pellet, fission reactions can be induced by various high-energy reactions. This requires a compact accelerator. In the case of electrons, a superlaser could accelerate them to an energy of about 20 MeV, which would be sufficient to produce neutrons by electro- and photo-fission reactions in the pellet. Moreover, if sufficiently intense, the superlaser beam itself could be focussed directly on the pellet: high energy electrons generated on the surface would cause electrofission and photofission in the material surrounding the focal volume [536, 537, 571, 572]. Finally, a solution that would dispense with the need for a superlaser or a MeV-energy accelerator would be to direct a small amount of antiprotons at the pellet to generate the required number of initial neutrons [304]. As seen in Fig. 4.1, less than a microgram of antiprotons would be sufficient for such a purpose.

At present, possibly the most ambitious experimental microfission research program is at Phillips Laboratory (formerly, Air Force Weapons Laboratory, Kirtland Air Force Base, New Mexico) where antiprotons supplied by researchers from the Pennsylvania State University will be used to initiate subcritical burn in magnetically compressed pellets [304, 335].

Moreover, laser driven microfission experiments are under way at various national laboratories. But little is published on their results since all information on ICF targets in which "fissile material [is] driven to criticality" is classified [22, p.121].

4.3 Transplutonic and superheavy elements

Transplutonic elements are artificial elements produced in fission reactors or nuclear explosions by multiple capture of neutrons: $^{238}U + n \rightarrow {}^{239}Pu$, $^{239}Pu \rightarrow {}^{240}Am$, etc.; by particle accelerators firing protons, deuterons or various heavy-ions into a target; or by nuclear fusion[10] of heavy-ions. *Superheavy elements* are heavy transplutonic elements which cannot easily be produced in fission reactors, and which were first discovered in the debris of thermonuclear explosions [224, 225].

[10]"Nuclear fusion" refers to the fusion of heavy-ions, an endoenergetic process, while "thermonuclear fusion" refers to the exoenergetic fusion of light nuclei.

The first extensive unclassified analysis of the military significance of superheavy elements was presented in 1971, at the 10th Pugwash Symposium [234].

The military interest in transplutonic elements is that they are in general fissile and their critical masses are smaller — and, in the case of superheavy nuclei, potentially very much smaller [119] — than that of plutonium. This is because heavier elements tend to have larger fission cross-sections and to produce more neutrons per fission. For example, the critical mass of ^{245}Cm is about one-third that of ^{239}Pu [241]. This advantage however, has to be weighted against the intrinsic problems of transplutonic elements, namely their short lifetime, their large spontaneous fission cross-section, and the difficulty in producing them. In fact, even for relatively light transplutonic elements such as ^{245}Cm, which could be bred from ^{244}Cm in a fast neutron reactor, the technical difficulties of making a nuclear weapon (e.g., preinitiation of the chain reaction, evacuation of the spontaneous decay heat, etc. [66, 69]) would be considerably higher than when using reactor-grade plutonium.

Therefore, the military potential of transplutonic elements rests on the possibility that there might exist some relatively heavy transplutonic element which could be produced at a reasonable cost and which would have the right physical properties for making a critical or subcritical nuclear explosive. In particular, it would be of great practical interest to find a long-lived transplutonic or superheavy element with a critical mass in the range of grams,[11] instead of kilograms as is the case for ordinary fissile materials. This question can be investigated theoretically by means of the one neutron-group theory of criticality, which should give a reasonable first approximation.

As is well known, the critical mass of a bare sphere depends on a single parameter, the "critical neutron opacity" ω_c, and is given by the expression

$$m_c = \frac{4\pi}{3}\frac{{\omega_c}^3}{\rho^2} \quad . \tag{4.6}$$

ω_c is given by the expression

$$\omega_c = \frac{A}{\mathcal{N}\sigma_t}(\frac{\pi}{k_0} - z_0) \quad , \tag{4.7}$$

where A is the atomic weight, $\mathcal{N}$ Avogadro's number, σ_t the total neutron cross-

[11] This would be adequate for making very compact nuclear explosives with yields in the range of 1 to 10 *tons*. Moreover, milligram amounts of such a material would be enough to serve as very compact igniters for large ICF pellets.

section, k_0 the eigenvalue and z_0 the extrapolation distance. In the one neutron-group theory [59], k_0 and z_0 depend on a single parameter, the secondaries ratio, c:

$$c = 1 + \frac{\nu\sigma_f - \sigma_a}{\sigma_t} \quad . \tag{4.8}$$

Here, ν is the number of neutrons produced per fission, and σ_f the absorption and σ_a the fission cross-sections, respectively.

For ordinary fissile materials, i.e., plutonium, $c \approx 2$, and k_0 and z_0 are complicated functions of c [59]. For superheavy elements, however, $c \gg 2$ and one can use the first term of a development in series [59, p.58 and p.136]. In this approximation, the critical neutron opacity is

$$\omega_c \approx \frac{5}{4}\frac{A}{\mathcal{N}\sigma_t}\frac{1}{c} \quad . \tag{4.9}$$

The value of c can be estimated by considering that for a superheavy element $\sigma_f \approx \sigma_t$. In this limit, $c \approx \nu + 1$. According to nuclear model calculations, the fission of the superheavy nucleus $^{298}114$ would produce 10 neutrons and release 320 MeV of energy, respectively about three and two times more than the fission of plutonium [232].[12] Assuming a total cross-section of 5×10^{-24} cm^2, we find for $^{298}114$ a critical opacity $\omega_c \approx 12$ g/cm^2. This is about 8 times less than the critical opacity of plutonium. According to equation (4.6), assuming $\rho \approx 20$ g/cm^3, the critical mass of superheavy element $^{298}114$ is then about 500 times smaller than that of plutonium, i.e., about 20 g.[13]

However, even if their critical masses are small, superheavy elements can only be of practical interest if they are sufficiently stable. In particular, their spontaneous fission decay should be strongly suppressed.

Apparently, this possibility has always been sufficiently strong to motivate the investment of considerable resources in superheavy element research from the 1950s until the present. This is because early theoretical models gave rather optimistic estimates for their stability[226, 227] and later because theory predicted

[12] Reference [233] gives $\nu \approx 7.8$ instead of 10.

[13] Considering the approximations made, this critical mass is probably underestimated. For instance, extrapolating to superheavy elements a remarquable simple linear expression [67] correlating the measured critical opacities ω_c of the actinides to the fissility parameter Z^2/A, one obtains $m_c \approx 260$ g for $^{298}114$, and $m_c \approx 45$ g for $^{310}126$.

that there should exist an island of nuclear stability[14] near the predicted closed shells at $Z = 114$ and $N = 184$ [231].

The first technique to be used for producing superheavy elements well beyond the end of the Periodic Table was to try to synthesize them by multiple neutron capture in the extremely high neutron flux available within and near nuclear explosions. For this purpose, between 1961 and 1969, the American "Plowshare" program supported the design and testing of five dedicated peaceful nuclear explosions (PNE) and "add-on experiments" to some ten weapons tests at the Nevada Test Site[15] [237, 458]. In the Soviet Union, between 1975 and 1979, thirteen PNE were dedicated to transplutonic element production [458].

By the early 1970s, no transplutonic element beyond Lawrencium ($Z = 103$, $N = 157$) had been found. New methods of production were proposed: fast recovery and reuse of heavy elements in successive nuclear explosions, use of ICF as an alternative to full-scale nuclear explosions [235], and synthesis by means of heavy-ion reactions. But, by the late 1970s, many physicists working in the field became rather sceptical [239, 238], keeping heavy-ion nuclear fusion as their last hope.

Indeed, using heavy-ion reactions, elements $Z = 104$ to $Z = 109$ were finally discovered at Berkeley, USA, or Darmstadt, Germany, between 1969 and 1982. However, later, extensive superheavy elements searches using the Super-HILAC at the Lawrence Berkeley National Laboratory (LBNL) and UNILAC at the Gesellschaft für Schwerionenforschung (GSI) reported negative results [240]. It looked as if superheavy elements close to the islands of stability could not be produced [242].

The breakthrough came in 1993. As a result of a joint Livermore-Dubna experiment at the Flerov Laboratory of Nuclear Reaction (FLNR) in Dubna, near Moscow, a team of American and Russian scientists were able to synthesize a new heavy isotope of elements 108, i.e., $^{267}108$. This element was found to have a lifetime of 19 milliseconds [247], about ten times longer than that of $^{265}108$ [242]. Moreover, new isotopes of element 106, i.e., $^{265}106$ and $^{266}106$, where found to have lifetimes of about 10 seconds [245, 248], i.e., also larger

[14] According to the nuclear shell model, nuclei which contain a "magic" number (i.e., 8, 20, 50, 82, 126, 184, etc.) of protons or neutrons are especially stable. When numbers of both protons and neutrons are magic numbers, that is, nuclei are "doubly magic", they are expected to be particularly stable. Therefore among superheavy elements, nuclei which contain the doubly magic numbers $(Z, N) = (114, 184), (126, 184)$, etc. and nuclei around them should be stable and last for a long time once they are produced. Regions around these nuclei are called "islands of stability."

[15] Interest in superheavy element production played a key role early in the Plowshare program. In total, there were twenty-seven PNE explosions in the United States.

by an order of magnitude than isotope $^{263}106$, which was discovered in 1974. These experimental results confirmed sophisticated theoretical calculations by A. Sobiczewski [244], J.R. Nix [246], et al., regarding a considerable increase in resistance to spontaneous fission when neutrons are added to superheavy elements close to the island of stability [245, 247]. The experiment was made possible by the use of a new technique which opened the way to the synthesis of still heavier superheavy nuclei.

Towards the end of 1994 [249], elements with atomic number 110 and 111 were synthesized at the GSI heavy-ion laboratory in Germany, 13 years after element 109 was produced at the same laboratory and 25 years after GSI's founding. Then, in February 1996, element 112 was also synthesized at GSI [250], currently the heaviest ever produced. In the process, a new isotope of element 108, i.e., $^{269}108$, was discovered and found to have a half-life of 19.7 seconds, more than 1'000 times longer than the lifetime of the heaviest superheavy element known in 1991 [242]. This meant that the gap between the naturally occurring elements and the first island of stable superheavy nuclei had been crossed.

The discoveries of 1993-96 strongly suggest that even heavier atoms can yet be produced. Recent theoretical calculations predict that close to 400 superheavy nuclei between elements 106 and 136 should be stable and that at least a dozen of them should have lifetimes longer than 25'000 years, i.e., the lifetime of plutonium [254]. The problem is that the production of most of them might be extremely difficult, if not impossible. However, for military applications, it could be that the most interesting nuclei are among the easier ones to synthesize. Due to their extremely low production cross-sections, the cost of fabrication of macroscopic amounts of these materials might be very high.[16] Nevertheless, as is the case with the production of antimatter (see next section), efficient methods may be developed.

In a recent analysis of the way elements 110, 111, and 112 were produced [253], scientists from Los Alamos and GSI found that theoretical models developed at Los Alamos in the 1970s [236, 246] could explain the main features of the heavy-ion fusion reactions that were used to synthesize these elements at GSI. This finding implies that these models can be used with confidence to specify the most promising reactions for superheavy element production. For instance, some elements in the region $116 \leq Z \leq 122$ may be reachable using beams of stable ions, whereas radioactive ion beams would be required to reach other nuclei on the far side of the superheavy island [254, p.159]. The construction of a next-

[16] For the type of military applications considered in this report, tiny amounts — i.e., on the order of 10^{-9} to 10^{-3} grams — are enough to make them useful as powerful primary sources of neutrons or x-rays.

generation radioactive ion beam facility that will be important for such experiments has been selected as the top priority for future nuclear physics in Europe [255].

At present, there are only four institutes in the world at which superheavy elements with $Z > 103$ can be synthesized: LBNL at Berkeley (USA), GSI at Darmstadt (Germany), FLNR at Dubna (Russia) and PSI at Villigen near Zurich (Switzerland). However, France, with GANIL (Grand Accélérateur National de Ion Lourds) at Caen [252, p.9], and Japan, with the RIKEN (Institute of Physical and Chemical Research) Ring Cyclotron facility at Saitama [251], may soon join the club.

In January 1999, a team lead by Yuri Oganessian at FLNR, working in collaboration with nuclear physicists from the Lawrence Livermore Laboratory, announced that they had synthesized $^{289}114$, the heaviest element yet discovered. With 114 protons and 175 neutrons, the nucleus sits comfortably on a long predicted "island of stability" and has a half-life of 30 seconds [256, 257]. However, the formal report on this discovery was published in July by the Russian scientists alone [259]. In the meantime, physicists at the Lawrence Berkeley National Laboratory announced that they had created two new superheavy elements — 116 and 118 — [258, 261].

The creation of three new elements in 1999, one of them with a lifetime of about 30 seconds, definitely confirms that the *synthesis of nuclei near the island of stability with lifetimes on the order of years* should be possible [260].

4.4 Antimatter

Matter-antimatter interaction produces more energy per unit mass than any other means of energy production. For example, proton-antiproton annihilation releases 275 times more energy in the form of kinetic energy of charged particles than nuclear fission or DT fusion. Moreover, when antimatter is brought into the proximity of matter, annihilation starts by itself, without the need of a critical mass, as in fission, and without the ignition energy needed in fusion. In short, it is an ideal nuclear trigger, provided that methods to produce and manipulate sufficient quantities of antimatter be found.

It is therefore not surprising that the concept of using antimatter as an energy source has been in scientific literature for decades [273, 279], [275, p. 833], [277, p. 85–86, 97]. Other practical applications of antimatter are under consideration.[17]

[17] An extensive bibliography on antimatter science and technology has been published in 1988 [300].

These include, for example, antimatter propulsion systems [280, 344], space-based power generators and directed-energy weapons [283, 288, 293], high-pressure generation and acceleration of macroscopic particles [284], and cancer therapy [281, 325]. Finally, both Edward Teller [262, 266, 271, 272, 276] and Andrei Sakharov[18] [278], two key scientists in charge of the development of the H-bomb in their respective countries, show in their published scientific works a major interest in the annihilation properties of antimatter, the nuclear process that after fission and fusion was expected to lead to a new generation of nuclear bombs.

In fact, in 1950, two years before the explosion of the first H-bomb, the ignition by antimatter of a mixture of deuterium and tritium was already being studied. However, as shown, for example, in an article studying specifically the problem of the capture of antiprotons by deuterium and tritium [263], and in an article trying to calculate the result of the interaction between an antiproton and a nucleus of ordinary matter [264], the major problem at that time was that there was not any experimental data on which one could rely to make a prediction of what would happen when an antiproton would encounter a proton (or a neutron). Moreover, how and when antimatter could be produced was not known. Consequently, for several years, applied research concentrated on more promising near-term techniques — and the problem of igniting the H-bomb was resolved by using an A-bomb as a trigger, and the existence of the antiproton remained theoretical until 1955.

Historically, the first antiparticle ever observed was the antielectron, also called positron, discovered in 1932 by Carl David Anderson. While observing cosmic radiation he noticed a particle of the same mass as the electron, but of opposite charge. Evidently many attempts were made to discover the antiproton, using the same method, but without success. With the detectors available at that time and knowing only its mass and electrical charge, it was practically impossible to identify with any certitude the antiproton within cosmic radiation. It had to be artificially produced. For that an accelerator, much more powerful than anything built to that time, was needed.

Briefly, antimatter is produced in the following manner: protons are accelerated close to the speed of light and then projected at a target. The ensuing collision is so violent that part of the energy is transformed into particle-antiparticle pairs. Once the accelerator was built in 1955 at Berkeley, antiprotons were "seen" for the first time[265]. By injecting them into a liquid-hydrogen filled detector, the energy liberated in the explosive encounter of an antiproton and a proton was seen to rematerialize into a scatter of other particles (essentially pions shooting off in

[18] In a 1968 article, Sakharov remarked: "The annihilation of 0.3 g of matter with 0.3 g of antimatter has the effect of an atomic-bomb blast" [270, p.218].

all directions) that carryed away most of the annihilation energy. To the weapons scientists, this was a big disappointment.

But Edward Teller and his student Hans-Peter Dürr did not stop there [266]. In 1956, they proposed a hypothesis: if instead of annihilating with a simple hydrogen nucleus, the antiproton annihilated with a proton or neutron situated in the heart of a complex atom, such as carbon or uranium, the nucleus in question would literally explode. This would result in a very large local energy deposition, thus raising the possibility again, of many civilian and military applications for antimatter.

Thirty years passed before a complex of machines necessary to accumulate and slow down antiprotons was conceived. The only system of this type in the world[19] is at the European Center for Nuclear Research (CERN), at Geneva, Switzerland. Finally, it became possible to study, on a large scale, the meeting of antiprotons with nuclei. As a result, it has been possible to demonstrate that the energy deposition, although less than Teller (or others more recently [282]) had hoped for, is sufficient to assure the feasibility of military applications of antimatter. On the other hand, due to its very high cost and the enormous amount of energy needed to produce it, it has also become clear that antimatter could never become a usable source of energy for a power plant.

Thanks to the results of CERN, we were able to publish in August 1985, an estimation of the number of antiprotons needed to start thermonuclear reactions, be it to ignite an H-bomb or to trigger the microexplosion of a thermonuclear fuel pellet [292]. We discovered that it is possible to build an H-bomb, or a neutron bomb, in which the three to five kilograms of plutonium of the primary are replaced by one microgram of antihydrogen. The result would be a so-called "clean" bomb by the military, i.e., a weapon practically free of radioactive fall-out because of the absence of fissile materials. For such a military use to be realistic, a technology capable of producing enough antiprotons for at least one antimatter trigger per day is needed. This corresponds to a minimum production rate of 10^{13} antiprotons per second, six orders of magnitude higher than possible at CERN today (10^7 antiprotons per second). However, there are numerous ways to increase this rate [292, 288, 299].

[19] At the end of 1986, an antiproton production and cooling system has been was into operation at Fermilab, the Fermi National Accelerator Laboratory (FNAL) near Chicago. However, there are still no definitive plans to construct in the United States a system comparable to that of CERN, namely one capable of sufficiently slowing down the antiprotons so they can be immobilized and captured in a magnetic trap [323]. As far as Russia is concerned, few details are available on the status of their antimatter projects. The only potential competition to CERN's leading position is from Japan where low-energy antiprotons should become available around the year 2003.

What we were unaware of in 1985, was the fact that since the summer of 1983, the RAND Corporation had been carrying out a study for the U.S. Air Force "examining the possibilities for exploiting the high energy release from matter-antimatter annihilation" [288]. The RAND study was completed in 1984. The version published in 1985 constitutes a serious evaluation of the development possibilities for such an undertaking in view of military applications. According to this document, a definitive evaluation of the possibility of producing and manipulating 10^{13} antiprotons per second, and of constructing transportable antiproton reservoirs, could be realized by the early 1990s. This was felt to be possible because many important technological problems can be studied with ordinary particles instead of antiprotons. This same report mentions four main categories of applications: *propulsion* (fuel for spacecrafts and ultra-fast anti-missile rockets), *power generators* (light and ultra-compact generators for military platforms in orbit), *directed energy weapons* (antihydrogen beams or pumped lasers relying on very-short-duration energy release) and *classified additional special weapons* (various bombs triggered by antimatter).

In the beginning of July 1986, we went to Madrid where a full session of the Fourth International Conference on Emerging Nuclear Systems was dedicated to antimatter energy concepts. Four presentations were scheduled by Los Alamos scientists on various aspects of antimatter science and technology. To everyone's surprise, the Americans did not come. Ten days before the conference, they announced their withdrawal without giving any convincing explanation. The participants to the conference quickly realized that American Authorities had reevaluated the military importance of antimatter and had probably prevented the Los Alamos scientists from coming to Madrid.[20] This may have been due to the fact that at this same conference we were to present the point of view that the only realistic applications for annihilation energy technologies were in the military domain [290].

At Madrid, we showed that an antimatter triggered thermonuclear bomb is scientifically and technically feasible. In one possible design that we evaluated in detail [290], the antimatter is in the center in the form of a pellet one-tenth of a millimeter in diameter. It is surrounded by, and isolated from, the thermonuclear fuel (a 100 g hollow sphere of Li_2DT). After compression by explosive lenses, the fuel comes into contact with the antihydrogen. Annihilation reactions start spontaneously, providing the energy to ignite the thermonuclear fuel. If the

[20]The titles of the withdrawn communications were as follows: W. Saylor, S. Howe, D. Holtkamp, M. Hynes (invited paper): *Antimatter production factory - systems trade-offs*. M. H. Holzscheiter: *Antiproton storage - A new concept for future energy systems*. L. J. Campbell: *Antiproton storage in condensed matter - The promise, the prospects*. S. Howe (invited paper): *Use of antimatter annihilation products to produce usable power for space based applications*.

chosen degree of compression is high, a bomb with increased mechanical effects is obtained, and if it is low, a neutron bomb is created. In both cases, because of the absence of heavy materials, the electromagnetic pulse effect (which is mainly due to the γ-rays from the de-excitation and decay of radioactive heavy nuclei) and the radioactive fall-out are substantially lower than that of a present-day A- or H-bomb of the same yield (1 *kt*).

Soon after this conference, on the night of the 17th to the 18th of July 1986, antimatter was captured in an electromagnetic trap for the first time in history [289]. Due to the relatively precarious conditions of this first successful attempt, it was possible to conserve the antiprotons for only about ten minutes. This was, nevertheless, much longer than the Americans scientists, working at CERN under U.S. Air Force sponsorship [294], had hoped for. This result was particularly important to the Americans because many experiments that can only be carried out with antimatter are necessary to investigate the feasibility of the military applications of antimatter. As long as antiprotons made in Europe (on Swiss Territory) could be bottled and brought back to the United States, the RAND Corporation concluded that a production/accumulation facility, such as the one at CERN, although desirable, would not in the near future have to be built in the United States [288, p.43].

The events at Madrid, the immobilization of the first antiprotons, and their strategic consequences were the subject of several papers [291, 293, 295]. These were later reproduced in a collection of articles on the subject of antimatter technology for military purposes, together with an assessment by prominent physicists working in the fields of disarmament or arms control [296].

In the following ten years, from 1986 to 1996, an enormous amount of research, both experimental and theoretical, was done on the many problems which directly or indirectly pertain to the practical applications of antimatter. In particular, a major issue is the development of simple and compact antimatter storage techniques. For this, two major approaches are being considered. The first consists of making antihydrogen by combining antiprotons with positrons. The first atoms of antihydrogen were synthesized at CERN in 1996 using a rather inefficient technique [314].[21] Large scale production of antihydrogen requires the development of electromagnetic traps in which particles of opposite electric charges and very different mass can be stored in the same spatial region. The successful operation of such a trap was first demonstrated in 1995 at Garching in Germany [313]. The next step will be to form solid antihydrogen pellets [297] which could be stored and manipulated with the help of various electromagnetic and optical levitation

[21] In year 2000, the first truly efficient technique for making antihydrogen was discovered by a Dutch-American team working in Holland [341, 342].

techniques. Very high storage densities would be obtained — but only in cryogenic enclosures and extremely good vacuums.

The most appealing approach, however, would be to store the antiprotons in ordinary matter. In fact, if all antimatter particles have a tendency to spontaneously annihilate when coming into contact with matter (whether from the effects of electromagnetic attraction, in the case of positrons and antiprotons, or from van der Waals forces for antihydrogen), the existence of metastable states of antiprotons in condensed matter cannot be ruled out *a priori* [298]. For example, if a very low energy antihydrogen atom is diffused into a solid, it moves about until its positron annihilates with an electron. The antiproton may then take the place of this electron, and under some conditions, remain confined at certain points within the crystalline structure. At present, the kind of substance that could be used is not known, but an enormous variety of chemical compounds and crystal types may potentially provide an optimum material.

Other less obvious solutions could still be discovered. For example, antiprotons might, as electrons do when placed in liquid helium, form a bubble at the center of which they could subsist indefinitely [286]. Also, similar to the electron pairs responsible for superconductivity, antiprotons might possibly form Cooper pairs if placed in a suitable material, becoming thereby unable to lose kinetic energy by shock, and thus to annihilate [296, p.450]. Another possibility is that antihydrogen in a crystalline solid could behave under certain conditions as a "Bloch state," i.e., that it would not behave as a particle colliding repeatedly with the host atoms, but as quantum mechanical waves extended over the entire crystal. Such a behavior has recently been demonstrated for muonium (a light isotope of hydrogen whose proton is substituted by a positive muon) [338].

As low energy antiprotons became routinely available, a number of physical quantities of military interest could be precisely measured at the Low Energy Antiproton Ring (LEAR[22]) at CERN. For example, about 16 neutrons are produced by stopped annihilation in uranium [243].[23] This means that a relatively small number of antiprotons would be sufficient to initiate a chain reaction in a highly compressed pellet of plutonium or uranium. This could solve the initiation problem of microfission explosions because, contrary to neutrons, antiprotons can easily be directed and focused onto a very small target. In the United States, this option is being studied at the Los Alamos [305] and Phillips[24] laboratories [308].

[22]LEAR was an 80-meter circumference ring that permitted the storage and slowing of antiprotons down to energies as low as 5 MeV. It was the first large machine ever built to decelerate, rather than accelerate, particles. Commissioned in 1980, LEAR was shut-down in 1996.

[23]In compressed uranium targets, the average neutron yield per antiproton annihilation increases from 16 to about 22 [307].

[24]"Phillips Laboratory" is the new name of the "Air Force Weapons Laboratory" at the Kirtland

However, as explained is section 4.2, subcritical burn is potentially a much more promising method for making a very-low-yield nuclear weapon: directed onto a subcritical assembly, antiprotons can initiate subcritical burn of fissile materials. This opens the prospect of making very-low-weight fission explosives with yields in the sub-*kiloton* range. Experiments are under way at the Phillips Laboratory to investigate this possibility [304]. The types of devices under consideration are based on plutonium pellets with masses between 0.014 and 0.700 gram which would have yields of 0.2 to 12 *tons* of high-explosive equivalent. In order to trigger these pellets, which are compressed by means of magnetic compression, much less than a microgram of antiprotons is enough (see Fig. 4.1).

For these experiments, American researchers expect to use antiprotons produced at CERN. "Bottled" in an electromagnetic trap, they will be sent to the Phillips Laboratory by air.[25] The design and construction of this trap has been undertaken by the Los Alamos National Laboratory [305] and is being tested at CERN. In 1996, more than one million antiprotons from a single LEAR shot were captured and up to 65% of the captured antiprotons were subsequently cooled and stored for up to an hour [317, 318, 324].

Another important application of antimatter to fourth generation nuclear explosives is the triggering of ICF pellets [303, 309]. For this purpose, as we had found in 1985 [292], an important issue is to transfer as much of the annihilation-energy as possible to the DT or LiD plasma.[26] An attractive possibility — which Edward Teller must already have considered in 1956 [266] — is to annihilate the antiprotons in some special material that would "explode" into light fragments that in turn would heat the plasma. For this and other reasons, numerous measurements have been made in order to study the annihilation properties of antiprotons in various nuclei, e.g., [302, 316]. The prospect is that what has been observed in explosive multi-fragmentation of heavy nuclei bombarded with light-ions [312] could happen with antiprotons [315]. For example, it is expected that a gold nucleus containing 197 nucleons may break up into 40 or more pieces, mainly small

Air Force Base near Albuquerque, New Mexico.

[25]Reference [319, p.1418] gives the following details: "The portable trap is one meter tall, 30 cm across, and weighs 55 kg. It operates at 4 ^{0}K temperature, supported by cryogenic nitrogen and helium reservoirs, and has as a unique feature that the confining magnet is made of permanently magnetic $SmCo$ materials, which should prove to be robust. This trap will be tested at CERN in late 1995, then sent to CERN for a fill and demonstration journey across Europe. We plan to return a filled trap to the U.S. in 1996 for experiments planned under USAF sponsorship." However, due to experimental difficulties and the shut down of LEAR in December 1996, no antiprotons were yet shipped from CERN to the United States. See also [325].

[26]In spacecraft propulsion applications, the same problem exists because the propellant to be heated is generally a low-weight substance, e.g., hydrogen [326], in order to maximize the specific impulse.

clusters and individual neutrons and protons [315].

Independently of the existence of a medium- or heavy-weight nucleus that would multi-fragment under antiproton bombardment and be suitable for heating a thermonuclear plasma, this concept leads to the idea of putting a small, heavy metal or fissile material inclusion at the center of ICF pellets in order to heat their fuel and start the thermonuclear explosion at the end of the pellet implosion. This antimatter-driven "sparkplug" idea has been investigated at the Lawrence Livermore laboratory [339]. It consist of configurating the pellet in a way that it would be almost identical to the H-bomb depicted in Fig. 1.3, with the sparkplug replaced by a small inclusion of heavy material (see Fig. 4.5). Using this technique, the estimated number of antiprotons required to initiate ignition of a typical ICF capsule is only 3×10^{13}, about one hundred times less than our 1985 estimate for a homogeneous pellet without a sparkplug [292].

If antimatter is to be used for *indirect drive* ICF, the problems are significantly less. For example, antimatter could simply be used to activate a small x-ray source that would take the place of the "A-bomb" in Fig. 1.3, where the secondary would be the ICF pellet itself. This x-ray source could be a pellet of fissile material that would be fissioned and brought to very high temperatures following the annihilation of a small amount of antiprotons on its surface. Apart from the capsule containing the fission and fusion pellets (i.e., the "primary" and the "secondary"), the only other major components of the device would be a system to store the antiprotons, and an injector to focus them on the fissile material at the moment of ignition. The result is a miniature thermonuclear explosive that could possibly be made sufficiently small and lightweight to make a weapon. Of course, there are many possible variations for designing such a device. Moreover, both the primary and the secondary could be made of more exotic materials than those used in contemporary microexplosion experiments.

At the present time, three main laboratories are involved in the production of antiprotons: CERN (Switzerland and France), FNAL (USA) and the Institute for High Energy Physics (IHEP) at Serpukhov (Russia). These laboratories use large accelerators to produce antiprotons in very small amounts. Concerning the production of positrons (i.e., the antielectrons that are needed to make antihydrogen), many more laboratories are involved. However, the generation of very intense positron beams is a specialty of military establishments such as the Lawrence Livermore National Laboratory [287]. Positron beams are used to investigate experimentally the atomic and electronic structure of crystals, especially in order to detect material defects that are important for nuclear weapon stockpile stewardship [336].

A number of different proposed methods for large-scale antimatter production

(stressing their fundamental limitations) are reviewed in [331].[27]

To produce large quantities of antiprotons, the use of superlasers may result in conversion efficiencies one million times higher than those achieved with the use of accelerators [301]. For this purpose, high-energy superlasers with extremely short pulse durations are mandatory [276, p.9–10]. In effect, the first published estimates of laser production of proton-antiproton pairs showed that this process would need a superlaser with an intensity of at least 10^{18} W/cm^2 [274, 275] — a relatively modest intensity by today's standards. In this calculation, the actual generation of proton-antiproton pairs is by the so-called trident (or Bhabha) process. This requires the laser beam to be very precisely focused onto a 30×10^{-6} m radius solid hydrogen pellet. However, later estimates showed that this process would in fact need a more powerful CO_2 superlaser, i.e., a driving energy of about 1 MJ, a minimum intensity of 10^{23} W/cm^2, and a pulse length of about 0.3 ps [301]. These requirements are enormous, but "only" about a factor 100 or 1000 away from the LLNL 'Petawatt' $Nd : glass$ laser design characteristics, i.e., 1kJ at 10^{21} W/cm^2 in 0.5 to 20 ps [542, 543].

Beside the trident process, there are other methods to produce antimatter with a superlaser. The most promising is to collide a powerful laser-beam with a high-energy particle-beam. For example, with an electron beam, positrons can be produced by the so-called "multi-photon Breit-Wheeler electron-positron pair production process" [267, 268, 269]. This method has recently been successfully demonstrated, using a tabletop superlaser generating 1.6 ps long pulses of 0.65 J energy and an intensity of 10^{18} W/cm^2, in collision with the 46.6 GeV electron-beam of the Stanford linear accelerator (SLAC) [333, 334]. Because real photon-photon pair-creation had never been observed before in the laboratory [269], this was "the first creation of matter out of light" [334]. To use this method for the production of antiprotons instead of positrons would need a much more powerful laser. It would also require a careful comparison with the trident and other processes that have the potential to make antimatter with superlaser systems.

In the near future, independent of the availability of superlasers, various experiments on the production of antimatter (i.e., electron-positron pairs) are planned at NIF [547]. To start with, these experiments will study relativistic plasmas and ponderomotive effects near the energy density for electron-positron production [21, p.46], [28, p.C-6].

At the end of 1996, CERN's LEAR facility was decommissioned as part of a major reorganization of the CERN accelerator complex in view of the construction of a new very large accelerator —the Large Hadron Collider (LHC) — which will

[27] For references to earlier reviews see [292].

be the highest-energy hadron accelerator ever built.[28] The construction of LHC will start at the end of year 2000 and last about five years. During this period, there will be no *high energy* physics at CERN. This is because the LHC will be installed in the same tunnel as the LEP, the Large Electron Positron ring, which is currently the main accelerator of CERN.

In order to continue its program of research on antimatter — which will be the only major physics research program at CERN in the years 2001 to 2005 — a new antiproton source, the Antiproton Decelerator (AD), has being constructed [322]. The AD was built using the former Antiproton Collector (AC) ring (commissioned in 1987 to boost CERN's antiproton levels by a factor of ten) and various components of LEAR (such as the antiproton cooling system). More than half of the cost of building the AD was contributed by Japan [320, 321].

In fact, Japan initiated an ambitious antimatter research program. The Japanese Ministry of Education, Science and Culture (Monbusho) announced in 1997 that "Antimatter Science" had been selected as one of the two most important research projects to be conducted as of 1998 [328]. This is why Monbusho supported the construction of the AD and the participation of Japanese scientists in the CERN antimatter experiments. In return, Japan salvaged various obsolete components of the CERN antiproton complex to build its own antiproton source [327].

On 2 December 1999 the AD delivered its first bunch of antiprotons to an experiment [340]. In the months that followed the machine became fully operational and three main experiments started taking data during Summer 2000 [343].

The two major experiments at the AD include participants from the United States, Germany, Denmark, Italy, Poland, the Netherlands, Korea, and Japan [329, 330]. Both experiments include participants which are supported in part by the U.S. Air Force antimatter technology program (see, e.g., [310, 317, 318]). A third experiment is a Japanese-European collaboration continuing the search for metastable states of antiprotons in ordinary matter [328]. These experiments use all the latest advances made in antimatter technology [343], including the new Dutch-American method for the formation of neutral antimatter [341, 342].

Starting in year 2001, after the shut down of the LEP, there will be enough antiprotons for more than these three antimatter experiments at CERN. Moreover, using antiprotons produced and trapped at CERN, numerous other experiments will be conducted in various American and European laboratories.[29] Apparently, the only competition will come from Japan, where low-energy antiprotons should become available around the year 2003, but only in very small quantities. There-

[28] For instance, LEAR will be used as a heavy-ion accumulation ring for the LHC.

[29] In this perspective, the AD system is optimized for antiproton transfer to the traps [322].

fore, for at least a decade until future projects come on line (e.g., the new 50 GeV proton synchrotron which is likely to be constructed at Tsukuba, Japan), the AD facility at CERN will play an important role as a unique source of low-energy antiprotons [337].

Today, antimatter research is possibly the most important and vigorous of the fourth-generation nuclear weapons research and development programs.[30] The reason is because matter-antimatter annihilation does not pose any fundamental research problem anymore: its military use is now mostly a question of technological development.[31]

4.5 Nuclear isomers

Nuclei are of made of nucleons, i.e., protons and neutrons. They are identified by their chemical symbol and a superscript indicating the total number of nucleons, $A = Z + N$. Sometimes, the number of protons (implied by the chemical symbol) is written instead of the chemical symbol, i.e., ${}^{A}Z$. For example, uranium-235 can be written ${}^{235}U$ or ${}^{235}92$. Nuclei with identical Z are called *isotopes*, those with identical N, *isotons*, and those with identical A, *isobars*. Finally, some nuclei with identical Z and N can have very long-lived excited states (i.e., metastable states). The nuclei in the ground state and those in the metastable state can then co-exist as if they were different species.[32] Thus two nuclei of the same species but in different energy states, of which one is metastable, are called *isomers*. The ground state is represented by the symbol ${}^{A}Z$, and the isomeric state by ${}^{A}Z^{m}$.

The isotope ${}^{180}Ta^{m}$ carries a dual distinction. It is the rarest stable isotope occurring in nature and the only naturally occurring isomer [354]. The actual ground state of ${}^{180}Ta$ has a half-life of 8.1 hours, much less than the $\approx 10^{15}$ years half-life of its isomeric state ${}^{180}Ta^{m}$. This isomeric state has an excitation energy of 75.3 keV.

The military interest of isomers is three-fold: first, they may provide a route to the development of gamma-ray lasers [349, 365], [358, p.54]; second, they may prove useful as fuels, explosives and weapons [360, 362], [358, p.54]; and third, certain fissile isomers are expected to have electro- and laser-induced fis-

[30] This leading position is only challenged by inertial confinement fusion and superlaser research.

[31] We stress again that many technical problems with antimatter can be solved by using protons, H^{-} atoms, or positrons instead of antiprotons. For example, methods for trapping and manipulating antimatter with laser light can be tested with ordinary atoms [306], and the lifetime of antimatter confined in a magnetic trap can be studied with positrons [332].

[32] The lifetime of the excited state may even be longer than the lifetime of the ground state.

sion threshold energies somewhat less than those characteristic of ordinary fissile materials [536, p.558].

For instance, high explosives have energy contents on the order of 5 kJ/g. Nuclear isomers have available energies from a few kJ/g to about 1 GJ/g, close to those released by nuclear reactions (e.g., 80 GJ/g is released by fission).[33] Compared with existing nuclear explosives, an advantage of isomers is that they might not produce radioactivity:

> "A major advance could be made if the enormous potential of nuclear energy storage could be tapped without the attendant penalty of radioactive by-products. Major breakthroughs in energy storage, propellants, weapons, and power sources can be imagined. Even if the practical energy density achieved is several orders of magnitude less than fission or fusion, it would still be orders of magnitude greater than anything ever attainable with chemical technology. Recent research has uncovered a promising new method for nuclear energy storage which has the property of high energy density and for which we have identified cases where there is no residual radioactivity" [360, p.1].

In an isomer, the stored energy is in the excitation energy of the isomeric state. If the isomer is produced in a nuclear reaction in such a way that it is left in the excited state (i.e., in heavy ion beam fragmentation [363]), the main problem is to find a method to control the release of the stored energy. If the isomer of interest is produced in the ground state, an additional problem is then to "pump" it to the isomeric state. This can be done by various means: neutron interaction [372], bremsstrahlung [371] or laser photoexcitation [355, 532], inverse internal electron conversion [347, 348], etc. One of the first laser nuclear excitation techniques to have been demonstrated used a TEA CO_2 laser of 1 J to pump the 73 eV isomeric level of ^{235}U [347].

To pump keV to MeV isomeric states, as well as to initiate energy release from them, will require powerful superlasers [532, 362].

There are two types of nuclear isomers: *nuclear spin isomers* and *nuclear shape isomers*. Both types release energy electromagnetically; thus, they produce no radioactivity. In many cases, their final nuclear state is stable, so they produce no *residual* radioactivity.

Nuclear spin isomers have been studied for over sixty years, and hundreds have been identified. For instance, in the region $A < 90$, there are about seventy

[33] For example, the energy content of $^{235}U^m$ (73 eV, $T_{\frac{1}{2}} = 25$ mn) is 30 kJ/g, and that of $^{93}Nb^m$ (30.7 keV, $T_{\frac{1}{2}} = 13.6$ y) is 32 MJ/g.

isomers with lifetimes in the range 0.1 s to 2.44 days [372]. In this type of isomer the quantity of energy available is extremely large. But the spin isomeric nuclear states (which normally decay by emission of an electron or positron) are very stable against electromagnetic decay, and would thus require a very powerful trigger to initiate energy release [362, p.102]. Moreover, none of them is stable. It is therefore unlikely that spin isomers will provide a basis for practical applications [353].

Nuclear shape isomers were accidentally discovered in 1962 by S. M. Polikanov[34] while he was trying to synthesize the superheavy element $Z = 104$ [345]. What he discovered was an unusual isotope of americium, $^{242}Am^{m}$, with the probability of spontaneous fission at least twenty orders of magnitude higher than for the ground state. This phenomenon had never been predicted and greatly influenced the further studies of heavy and superheavy nuclei. Such states are called shape isomers, as their electromagnetic decay back to the ground state is inhibited by the difference in shape of the nucleus in the exited and ground states.[35]

Approximately forty shape isomers have been observed in the region between thorium and berkelium, with $A = 225$ to $A = 250$. Due to their rather large spontaneous fission decay probability, the half-life of these isomers is in the range 0.5 ns to 14 ms. These lifetimes are too short for practical applications. However, it is believed that for some uranium isotopes, and possibly for other relatively light transuranic elements, the spontaneous fission decay becomes sufficiently long, and thus some of their isomeric states could have much longer live-times [346, p.408]. But these states have not been observed yet [367].

There is no reason in principle that would make unlikely the formation of shape isomers in nuclei spread over the rest of the Periodic Table where, in general, fission is considered as an inhibited mode of de-excitation. In fact, the likelihood of this possibility increased enormously in 1986 with the discovery of the first non-fissile superdeformed nucleus, ^{152}Dy [352]. This discovery was made in England, at the Daresbury Laboratory [352]. Since then, superdeformed nuclei have been observed in nuclei with atomic masses in the region of $A = 130, 150, 190$ and, recently, for $A = 80$ [367], in particular for some isotopes of strontium and yttrium.

[34] For an obituary of S.M. Polikanov (1926-1994) and several interesting comments related to isomers, see [368]. Polikanov also had a special interest in antiproton interactions with nuclei and in the possible use of antiprotons for plasma heating [285].

[35] Shape isomers have very elongated ellipsoidal shapes (axis ratio of roughly 2:1). As ordinary nuclei are usually slightly non-spherical, such large deformations are called *superdeformations*. Since the natural decay mode of shape isomers is by spontaneous fission, they are also often called *fission isomers*.

In 1988, the first shape isomer outside the actinide[36] region, ^{68}Ni, was discovered at Orsay, near Paris, in a heavy-ion collision experiment by a team of scientists led by M. Girod, a physicist of the Centre d'Etudes de Bruyères-le-Châtel (a major French nuclear weapons laboratory) [356].

This discovery prompted an important theoretical effort to establish an extensive list of non-fissile nuclei which might develop shape isomers. This work started in France [358, p.54] (in particular at Bruyères-le-Châtel [357]) and developed into a French-American collaboration under former SDIO (Strategic Defense Initiative Organization) and NATO contracts [359].

For practical applications, e.g., for gamma-ray lasers or explosives, shape isomers are required to be located at a relatively low excitation energy [357, 362]. This is mainly in order to enable the de-excitation of the isomeric state to be induced by a relatively low-energy primary. Possible triggering mechanisms include laser-electron coupling [351, 355], [362][37] (a possibility that is also discussed in Russia [366]), and neutron- [350, 362] [372, p.1058] or gamma-catalysis [354].

The search for militarily-useful shape isomers over a broad mass region represents a formidable theoretical and experimental task. In the United States, the most modern and sensitive facility used for this purpose is the "Gammasphere" detector at the Lawrence Livermore Laboratory [369].

In France, an extended program to search for nuclear isomers is a major priority of GANIL.[38] In March 1993, a beam of ^{42}Sc in its 0.62 MeV isomeric state (half-life 61 seconds) was obtained at GANIL by a nuclear physics team from Bruyères-le-Châtel. This type of beam, a first in Europe (the only other one being in the United States at the National Superconductive Cyclotron Laboratory at Michigan State University), enables one to probe more deeply into the structure of exotic nuclei in a given isomeric state [361, p.40], [364]. Moreover, in 1995, a new isomer ($^{32}Al^{m}$) was identified at GANIL by a French-Russian collaboration [370].

None of the nuclear isomers discovered so far are suitable for practical applications. However, the discovery of an isomers with practical applications could be a matter of chance. It might be found in a relatively small country such as Hungary [371] or in a larger non-nuclear-weapon State such as Germany [373].

[36] The actinides are the series of nuclei from Actinium ($Z = 89$) to Lawrencium ($Z = 103$).

[37] Three different laser-triggering schemes are under investigation at LLNL.

[38] During the construction time of GANIL, between 1975 and 1982, one of us (A.G.) was working at CERN and FNAL. A persistent rumor suggested that the *Direction des applications militaires* (DAM) was one the main supporters of GANIL. This is confirmed by the fact that many references to GANIL's work, e.g., [358, 361], appear in the military section of the annual report of the French atomic energy commission (CEA).

As far as production is concerned, the difficulty might not be as large as was thought only a few years ago: a surprisingly large isomer yield was discovered in 1993 in heavy-ion-beam fragmentation reactions [363].[39] This method is now routinely used to produce beams of isomers [364]. These beams are of great interest because they enable one to experimentally study the detailed properties of isomers, as well as the various laser and nuclear techniques that have been proposed for their de-excitation [362] — and which to date could only be studied in a few special configurations [350, 351, 354].

It remains to be seen whether or not "a demonstration of significant energy release [from isomers] will be possible within the next five to seven years," as was anticipated by a Livermore scientist in 1993 [362, p.102].

A major step in this direction was made in 1998 by a team of a dozen of researchers from five different countries working under U.S. Air Force sponsorship and lead by C.B. Collins of the University of Texas [376, 377]. A sample of an isomer of ^{178}Hf (having a half-life of 31 years and excitation energy of 2.4 MeV) produced with a particle accelerator was irradiated with x-ray pulses from a device typically used in dental medicine. Intensities of selected transitions in the decay of the isomer were found to increase significantly. Such an accelerated decay is consistent with the resonant absorption of x-rays to induce gamma decay [376], therefore providing an experimental proof that this method can be used for triggering energy release from isomers:

> "Even if it falls short of a laser, the phenomenon the researchers have observed, called induced gamma emission, could find plenty of uses. A table-top gamma machine, with its supershort wavelength, could push photolithography [...] to atomic dimensions, serve as an energy source for an x-ray laser, or sterilize areas contaminated by micro-organisms released, for example, by terrorists. Says Collins:"You could set off something of the size of a match head" to do the job" [377, p.770].

According to reference [377], "Two years ago, French researchers reported that they had succeeded in triggered the hafnium-178 emission. They have not provided further details, however, and some researchers were skeptical" [377, p.770]. But, what is sure, the Direction of military applications of the French atomic energy commission is working hard on nuclear isomers, see, e.g., reference [375]...

[39] The beam fragmentation facility at the Michigan State University where this discovery was made is currently being upgraded to improve the production rate of radioactive isotopes by a factor 10^2–10^4, depending on the isotope [374].

A comprehensive review article on nuclear isomers explicitly mentioning the possibility of their use as "new forms of energy storage" has been published in *Nature* of 6 May 1999 [378].

4.6 Super-explosives and metallic hydrogen

Chemical *high-explosives* have specific energies on the order of 5 kJ/g and maximum mass densities of about 2 g/cm^3. This corresponds to a maximum energy density of approximately 10 kJ/cm^3. A chemical *super-explosive* is a chemical explosive that would have an energy density of at least 100 kJ/cm^3.

The discovery of a usable super-explosive would have dramatic consequences on nuclear weapons technology.[40] For instance, in a fission-bomb (or an H-bomb primary) the lower-limits on the weight and size are determined by the amount and volume of the chemical explosive used to implode the fissile material and the tamper/reflector surrounding it. In effect, assuming a relatively large fission efficiency, the weight of the fissile material is set by the desired weapons yield. Therefore, as about 10–20 kg of high-explosives are needed to implode 2–3 kg of plutonium surrounded by a 3–4 kg tamper,[41] the availability of a super-explosive would result in a weapon in which the weight of the high-explosive would be less than the weight of the fissile material. Similarly, the volume of the weapon's core would shrink considerably, implying substantial reductions in total weight and size because of the decrease in the surface area of the casing. Obviously, since the size and mass of H-bombs have a lower bound given by the characteristics of the primary, such reductions would in turn have a large impact on thermonuclear weapons technology.

As for application to fourth generation nuclear weapons, the interest of super-explosives comes from the fact that in a detonation the maximum pressure is $\propto \rho Q$ and the detonation velocity $\propto \sqrt{Q}$, where ρ is the mass density and Q the specific energy density (see, e.g., [189]). Therefore, a super-explosive 100 times more powerful than a conventional high-explosive of the same density would be $\sqrt{100} = 10$ times faster. This might be enough to improve the prospect of high-explosive driven microfission, section 4.4, or high-explosive driven pure-fusion, section 4.7.

Apparently, no useful super-explosive has been discovered yet. Nevertheless,

[40] Of course, if the cost of such a super-explosive were low, it would also have enormous implications for conventional warfare.

[41] We assume the use of a relatively thin beryllium/steel reflector/tamper, as in Fig. 1.1.

there have been rumors (in particular after the collapse of the Soviet Union) that some uniquely powerful non-nuclear explosive, code-named "red mercury," could have been produced in the USSR [404, 407]. There might be an element of truth in this information: "red mercury" could refer to some kind of *atomic isomer*.[42] However, the atomic isomers that are known to exist have energy densities not much higher than those of high-explosives. This is because very highly-excited atomic states, in which some of the inner electrons have been dislodged, have very short live-times. Unless some technique is discovered to stabilize such very high energy[43] isomeric states, it is unlikely that they could be metastable long enough for an atomic isomer to be used as an explosive. Moreover, relative to nuclear physics, atomic physics is well known, so that the discovery of an atomic isomer suitable for use as a super-explosive would be a major surprise.

In order to obtain a super-explosive, one would have to discover a practical means to store a significant amount of energy in a small volume. In a chemical high-explosive, the storage mechanism is *chemical bonding*, and the useful energy derives from the formation heat necessary to synthesize the explosive. Considerable research over many decades has led to a number of different kind of high-explosives. But none of them has an energy density much larger than TNT. For example, a recently synthesized insensitive explosive, LLM-105, is "only" 60% more energetic than TNT [415, p.9]. New methods, such as computer-simulated chemistry and nanotechnology, may help finding more powerful chemical explosives [420]. However, it is unlikely that such methods may lead to an increase as large as a factor of ten.

A possible method for synthesizing a super-explosive is *compression*.[44] For instance, if any material is subjected to a high enough pressure — an endoenergetic process — the atomic electrons will be squeezed out of their shells, and the material could undergo a phase transition to a new state. If for some reason the material in the new state is metastable (i.e., if it remains in the state reached by compression after the external pressure is removed), the stored energy could become useful for practical applications. In particular, if the transition energy release is controllable,

[42] An atomic isomer is an atom in which an electron remains for a relatively long-time in an excited state. A related concept is that of an *excimer* (a contraction of *exci*ted di*mer*), i.e., a molecule — such as (KrF)* — which is formed by the interaction between two atoms or molecules, one of which is electronically excited. The bound molecule may then decay radiatively to the ground state and dissociate. Excimers are well known and have various practical applications. For example, they are used as efficient lasing media for high-power lasers, and they are extensively studied as potential high-energy density propellants for rockets, etc.

[43] The energy content of chemical explosives is about 10 eV per molecule. In this context, "very high energy" refers to atomic excitations in the 0.1 to 1 keV range.

[44] Of course, compression is being used in the chemical industry to synthesize various molecules. Here we think of compression at much higher pressures.

such material could be used as a fuel for aircraft or spacecraft propulsion. However, if the energy release rate is not controllable once the transition is initiated, the material in the metastable state would be an explosive rather than a fuel.

The most simple and abundant atom is hydrogen. It is also one of the few substances whose properties can, in many cases, be calculated from first principles. In 1926, J.D. Bernal proposed that at very high pressure all materials will become metallic, this is, a lattice embedded in a sea of loosely bound electrons that conduct electricity easily. This is indeed what happens in many materials.[45] In the case of hydrogen however, the problem of its transition into the metallic state is still an open question, despite sixty years and considerable amounts of theoretical and experimental work [414].

The first theoretical estimate of the pressure required to transform hydrogen from the molecular into the metallic state is that of Wigner and Huntington who predicted in 1935 that this transition would happen at a pressure of about 250 kbar [379]. Later calculations,[46] however, resulted in higher values, on the order of 2 Mbars, a pressure that could not be produced in the laboratory until quite recently. These calculations were motived by a number of considerations, including the fact that megabar range pressures are found at a depth of a few thousand kilometers within the Earth and the possibility that hydrogen in the interior of the giant planets such as Jupiter (which mainly consists of hot, dense hydrogen) could be in the metallic state.

The next major event, which had the effect of a "bombshell" in the scientific community [393, p.106], was the prediction in 1968 by Ashcroft that metallic hydrogen could be a high-temperature superconductor at atmospheric pressure [380]. This prediction was important from the practical point of view because a high-temperature superconductor would have many industrial and military applications, and because Ashcroft's argument opened the discussion on the possible long-term stability of metallic hydrogen at ordinary pressure.

Following the publication of Ashcroft's article, a number of papers were published on the question of the metastability of metallic hydrogen [384, 385, 386],[47] and the first refined calculation of both the lattice structure and the superconducting properties of metallic hydrogen were published in Switzerland [381, 382, 383, 391][48].

[45] For example, insulating molecular iodine transforms gradually to a metallic state between 40 and 170 kbar of pressure at room temperature [395].

[46] For a review of the metallic hydrogen work prior to 1975, see reference [393].

[47] None of these papers cites Ashcroft's work explicitly.

[48] These articles of Schneider and Stoll, two Swiss solid state physicists, are often cited by the Soviet scientists but seldom by the Americans. It is not known whether or not Schneider or

Soon after, the first claim of the metallization of hydrogen was made in Russia [387]. This began an ongoing series of claims and disclaimers that is still continuing [414]. The method used in that experiment was isentropic compression of a cylindrical shell by means of a chemical explosive charge, a technique described in [389]. At about the same time, the technique of using high-energy lasers (i.e., ICF facilities) for making metallic hydrogen was proposed by Anisimov in the USSR [388] and Teller in the USA [390].

A second Russian claim for the production of metallic hydrogen was made in 1975 by a team working with a diamond anvil cooled to 4.2 ^{0}K [394], and a similar claim was made the same year by a team of Japanese geophysicists compressing hydrogen gas at room temperature until it became electrically conducting [392].

These claims prompted the publication of a comprehensive review of the metallic hydrogen issue by the RAND Corporation as part of a continuing RAND study of selected areas of science and technology, a project sponsored by the U.S. Defense Advanced Research Projects Agency [396]. Apart from expressing doubts about whether the molecular-metallic transition had really been observed, the main thrust of the report was to openly recognize the considerable military potential of metallic hydrogen:[49]

> "The potential usefulness of metallic hydrogen can be attributed to several factors. As a result of its high Debye temperature ($\approx 2000 - 3000\ ^0$K) it may be an elevated-temperature (possibly room temperature) superconductor.[50] The high specific impulse of metallic hydrogen (≈ 1400 s) compared with that of a rocket fuel, such as JP4 plus liquid oxygen (≈ 400 s), makes it potentially attractive as a rocket fuel. Metallic hydrogen has an energy content of 400 kJ/g mole, or 300 times greater than the best currently available aircraft fuel. This would make it attractive for aircraft propulsion. However, if the transition energy release rate is not controllable once the transition is initiated, metallic hydrogen would be an explosive rather than a fuel.

Stoll were involved in the Swiss atomic bomb program, which led to the publication of a number of results that were (at the time) classified in other countries. Their work, however, shows that world-class expertise on high-pressure condensed matter physics existed in Switzerland at the time of this program.

[49] Although metallic hydrogen is a recurring subject in non-specialized scientific journals, its military potential is seldom mentioned. Apparently, the only explicit reference to the RAND report appeared one year later in *Science* [399]. The only previous reference to possible military implications was in *New Scientist*, were they were indirectly implied by the suggestion that metallic hydrogen "could be used in laser fusion and energy storage" [397].

[50] Unfortunately, the high Debye temperature of metallic hydrogen also indicates that it may be a quantum liquid [396, p.5].

> If so, with an energy of 50 kcal/g and a density of $\approx 1 - 1.3$ g/cm^3, it is an explosive that is approximately 35 times more powerful than TNT (Q = 1.345 kcal/g). Its high density should also make metallic hydrogen useful in nuclear weapons"[51] [396, p.5].

A similar review of the advances and prospects of metallic hydrogen was presented in September 1980 to the Academy of Sciences of the USSR. Unfortunately, the paper was published in condensed form, summarizing problems that have a bearing only on static pressure experiments, and emphasizing that the metastable state would probably not exist at ordinary temperatures and pressures [401].

The first American claim concerning the metallization of hydrogen was made in 1978 by a team of Livermore scientists using an explosive-driven magnetic-flux compression device [398]. The next claim came in 1988–1989 by a team geophysicists from the Carnegie Institution of Washington working with a diamond cell. Again, the claim was premature. Nevertheless, funding agencies continued to foster research at several laboratories trying out different methods to produce metallic hydrogen. Obviously, as recalled in a review published in the magazine of the U.S. National Science Foundation, "if metallic hydrogen is metastable, and if it remains superconducting at or near room temperature, it could revolutionize the generation, transmission and uses of electricity. [...] [Moreover,] weapons designers have also speculated that metallic hydrogen might be used as an explosive; it would be much more powerful than any known nonnuclear explosive" [402, p.25].

Finally, after some encouraging measurements in the 0.1–0.2 Mbar range [403] and further experiments up to 0.83 Mbar [406] and 1.8 Mbar [409, 413], another team from Livermore (working with a two-stage light-gas gun) announced in 1996 the discovery of a continuous transition of compressed hydrogen from a semiconductor to a metallic state at 1.4 Mbar.

There have been many claims in the past of the successful metallization of hydrogen, but none so far has passed the requirement of verifiable reproducibility. It is therefore not surprising that Livermore's last announcement was met with some skepticism, e.g., [410, 411, 412, 414, 417]. In particular, while past expectations concentrated on low-temperature, solid metallic hydrogen, the discovery of metallic hydrogen under conditions of high temperature and relatively low pressure was unexpected [412]. This points to the facts that the simplest element in the Periodic Table is not understood at extreme conditions [417], and that true

[51] With a density of 1.3 g/cm^3, the energy density of metallic hydrogen would by ≈ 270 kJ/cm^3. Since hydrogen is the lightest element, metallic hydrogen could possibly be the most powerful chemical explosive conceivable.

metallic hydrogen is still to be found somewhere in a much more complex phase diagram than previously expected [414].

Nevertheless, as far as the short term practical applications are concerned, the Livermore scientists are more than satisfied:[52]

> "The findings will lead to new databases affecting weapons and laser fusion programs, both of which use isotopes of hydrogen. Laser fusion scientists use the compressibility of hydrogen to tune laser pulses to obtain a maximum energy yield. These new results indicate that the equation of state of hydrogen is such that higher fusion yield are expected" [408].

Finally, in 1998, after the diamond-anvil, explosive-driven magnetic-flux compression, and gas-gun techniques had been tried at Livermore, another group of Livermore scientists used the NOVA laser to shock a deuterium sample to a pressure of about 340 GPa [418, 419], more than ten times the 20 GPa reached in the Livermore gas-gun experiment that showed that hydrogen conductivity increased to that of a semiconductor at this pressure [409]. This laser experiment confirmed the evidence of high electrical conductivity observed by the gas-gun group, and demonstrated that deuterium shocked above 55 GPa has an electrical conductivity characteristic of a liquid metal [418].

Therefore, the extraordinary potential of laser compression techniques already demonstrated on NOVA (e.g., [212]) enabled the method proposed twenty five years earlier by Anisimov [388] and Teller [390] to be put into practice. Further metallic hydrogen research on kJ (e.g., [405, 419]) and MJ (e.g., [21, p.45]) class laser facilities may therefore provide a final answer to the still open questions: Does solid metallic hydrogen exist? Is it metastable? Can it be manufactured at a reasonable cost? And — if yes — is it usable[53] as a fuel or a super-explosive?

While these scientific questions are still open, *Scientific American* has already the answer on the title page of the May 2000 issue: "Metallic Hydrogen —

[52]The considerable astrophysical interest of these results should not be underestimated. However, those who claim that such studies should not be limited by international arms control agreements should be reminded that astronomy and astrophysics are *the* examples of so-called "pure" sciences, which at all times have been a considerable source of political and military *power* (e.g., navigation, $E = mc^2$, etc.). While scientists working at weapons laboratories are not shy about showing how *defense programs* have "pure" science implications [400, 416], it is generally the "pure scientists" working at universities who "forget" to mention the military importance of their academic research (e.g., [414, 332]).

[53]In particular, the metastable phase should be sufficiently "insensitive" so it may be used as a reasonably "safe" military explosive. For a discussion of these concepts, see [20].

The stuff of Jupiter's core might fuel fusion reactors" [421]. In this cover story, Livermore's researcher William Nellis speculates on the "myriad uses of metallic hydrogen:" room-temperature superconductor, lightweight structures, clean fuel, and fusion pellets. The only allusion to the many military applications is the suggestion that: "If the stored energy could be released extremely rapidly, solid metallic hydrogen could be used as an explosive" [421, p.65].

4.7 Pure-fusion explosives

> "Until now we have had two essentially different types of nuclear weapons, the fission bomb and the hydrogen bomb. It is not necessary to discuss in detail how these things work. A fission bomb cannot explode at all unless it contains a certain quantity (the critical mass) of extremely expensive metal. [...] A hydrogen bomb is able to extract its energy from a much cheaper and much more abundant fuel (heavy hydrogen), but it requires at least a moderately efficient fission bomb to ignite it. Thus every hydrogen bomb costs at least as much as a fission bomb. [...]
>
> Below a certain explosive yield on the order of a kiloton, nuclear weapons are grossly inefficient and extravagant. However, for military purposes other than wholesale annihilation, a kiloton is already an unreasonably big bang. There is a clear and acute need for an explosive which would fill the gap between a ton and a kiloton of TNT with a cost which is proportional to the yield instead of being independent of it.
>
> There is theoretically a simple way to escape from the tyranny of the critical mass. This is to burn heavy hydrogen without a fission bomb to ignite it. A fission-free bomb, containing a small quantity of heavy hydrogen and no fissionable metal, is logically the third major step in weapon development after the existing fission and hydrogen bombs" [427, p.458].

This excerpt from a famous Freeman Dyson article in the prestigious American quarterly review *Foreign Affairs*[54] [427] is a perfect summary of the kind of thinking and rhetoric that was prevailing among those who in the late 1950s were defending the weapons laboratories and fighting a possible nuclear test ban. Nineteen years

[54] At the time, the editorial board of *Foreign Affairs* included, among other influential and eminent personalities, the physicist Isidor I. Rabbi, one of the founders of JASON.

later, in his book *Disturbing the Universe* [441], Dyson summarized his April 1960 article:

> "The main thesis of the article is that a permanent test ban would be a dangerous illusion because future improvements in weapons technology would create irresistible pressures toward secret and open violations of any such ban. In other words, fission-free bombs are the wave of the future, and any political arrangement which ignores or denies their birthright is doomed to failure" [441, p.128–129].

Then Dyson observed that his 1960 "argument was wrong on at least four counts: wrong technically, wrong militarily, wrong politically and wrong morally" [441, p.129].[55]

In 1960 Dyson was campaigning *against* a test ban and was thus opposed to "Hans Bethe[56] [who] was pushing hard, in public and within the government, for a comprehensive test ban" [441, p.127]. The irony is that, *today*, Bethe is using Dyson's 1960 arguments — namely the fact that pure-fusion explosive are scientifically feasible and militarily attractive — to ask the U.S. Government *to ban* "all physical experiments, no matter how small their yield, whose primary purpose is to design new types of nuclear weapons" [459], [461, p.438].[57]

However, as for full-scale nuclear explosions, there is no way to distinguish between "military" and "peaceful" microexplosions at ICF facilities such as Nova, Gekko, NIF, LMJ, etc. Therefore, the acceptance by the U.S. Government of Bethe's proposal would be equivalent to recognizing that the Science Based Stockpile Stewardship (SBSS) program and the powerful NIF facility could lead to a fourth generation of nuclear weapons. Moreover, Bethe's proposal would require to changing the official interpretation of the scope of the CTBT in such a way that

[55] Only one year after Dyson published this book, i.e., in 1980, the question of the links between ICF and pure-fusion weapons was raised by W.A. Smit and P. Boskma [444]. This publication — one of the rare well-informed publications on this subject to appear in the arms-control/disarmament literature in the period 1975–1990 — was based on a report published in 1978, see [8, Ref.6].

[56] Hans A. Bethe, born in 1906, who directed the Theoretical division at Los Alamos during World War Two, received the Nobel prize in 1967, mostly for his work in astrophysics — e.g., the "carbon cycle" which powers the Sun. In 1950, he wrote [75] one of the four-articles in a series against the hydrogen bomb that was published by *Scientific American* [74, 75, 76, 77]. It is important for the younger generation to read these articles, especially to get a feeling for the enormous technological drive that is pushing everything aside to breed new weapons, despite the awareness of their intrinsic dangers and despite the existence of an open debate on them.

[57] Hans Bethe's letter to President Clinton, and later President Clinton's answer of 2 June 1997, were distributed by the Federation of American Scientists at the same time as an analysis of the question of pure fusion explosions under the CTBT [460]. See also [462, 50, 466, 471].

microexplosions would be banned. This is almost impossible, especially since the SBSS program and the construction of the NIF were *accepted* by the U.S. Government in order that the nuclear weapons laboratories *accede*[58] to the *Comprehensive* Test Ban Treaty (CTBT), signed in September 1996.

In fact, after almost forty years, we are back to 1960. With the signature of the *Partial* Test Ban Treaty (PTBT) in 1963, the Los Alamos Laboratory got a number of powerful instruments: the PHERMEX flash x-ray radiography facility [500], the Los Alamos Meson Physics Facility (LAMPF) particle accelerator [503], and the Weapons Neutron Research Facility (WNRF) storage ring [502].[59] At that time, there was not much news in the media about these machines, but they are the counterpart of today's Dual–Axis Radiographic Hydrotest facility (DARHT) [20, p.28] [510] and the Los Alamos Neutron Science Center (LANSCE), a substantial addition to the WNRF [20, p.57–69].[60] Moreover, together with the upgrade of its Flash X-Ray (FXR) facility [520], the Livermore Laboratory got the National Ignition Facility (NIF) [514], which certainly has a much more exciting military potential than the low-fission-yield explosives developed between 1961 and 1977 as part of the *Plowshare* program for "peaceful uses of nuclear explosions." Consequently, as with the PTBT, the quality[61] and the number of nuclear tests (e.g., with NIF, etc.) will go *up*!

Even before the PTBT, and in particular during the 1958–1961 moratorium on nuclear tests, there has been considerable research on pure-fusion concepts at all nuclear weapons laboratories.[62] Moreover, in 1955 already, the U.S. Atomic Energy Commission regarded the effort of the recently created Lawrence Livermore laboratory to develop low-fission-content weapons as an "urgent project." In fact, Livermore proposed a device for Operation *Redwing* that would have served as the sole large weapons program of the laboratory at that time [14, p.5]. Later, when "clean" bombs proposals surfaced in Europe following the work of J.G. Linhart at Euratom in Frascati and F. Winterberg at ICTP in Trieste, *neutron bombs* were advocated by Same Cohen as pure-fusion explosives for both military and peace-

[58] On this point, see, for example, the statement of C. Paul Robinson quoted in section 2.3.

[59] The importance of the 1958-1961 moratorium as an added impetus to get LAMPF and WNR is stressed by Carson Mark in [449, p.49]. For a historical analysis of the links between particle accelerator development and national security concerns see [513]. See also [519].

[60] Needless to say, electronic computing facilities got a proportional boost, as is today the case with the Advanced Strategic Computing Initiative (ASCI).

[61] It is seldom noticed that *underground* nuclear tests were in fact more suitable for nuclear weapons development than atmospheric tests.

[62] For many interesting aspects of the "clean bomb episode" and the nuclear weapons design politics of the 1950-60s see [117, 33]. For the "peaceful" nuclear tests during the moratorium in the United States and the Soviet Union see [237, 458] and [14, p.7-8].

ful applications [430, 432].[63] We will not review these developments in detail[64] but will attempt to give an overview of the kinds of technologies that have been (and are still) considered as candidates for making pure-fusion (i.e., fission-free) explosives:

• *Chemical explosives* can be used to implode small amounts of fusion fuel (e.g., DD or DT gas), resulting in measurable production of fusion neutrons. In 1977, using a concentric explosion with an exceptional degree of symmetry, a group of Polish scientists were able to produce 3×10^7 neutrons by purely explosive means [435, 436]. The publication of this result in the journal *Nature* [437] prompted a letter from Russia, recalling that similar results had already been made public in 1958 at the Second international conference on the peaceful use of atomic energy in Geneva [438]. Moreover, as early as 1955, 10^8 neutrons per shot were generated in USSR. In 1963, for UD_3 and gaseous D_2 targets, this number increased to 3×10^{11}.

Similar research has been done in Western countries. But only few results have been made public. For example, in an experiment made in collaboration between a Canadian and an Israeli scientist, an explosive driven implosion facility was used to produce a few 10^3 fusion neutrons in a $D_2 - O_2$ mixture [447].

In 1990, Chinese scientists published the description of a concentric shell device producing on the order of $10^4 DD$ fusions in the center of a UD_3 core, and reported the result of experiments performed between 1976 and 1982 in which on the order of 10^7 fusion neutrons were generated per shot [453].

At present, the largest published neutron yield from a chemical explosive driven device is $1-4\times10^{13}$ [454]. This result was obtained at the Chelyabinsk-70 laboratory with a spherical chemical explosive device of 375 mm in diameter imploding a multilayered medium [478] in order to achieve a higher energy cumulation level (compared to a homogeneous media). However, since this experiment used DT [455] (which under similar conditions produces about 100 times more fusions that DD), the progress relative to 1963 is not significative.[65] This illustrates the considerable difficulty of initiating thermonuclear fusion with chemical explosives

[63] Winterberg's paper [431] is the first open proposal to use high-power electron beam generators for thermonuclear microexplosion ignition.

[64] One should nevertheless mention that, as part of their respective PNE programs, both the American and Soviet laboratories developed very-low-fission-yield thermonuclear explosives. In the case of the Soviet program, a thermonuclear explosive was developed in 1970 which had less than 0.3 kt of fission-yield for a total yield of 15 kt, i.e., a "98% pure" fusion explosive [458, p.20].

[65] Previously, a record (for all ICF devices of that time) yield of $5 \times 10^{13} DT$ fusions had been obtained in 1982 already with spherically symmetric objects made of liquid explosive and with the use of a set of shells: V.A. Shcherbakov cited in [464, p.1058].

alone. In particular, while elementary consideration indicate that the temperature and pressure may reach infinity in the center (or on the axis) of a device, various imperfections and the onset of instabilities is usually limiting the amount of energy cumulation achievable in practice [477, 484].[66]

In fact, since existing types of chemical explosives cannot create sufficiently fast and strong detonation waves, the temperature and the degree of compression achieved are always such that the thermonuclear yield is smaller than the energy of the chemical explosives used in the device. However, the analysis of the results obtained in the Russian experiments shows that the thermonuclear burn occurred at a temperature of about 0.65 keV [454] and that the device was only two orders of magnitude below the ignition threshold [455]. Therefore, the discovery of some powerful chemical super-explosive, or the synthesis of metallic hydrogen, may be sufficient to make high-explosive driven pure-fusion a reality.

The results of the Russian experiments [454, 455] have recently been reanalysed in the light of a better insight in the nature of the instabilities that prevent thermonuclear ignition in shock wave implosion experiments [484], confirming that they approached the threshold for thermonuclear explosion quite closely [473].[67]

• *Impact fusion*. Instead of compressing a thermonuclear fuel by means of a spherical device (with or without velocity multiplication to increase the cumulation of energy) it is possible to take advantage of the possibility to accelerate a macroscopic object to high velocity and then to use its kinetic energy to compress and heat a target [428, 429].[68] This technique may deliver the few MJ of energy in a time period of about 10 ns into a volume of less than 1 cm^3 that is necessary to ignite a thermonuclear fuel. Since the target has often the shape of a conical DT region embedded in a heavy metal slab, the concept is sometimes called "*conical target fusion*" instead of "impact fusion."[69] There are a number of variations for this technique: e.g., the thermonuclear fuel might be embedded in the projectile rather than in the fixed target, or two projectiles of opposite rectilinear motion might be fired against each other and around some fusionable gas.

The Polish chemical-explosives-driven experiment of 1977 used a conical target compressed by the jet produced by a specially designed high-explosive shaped charge [435, 436]. It can therefore be considered as a kind of a "conical target impact fusion" device. The first significant result using a flat flyer plate acceler-

[66] A few interesting comments on the difficulty of initiating a thermonuclear explosion with nothing but high explosives can be found in [449, p.50-51].

[67] Further progress towards thermonuclear ignition might result from the successful implementation of the phenomenon referred to as "super-spherical cumulation" [499].

[68] For a recent review of impact fusion, see [465].

[69] For a review of conical target fusion experiments, see [450].

ated by chemical explosives, i.e., the production of 10^6 DD-fusion neutrons, was published in 1980 [443]. In that experiment, the flyer was accelerated to a velocity of 5.4 km/s. Since then, little progress seems to have been made. Recently, however, a 5 g mass plate was accelerated to a velocity of 10.5 km/s, a world-class achievement, using ≈ 50 kg of explosives [463]. But this would not be sufficient to achieve much higher thermonuclear yields.

In fact, to reach ignition, impact fusion requires a projectile with an energy of about 10 MJ, which means accelerating a 0.5 g object to a velocity of about 200 km/s [440, p.iv]. To achieve such velocities, other techniques than high explosives[70] have to be tried: electron-beam [433][71] or laser-beam [124, 434] acceleration, electromagnetic acceleration [439], or matter-antimatter annihilation acceleration [284].[72] However, as shown by a simulation published in 1987, a velocity of 25+25 km/s may in theory be sufficient to yield up to 10^9 DD-fusion neutrons per head-on impact of two colliding shells [451]. Further progress might be achieved by magnetizing the fuel within the projectile or the target.[73] Impact fusion with magnetized fuel targets has the advantage that much lower velocities (≈ 10 km/s) could conceivably be used instead of the 200 km/s value usually quoted as necessary for small high-density unmagnetized pellet implosions [442].[74]

Finally, high velocity impact could be used as an *indirect* driver for imploding an ICF pellet [448, 85]. The idea is that instead of compressing a small amount of thermonuclear fuel, an impact fusion driver could be used to generated x-rays in a cavity containing an ICF pellet, or to compress a cavity containing a preexisting blackbody photon gas that is imploding an ICF pellet by ablative compression. Therefore, as high-gain ICF pellets will become available, impact fusion driver technology will provide a compact igniter for such pellets.

Progress in impact fusion is intimately linked to the development of very high velocity electromagnetic guns, a technology which is vigorously developed because of its military potential for applications such as ballistic missile defence [485, 490], magnetic artillery [483], and rapid fire assault vehicles [489].

- *Magnetic Confinement Fusion (MCF)* research and development was long

[70] Velocities as high as 90 km/s have been observed for beryllium jets in 1952 already, but with very little mass however [422, 423].

[71] This experiment is the first ever published where x-ray ablative compression is used to generate very high pressure.

[72] For an extensive review of work on methods of acceleration of macroscopic particles published until 1981 see [446].

[73] This concept will be discussed below in a more general perspective.

[74] For a review of non magnetic, as well as well as magnetically insulated, impact fusion concepts, see [452].

classified in Unites States under the code names *Sherwood* and *Matterhorn*. In 1955, for instance, the only information concerning the "Controlled Thermonuclear Reactor" that was declassified was the fact of interest in such a program and the sites where work was underway. In 1959, all information regarding this program was declassified [22]. In the United Kingdom, declassification of controlled thermonuclear fusion research started by the publication, in 1957, of a series of six articles in the *Proceedings of the Physical Society* comprising the fundamental paper of J.D. Lawson defining the "Lawson criterion" for break-even in thermonuclear fusion [79]. In particular, it was thought that some MCF schemes, i.e., "pinch effect" devices (the most widely and intensively approach studied at the time, e.g., [424, 425]) could lead to pure-fusion explosives [426].

• In *plasma pinch* devices, a large current is heating a narrow plasma column which is "pinched" by its own magnetic field. The plasma is compressed, and neutrons are produced. Unfortunately, the pinch is very quickly disrupted by instabilities, so that the concept can only be used as the basis for a pulsed device. In fact, after decades of improvements (and despite some significant progress [508]), it turned out that the pinch effect is possibly much more effective as a powerful x-ray generator, rather than a thermonuclear fusion device.[75] Therefore, its most promising application today is as an *indirect* driver for ICF [165]. For instance, at the Sandia National Laboratory, the Saturn pulsed-power-driven Z-pinch produces about 0.3 MJ of x-rays in 4–20 ns [517], and the Particle Beam Fusion Accelerator (PBFA-Z) about 1.5 MJ, also in 5–30 ns [165, p.1820]. Considering that the big megajoule lasers which are under construction will yield at most 1.8 MJ of low-energy photons, that still have to be converted into x-rays, the x-ray outputs of the pinch machines are enormous. This is even more impressive considering that a Z-pinch machine is much smaller and less costly that a laser facility of comparable energy [168]. In fact, implosion experiments with simple ICF targets containing deuterium fuel are planned for 1998 at PBFA-Z. They are expected to yield about 10^{12} DD-fusion neutrons per shot [466, p.19].

• The *plasma focus* device has been independently discovered in Russia in 1962 and the United States in 1964.[76] Essentially, it is a fast dynamic Z-pinch in which the stored magnetic energy is rapidly converted into plasma energy and then

[75] However, a Z-pinch device could become a net energy producer if a thermonuclear detonation wave could be triggered and propagated axially fast enough to burn the fuel before the plasma column is disrupted[456, 474]. Such a detonation wave could be launched at the optimum time by ignition with a powerful laser pulse [472].

[76] The dense plasma focus is also known under the name of "Mather gun", from the name of its American inventor, Joseph W. Mather, who recently passed away. In his obituary [521], the DD neutron yield of the most powerful DPF device known to have been built is mistyped 10^{12} instead of 10^{18}.

compressed by its own magnetic field. It consists of two cylindrical electrodes between which a powerful electric discharge is initiated with a capacitor bank in a DD or DT atmosphere, and is therefore the simplest high-flux fusion neutrons and x-rays generator that exists [8, p.172]. Plasma focus devices are used at various weapons laboratories and other institutions, e.g., [507, 509]. In the United States, plasma focus development culminated in 1974 with a device called "DPF 6 1/2" which produced $\approx 10^{20}$ DT-fusion neutrons at a repetition rate of about four pulses per hour.[77] Further advance in plasma focus technology could result from the use of a solid DT or LiD fiber between the electrodes, an idea that was suggested in 1978 already [504] and first demonstrated in 1987 in a Z-pinch device [508]. In November 1968, at the Plasma Physics meeting in Miami, a paper suggested that combining a dense plasma focus with a laser system could provide a shortcut to a bomb [501].[78]

• *Magnetized fuel and magnetic compression* devices are based on the old idea that magnetic field can serve to thermally insulate the fuel from the walls and localize α-particle energy deposition in the fuel after ignition. This is of course what is done in MCF. But the same principle can be applied to a high density plasmas where the magnetic field decreases thermal conductivity and improves energy deposition. These effects are particularly pronounced when very strong magnetic fields are generated, either by mechanically compressing a liner (i.e., a metallic container) containing a magnetized fuel, or by magnetic compression of such a liner.

Magnetic compression can be driven by a capacitor bank [491] or by chemical explosives [497]. The technology of these energy cumulation devices is based on classical physics and has been under development for a long time [475, 476, 479, 118]. It is a domain in which Russian scientists have invested a lot of effort since the early 1950s [479, 486]. Because self-destructive high-explosive driven experiments are in general less expensive than capacitor-bank experiments, the former has been preferred in Russia, whereas big reusable electromagnetic implosion facilities have become the speciality of the Western laboratories.

In Russia, a concept called "MAGO," proposed in 1979 by V.N. Mokhov [482], enabled the stable production of 4×10^{13} fusion neutrons from the magnetic compression of a 10 cm radius, 15 cm length, chamber filled with DT gas [487].

In the Unites States, the technique of magnetic compression is under investigation using non-destructive devices, such as the "Shiva-Star" facility at Philips Laboratory [495], or explosive devices, such as "Procyon" at Los Alamos. Pro-

[77] This is on the same order as the $10^{19} DT$ neutron yield expected per ICF shot at NIF or LMJ.
[78] See [472] for a similar idea in the context of a plasma pinch.

cyon is an explosive pulsed-power system designed to drive 1-MJ plasma Z-pinch experiments [488].

The concept of electromagnetic implosion of cylindrical plasmas shells (i.e., imploding plasma liners or hollow Z-pinches) has become a speciality of the Phillips Laboratory (formerly, *Air Force Weapons Laboratory* at Kirtland Air Force Base, New Mexico). These imploding liners can be used as intense sources of neutrons or x-rays. In 1980, for instance, neutron yields of $\approx 10^7$ and x-ray yields of > 1 kJ above 150 eV have been obtained [445]. This experiment used a 1.1 MJ facility. Today, the "Shiva Star" magnetic compression facility is the world's largest pulsed-power, fast-capacitor bank. It is activated by a 1.2 MA, 4.8 MJ electric capacitor discharge [492, 493]. In 1995, a Shiva Star experiment in which a 4 cm radius, 0.1 to 0.2 cm thick, aluminum shell was compressed to 16.8 g/cm^3, demonstrated the feasibility of electro-magnetically driven spherical liner implosion in the cm/μs regime [495]. This technique is being developed, in particular, for antiproton-driven subcritical microfission burn (see sections 4.2, 4.4, and the references therein).

The chemical explosive approach to magnetic compression is now the object of a major collaboration between Los Alamos and Arzamas-16 [497]. The first ever joint scientific publication of a team of American and Russian nuclear-weapon scientists was the result of this collaboration [496]: A hot plasma was produced and 10^{13} DT fusion reactions were observed — possibly the maximum ever in a high-explosive driven experiment performed outside of Russian territory. According to the authors of this publication, these experimental results are in reasonable agreement with computations suggesting that the technique could be used to yield 1 GJ of fusion energy, i.e., a yield equivalent to 250 kg of TNT. The prospect of a militarily useful explosive based on this concept has been examined in detail in several recent assessments of the arms-control implications of such a pure-fusion devices [466, 467, 471].

In the future, much more powerful magnetic compression experiments will be conducted at the Nevada Test Site. A facility named "High-Explosive Pulsed Power Facility" is described in the Stockpile Stewardship and Management Programmatic Environmental Impact Statement. "In broadest terms, the facility could support experiments that could make 100 to 1'000 MJ of electrical energy available to power experiments. Typical proposed experiments could involve 4'536 kg (10'000 lb) or more of conventional high explosives in a variety of configuration" [498, p.A-15].

• *Beam-driven devices*, in which a powerful radiation (light or x-rays) or current (of heavy-ions, light-ions, electrons, or antiprotons) is used to evaporate the surface of a fusion- or fission-fuel pellet (resulting in a colossal reaction-pressure which

implodes the fuel) are today's most important devices used to study the physics of primaries and secondaries of thermonuclear weapons (See chapter 3). Whether or not very-compact lasers, superlasers, or particle-beam-generators can be designed (thus opening the possibility of *beam-triggered pure-fusion bombs*), beam-driven inertial confinement fusion enables the development of the technology of mini-secondaries for pure-fusion devices. Militarization of these devices will then be a matter of miniaturizing a direct or indirect driver based on a physical process of the kind we have described in various sections of this chapter.

To this list should be appended a number of other more or less promising concepts — and possibly some classified ones. Nevertheless, the progress made in at least two of these techniques (namely inertial confinement fusion and magnetic compression) is so impressive,[79] that "pure-fusion" and "subcritical microfission" explosives are today very close to becoming technologically feasible.

In this context, a June 1994 interview of the Russian Nuclear Energy Minister Viktor Nikitovich Mikhailov is significant. V.N. Mikhailov is one of the scientists who helped develop the current generation of nuclear weapons.[80] According to a Reuter press release he said that:

> " a new generation of nuclear weapons could be developed by the year 2000 unless military research is stopped. [... This] fourth generation of nuclear weapons could be directed more accurately than current arms. [... The] new weapons could be programmed to wipe out people while leaving buildings standing. [... It is] a toss-up whether Russia or the United States would be the first country to devise the new arms" [457].

In 1998, in the wake of the 1997 letter of Hans Bethe asking President Clinton "not to finance work on new types of nuclear weapons, such as pure-fusion weapons," the debate on such weapons started to take some momentum: The work of Suzanne Jones and Frank von Hippel at Princeton University [466] lead to a widely read opinion piece in *Physics Today* [471], and a 92-page report on the development of pure-fusion weapons by the Institute for Energy and Environmental Research [467] received considerable attention from the media [468, 469, 470].

[79] It is interesting to note that much of this progress happened in the few years that preceded the final negotiation and signature of the CTBT.

[80] He is also the editor of the compilation *Nuclear Explosions in the USSR* (Khlopina Radium Institute, Moscow, 1994).

4.8 Superlasers (Figs. 4.3–4.4)

Figure 4.3 shows that over the past ten years, laser intensities have increased by more than four orders of magnitude [542, 558] to reach enormous intensities of 10^{21} W/cm^2. These instantaneous intensities are sufficient to induce strong relativistic and nuclear effects, as can be seen in Fig. 4.4.[81]

This very rapid evolution is the result of two major inventions made in 1984 and 1985:

- The expansion and recompression of ultrashort pulses by means of diffraction gratings, by Oscar Eduardo Martìnez, an Argentinean working at Bell Laboratories as an external post-doctoral fellow [529, 533];
- The amplification and subsequent recompression of optical chirped pulses, by Gérard Mourou, a French working at University of Rochester [530, 535].

These inventions enabled the amplification of picosecond and femtosecond laser pulses to very high energy by a technique call "chirped-pulse amplification" (CPA), an accomplishment that has revolutionized high-power laser technology. This technique consists of producing a high-bandwidth, low-energy pulse of extremely short duration (femtoseconds[82] to picoseconds), stretching the pulse for amplification, and recompressing it back to its original duration. When Mourou became aware of the "compressor" designed by Martìnez, he immediately demonstrated the validity of his pulselength compression technique, and produced the first tabletop terawatt laser system [535].

In the few years following the invention of the laser in 1961, tabletop laser intensity reached a maximum of about 10^{14} W/cm^2, and then plateaued at this value for about 20 years, due to limitations caused by nonlinear effects (see Fig. 4.3). This technology is today the basis of the big lasers, such as NIF and LMJ, that are under construction for ICF and similar applications.

Since 1988 the intensity has been increasing again, crossing into fundamentally

[81] These relativistic and nuclear effects are possible because, in very high density photon fields, multi-photon processes become more probable than single-photon processes [267, 269]. This behavior can be ascribed to the fact that the photon is a boson, which allows a large number of them to be in the same state [269, p.1075].

[82] A femtosecond, i.e., 1 fs = 10^{-15} s, is on the order of the time taken by an electron to circle an atom. This gives the order of magnitude of the minimum pulselength of an optical laser pulse. A brief review of how it has been possible to decrease laser pulse durations from 10^{-6} down to 10^{-15} seconds since 1960 is given in [565].

new physical regimes. At present, there is no indication that this increase will not continue until the laser intensity limit[83] of $\approx 10^{23}$ W/cm^2 is reached [535].

What is most spectacular is that the superlasers are extremely compact (for many applications they fit on a tabletop) and relatively inexpensive — costs run around $500'000 [558, p.22].

One of the mains advantages of the CPA technique is that it can be applied to existing large-scale $Nd:glass$ laser systems which are able to produce kJ pulses in one beam.

The potential military applications of superlasers[84] are so impressive that their principles have been implemented on existing large laser systems built for inertial confinement fusion, pushing their peak power by three orders of magnitude from 1 TW to 1 PW. For example, the LLNL 'Petawatt' laser is the result of transforming one of the ten Nova laser beams (see Table 3.2) into a superlaser beam [558, p.25], [575]. As can be seen in Table 4.1, it is the most powerful laser ever built [547], that overtook the French 55 TW superlaser P102 [542, p.917] which was the world leading superlaser until June 1996. Since then, Japan has put a 100 TW laser in operation in April 1997 [554], and the United Kingdom a 200 TW one in January 1998 [559], after transforming one beam of the Vulcan laser into a superlaser.

In France, the 55 MW superlaser (which now operates at a power of about 80 TW) was the result of adapting the CPA method to P102, a small-scale laser able to produce 100 J [541]. In Japan, similarly, an obsolete laser has been transformed into a 100 TW superlaser, and added as the 13th beam to the GEKKO-XII laser system [554].

The whole subject of superlaser research and development is presently a domain of very intense activity. New institutes and specialized laboratories have been created in several countries. For example, the *Center for Ultrafast Optical Science* at the University of Michigan, the *Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie* (MBI) in Berlin Adlershof, the *Centre Lasers Intenses et Applications* in Bordeaux (CELIA), or the *Advanced Photon Research Center* (APRC) near Osaka. As shown in Table 4.1, all the most advanced industrialized countries have now superlasers with powers of at least 10 TW in operation, and 100-1000 TW superlasers under construction. In Germany, the atomic and plasma physics departments of *GSI Darmstadt* have started a petawatt high-energy ND:glass laser project — PHELIX — as a joint venture together with

[83] This limit is the maximum possible stored energy (complete population inversion) divided by the minimum pulselength (the reciprocal of the gain bandwidth), for a beam of 1 cm^2 cross-section.

[84] They are called *super*lasers because their interactions with matter are qualitatively very different from those of ordinary lasers.

the *Lawrence Livermore National Laboratory* and the *Max Born Institute* in Berlin [564].[85] Offering pulse energies up to 5 kJ in nanosecond pulses or alternatively petawatt peak power in pulses of less than 500 femtoseconds PHELIX will be among the leading laser facilities. The ground-breaking ceremony of the PHELIX superlaser took place on December 7th, 1999, the month that the construction of the laser building has started [574].

In the new institutions, the emphasis is on new generations of high-energy superlasers. These superlasers use a broadband amplifying medium such as *Ti:sapphire* to produce multiterawatt pulses of femtosecond duration at a repetition rate of a few Hz to several kHz.[86] Using this technique, Germany will soon have a 100 TW superlaser [561, p.7]. Moreover, in collaboration with the University of California at San Diego, MBI is working at decreasing the pulselength and increasing the energy of an already existing (2.5 mJ, 30 fs) *Ti:sapphire* laser which has a repetition of 1 kHz [557]. Using similar techniques, the Japan Atomic Research Institute is working on a 30 fs, 1000 TW, superlaser to be operational at APRC in year 2000 [552].

Throughout this report, we have already mentioned a number of fourth generation nuclear weapons's applications of superlasers. We now review them briefly, together with some additional ones, following the rise in the curve shown in Fig. 4.4, which gives the "electron quiver" energy (i.e., the oscillation energy of an electron in the laser electromagnetic field) as a function of the laser intensity:[87]

• *Generation of x-rays*: Superlasers can be used to generate x-rays with submicron spatial resolution and sub-picosecond temporal resolution, e.g., [538, 549]. Such ultrafast pulses can be used for x-ray tomography, imaging, and other diagnostics of fast processes such as the implosion and burn of ICF pellets.

• *Study of metallic hydrogen*: See section 4.6 and [558, p.28]. Metallic hydrogen is potentially the most powerful chemical explosive conceivable.

• *Excitation of nuclear states*: See section 4.5 and [532, 362]. Superlasers are needed to pump isomeric nuclear states for gamma-ray lasers, energy storage, and new military explosives. When used to excite the first isomeric state of ^{235}U, superlasers may lead to a very effective and compact technique for 100% uranium

[85] Since Germany in a non-nuclear-weapon State, it is politically very disturbing that this project will be done in collaboration with the *Lawrence Livermore National Laboratory* (LLNL), and that there will be a "cooperation agreement" between GSI and LLNL (see [564, p.60]) that will be very similar to those LLNL has with the French and British nuclear weapons laboratories.

[86] In comparison, high-energy *Nd:glass* superlasers repetition rates are limited to a few pulses per hour, because of the necessity to let the amplifiers cool down in between successive pulses.

[87] There are of course many non-military applications of superlasers. An overview can be found in several recent review papers [542, 544, 558, 560, 577].

enrichment in one stage [528].

• *Electron and ion acceleration*: The possibility of accelerating particles with a focussed laser beam was discussed in 1970 already [526]. In particular, electrons can be accelerated to MeV energy over extremely short distances. The accelerated electrons have a low energy spread and are narrowly collimated in the laser propagation direction [548]. This effect has now been observed and opens the way to a number of applications: ultra-compact particle accelerators, electro-fission of fissile materials, heating of small pellets ("fast ignitor"), etc.

• *Focusing of charged-particle beams*: A 1-ps laser pulse produces an electric field of about 100 GV/m. Such a field can be used to very precisely focus a beam of charged particles on a very small spot [534]. This technique can be used, for example, to direct an intense beam of antiproton at a very small target.

• *Hole boring and ultra-high magnetic field generation*: At an intensity of 10^{19} W/cm^2 the light pressure[88] of a beam focussed on a target, $p_L = 2I/c \approx 6$ Gbar, is much higher than the material ablation pressure. Hence, while the light pressure is negligible relative to the ablation pressure in low intensity laser-matter interactions, the opposite is true in superlaser-matter interactions. The consequence is that the beam is boring a channel through the plasma by ejecting the electrons from it much faster than the matter (i.e., the ions) can move hydrodynamically [540]. As relativistic electrons are set into motion by the pulse, magnetic fields up to 100 MG are generated [545]. These fields survive after the laser pulse has passed and will decay over some 100 ps. Such magnetized channels could be used to collimate and direct streams of particles, such as pions or muons from antimatter annihilation [293, 539].

• *Fast ignition of ICF*: Superlasers enable a two step approach to ICF similar to the "sparkplug" ignition of a cold compressed fuel in H-bombs [543, 547, 551, 553, 555, 578]. The proposed "fast ignitor" scheme is as follows: First, a capsule is imploded as in the conventional approach to inertial fusion to assemble a high-density fuel configuration. Second, a hole is bored by a superlaser through the capsule corona composed of ablated material, as the critical density[89] is pushed closer to the high-density core of the capsule by the ponderomotive force associated with high-intensity laser light. Finally, the fuel is ignited by suprathermal electrons, produced in the high intensity laser-plasma interactions, which then propagate from the critical density region to the high-density core, heating the center of the pellet. This new scheme enables a factor of 10–100 reduction in total driver energy; it also

[88] The ponderomotive pressure of a light beam is given by momentum conservation as $p_L = 2I/c$ for completely reflected light, and $p_L = I/c$ for completely absorbed light.

[89] This density refers to the electron density responsible for the cut-off frequency above which a laser beam is reflected instead of being transmitted.

drastically reduces the difficulty of the implosion, and thereby allows lower quality target fabrication, and less stringent beam quality and symmetry requirements from the implosion driver [543, p.1626].

• *Optically induced thermonuclear fusion*: The first thermonuclear neutrons in laser irradiation of matter were observed in 1968 in Russia by focusing a 20 J, 20 ps laser pulse on a lithium-deuterid target [524]. The experiment was repeated in the USA but there was considerable debate about the thermal origin of the neutrons [525]. Today, it is understood that some of the observed neutrons were not thermonuclear-produced [527], but that the phenomenon can be interpreted as a rudimentary example of a "fast ignitor": the laser energy was partially transferred to high energy ions which induced suprathermal fusion reactions, and partially to high energy electrons which heated the target to thermonuclear temperatures and lead to some thermal fusion reactions. However, the *first unambiguous experiment* in which an ultrashort laser pulse was used to produce fusion reactions has been carried out in 1997 at the Atlas facility (see Table 4.1) of the *Max-Planck-Institut für Quantenoptik*, in Garching, Germany [562]. In this experiment, deuterium ions accelerated in a channel produced by the Atlas superlaser induced DD fusion reactions, thereby demonstrating that a new class of table-top devices were able to trigger substantial amounts of nuclear reactions. Using a different method, nuclear fusion from a table-top superlaser irradiated deuterium plasmas has been confirmed by LLNL scientists in an experiment published in April 1999 [567, 568]. Previously, another team of LLNL scientists showed that high-fluxes of DT fusion neutrons are produced with high efficiency when a thin tritium-frost layer on a deuterium-ice substrate is irradiated by a 'Petawatt' superlaser beam pulse [563].

• *Optically induced nuclear fission*: See section 4.2 and [537, 536]. The high energy electrons and the x-rays generated by focusing a superlaser pulse on a fissile target can induce electro-fission and photo-fission reactions. This mechanism can be used to start a neutron chain-reaction, or to provide initial neutrons for subcritical burn, in a highly compressed pellet of fissile material. Recent calculations show "that *already available* laser intensities are sufficient for producing, through a specially arranged cascade of processes, practically useful ultra-short-pulse, high-flux nuclear radiation with possible applications in material science, medicine, and nuclear engineering" [556]. Moreover, optically induced fission can be used to enhance the performance of fast ignition of an ICF pellet. Instead of just heating the compressed fuel, fast electrons generated by the superlaser can be used to fission a small piece of fissile material located at the center of the pellet, thereby multiplying their heating effect by a factor of 10 to 100 [123, p.140]. The configuration would then be almost identical to that of the H-bomb depicted in Fig. 1.3, with the sparkplug replaced by a small inclusion of fissile material (see Fig. 4.5). The optical stimulation of nuclear fission has been demonstrated by

LLNL scientists using the 'Petawatt' [569, 572] and by British scientists using the Vulcan superlaser [571].

• *Nuclear weapons physics*. In 1985, C.K. Rhodes of University of Illinois at Chicago predicted: "Intensities comparable to thermonuclear environments ($\approx 10^{21}$ W/cm^2) appear to be possible with pulselengths in the 100 fs range containing about 1 J of energy" [531, p.1348]. In 1995, the technology being available, and the 'Petawatt' laser under construction, M.D. Perry of LLNL was able to confirm: "At 10^{21} W/cm^2, the energy density of the pulse is over 3×10^{21} J/cm^3, which corresponds to a 10 keV blackbody and an equivalent light pressure of 300 Gbar" [542, p.917]. Looking at Fig. 3.3, one can see that these temperatures and pressures are well *within* the nuclear weapons-test regime. This is confirmed in the LLNL 1995 Annual Report: "Such high-energy fluxes [...] will allow researchers to measure in the laboratory important material properties at conditions *similar to* those that occur in the operation of a nuclear weapon" [546, p.29]. Therefore, whereas standard lasers like the NIF "will enable opacity and EOS measurements to be performed under *close-to*-secondary condition" [21, p.49], superlasers like the 'Petawatt' will enable such measurements to be performed under true thermonuclear weapons conditions.

• *Production of positrons, pions and antimatter*: See section 4.4 and [301, 547, 333]. While existing superlasers are sufficiently intense to produce electron-positron pairs [556, 333], they will be marginally capable to produce pions at their highest intensity. Future CO_2 superlasers operating close to the laser intensity limit will produce copious amount of proton-antiproton pairs much more effectively that the huge particle accelerators that are used today for this purpose [274, 301].

The novelty and the potential of superlasers are such that major advances can be made in any country sufficiently developed to master the sophistication of the underlying technology. For example, German scientists were the first to report the unambiguous production of neutrons from fast deuterium-deuterium fusion reactions initiated by ultrashort laser pulses [562].

Superlasers are an example of a breakthrough that is the result of pure technological innovation. It was known since many years that one day a way would be found to go from the 10^{14} W/cm^2 standard laser intensity to the 10^{20} W/cm^2 range because there is no *fundamental* obstacle until the laser intensity limit of 10^{24} W/cm^2 is approached.[90]

Superlaser induction of nuclear fusion and nuclear fission [567, 568, 569], as

[90] In contrast, developments such the discovery of shape isomers, or the synthesis of superheavy elements, are *scientific* breakthroughs. They now need important technological innovations to find practical uses.

well as superlaser production of matter-antimatter pairs [569], has been a highlight of the American Physical Society centennial celebration in March 1999 [566, p.35].

The LLNL superlaser 'Petawatt' was closed down in May 1999. However, superlaser research at LLNL continues with JanUSP, a significant upgrade of Janus, an over twenty years old ultrashort-pulse laser [576]. Although JanUSP has only a fraction of the power and energy of 'Petawatt,' it enables research begun on 'Petawatt' to continue in a different regime of laser matter interaction, until one (or several) much more powerful superlaser(s) will be installed on one (or several) beamline(s) of the National Ignition facility (NIF).

According to its 1999 annual progress report, the petawatt superlaser under construction at the Institute of Laser Engineering at Osaka University should be terminated in August 2001. At this date, Japan should therefore operate the most powerful superlaser in the world [573, p.I].

Apart from their many actual and potential uses in nuclear weaponry, either offensive (in warheads) or defensive (in ballistic missile defense [57]), superlasers have many applications in physics, chemistry, biology, medicine, and digital optical technology — and they may even prove practical in the decommissioning of weapons [577]. The future will show if the development of the superlaser is really one of the most important invention of the past decade. In any case, as is suggested in a comprehensive review of laser science and technology, the superlaser may well be the signal that the industrial civilization has definitely entered, for better or for worse, the *"Age of the photon"* [561, p.7].

4.9 Technology of fourth generation nuclear weapons (Fig. 4.5)

In this report the emphasis has been on scientific principles rather than on technology. This means that in order to appreciate the *technological distance*[91] of fourth generation nuclear weapons, we would need to review all the obstacles that may delay or prevent their realization. This would be difficult, especially since an appreciation of this kind strongly depends on political and economical factors as well as on science and technology. In this section we mention a few of the most important technological factors.

While fourth generation nuclear weapons will make use of a number of new

[91] That is, the time, cost, and difficulty which separates the hypothetical weapon from its manufacturing and deployment.

concepts (e.g., magnetized [146] or metallized [413] fuels, atomic or nuclear isomerism [362], antimatter [304, 292], etc.), they will also make extensive use of more classical concepts, such as *electromagnetic energy cumulation*[92] and *staging* (by which chemical or electrical energy from a compact source will be amplified to a higher yield and then used to trigger an even larger yield). For instance, in a conventional explosive, staging refers to the ignition of a large quantity of a relatively insensitive high-explosive (the secondary, TNT, for example) by a small quantity of primary explosive (the detonator, lead azide, for example). But staging can be applied to cascades of thermonuclear explosions of increasing power [131, 162], or to current amplification in a Z-pinch [494], etc.

Staging is the key concept that will allow miniaturization and "weaponization" of fourth generation nuclear weapons. As already mentioned, small plutonium or fusion-fuel pellets can be strongly compressed by various types of beams or by magnetic implosion, as in antimatter-boosted microfission experiments [304]. Either way, the question is whether it is possible to build a compact (but single use) device that can replace the huge accelerator, laser, capacitor bank, or magnet that is necessary for laboratory implosion of fusion or fission pellets.

A general method for this purpose uses chemical explosives as the primary energy source.[93] This is a well known technique in the case of magnetic flux compression, where large magnetic fields are generated in rather compact explosive-driven devices [491, 497]. But this technique can also be applied to lasers: a highlight of a 1991 international workshop at the Naval Postgraduate School, Monterey, California, was the first disclosure of a Russian chemical-explosive-driven megajoule laser by N.G. Basov [583].

An important aspect of staging is that it may involve the combination of several techniques which, at first, may be considered foreign to one another. This is concept behind the development of *hybrid* systems. An example is to combine high-explosive implosion with laser implosion. In fact, the idea of laser compression with a high-explosive pre-compression was developed and experimentally tried in Poland between 1972 and 1975. In these experiments, a pre-compression on the order of 10 was achieved by the high explosives, a further compression on the order of 5.5 was achieved with a two-beam laser system producing two opposite laser pulses, giving a total compression in the range 50 to 60 [581]. Another

[92] For an overview and introduction to energy cumulation processes, see [480, 481].

[93] While chemical explosives have specific energies on the order of 5 MJ/kg, and chemical super-explosives possibly on the order of 200 MJ/kg, emerging technologies such as *rechargeable* thin-film batteries and superconducting rings have specific energies on the order of 1 to 50 MJ/kg. An advantage of the latter systems, in which energy can be stored just before use, is that they are potentially much safer than chemical explosives.

example is to use of a powerful laser in combination with a dense plasma focus [501], or with a dense Z-pinch [522], etc.

The ultimate technique in staging consists in using a very small amount of nuclear isomer, metallic hydrogen, superheavy nuclei, or antimatter as the primary. Such materials are far too expensive and precious to be used as the main charge of an explosive[94] or the main fuel of a rocket [293, 309, 311]. In fourth generation nuclear weapons, the crucial advantage of antimatter is that it delivers a very large pulse of energy by simple contact with ordinary matter: there is no need for a big laser or any other bulky device. Picogram to microgram amounts of antiprotons are sufficient to initiate a chain-reaction or subcritical burn in a highly compressed pellet of fissile material [304] (or of a mixture of fissile and fusion materials [311]), or to initiate fusion burn [292, 296] or drive ablative compression [309] of a fusion pellet. Moreover, an even smaller amount of antiprotons could be enough to detonate a tiny amount of superheavy or other exotic material.

Hence, a number of techniques are available which have the potential to be used as the first stage of compact low-weight fourth generation nuclear weapons. The second stage may then be a powerful x-ray source, i.e., an exploding plutonium pellet, the third stage a more powerful thermonuclear fuel pellet, etc.

Fourth generation nuclear weapons may develop along two main paths. The first would be based on magnetic compression and could lead rather quickly to some "weaponizable" concept based on the Los Alamos – Arzamas-16 research on high-explosive-driven pure-fusion explosives [496, 497]. A similar rather near-term prospect exists for the antiproton-triggered subcritical fission explosives studied at Phillips Laboratory [304]. Such explosives would have total masses in the 10 to 100 kg range.

The second major path would be based on exotic materials and more advanced concepts. Although difficult to believe, this route points towards science-fiction-like "atomic bullets," which could weigh much less than 1 kg. Such fourth generation nuclear weapons would have yields between 1 and 10 *tons* equivalents of TNT. The central component of these weapons will most probably be an ICF pellet of the type sketched in Fig. 4.5, i.e., an indirect-drive pellet in which high compression and fast ignition is achieved by a two-step process similar to the "sparkplug" ignition concept used in early hydrogen-bombs.

The engineering of fourth generation nuclear weapons will make extensive use of *nanotechnologies* and of various miniaturization techniques which are being developed, in particular, for ICF diagnostic devices [590, p.13] and ICF target construction. Indeed, ICF target technology is extremely sophisticated [582, 148].

[94] Pure antimatter bombs would not only be very expensive, they are likely to be very unsafe.

Much of it is classified,[95] as much because of its military potential, as because of its future impact on industrial technologies.

Nanotechnology is certainly one of the most important emerging non-nuclear military technologies [585][96], [586][97], [587][98], [588][99]. It is crucial to fourth generation nuclear weapons in two respects: (i) Nanotechnology and microtechnology will enable the fabrication of very small mechanical assemblies (such as sub-millimeter-size microtraps for antiproton storage); and (ii) the production of very-fine-grain "super-plastic" materials[100] will enable the fabrication of very small components with highly predictable behaviors under stress (as a result of their well characterized metallurgical properties).

The techniques of mass production of fourth generation nuclear weapons will be similar to microcomputer manufacturing techniques. Since they will contain only small amounts of expensive special materials, their cost will be low. Their small size and weight will make them suitable for delivery by artillery or tank shells, cluster bombs, small missiles, drones, mini cruise-missiles, etc.

Designing and producing a cost-effective and operationally robust fourth generation nuclear weapon that would be attractive to the military is a formidable

[95] According to [148, Chap.X, p.229], the first unclassified paper on the subject was published by an Israeli scientist [580].

[96] This report is a good introduction to Micro-Electro-Mechanical Systems (MEMS).

[97] This documented briefing concerns seven emerging technological areas, i.e., biotechnology and bioengineering, micro- and nano-technologies, advanced energy and power technologies.

[98] At the Fourth Foresight Conference on Molecular Nanotechnology in November of 1995, the closing address by Admiral David E. Jeremiah, USN (Ret), former Vice Chairman of the Joint Chiefs of Staff, was a perfect example of today's post-nuclear military rhetoric:

"The [battlefield of the future will be dominated by] smart weapons that will allow us to reduce wholesale destruction and the tremendous expenditure of ordnance. The goal is finer and finer precision, more and more selectivity and less need for mass. Indeed, there is less need for weapons of mass destruction because they are increasingly less useful to us for military characteristics. Weapons of mass destruction are political tools used by one nation to influence the population of another, not tools we in the military need to carry out military operations. [...] Military applications of molecular manufacturing have even a greater potential than nuclear weapons to radically change the balance of power" [587, p.15–16].

[99] In a note to the preface of a collection of articles on nanotechnology, the editor (B.C. Crandall) cites the flyer he distributed at the Palo Alto conference on nanotechnology in November of 1991:

"The current 'reality' of Western culture is militaristic capitalism. Missile systems receive far more funding than prenatal health care and education (let alone general education). In the next few decades, a nanotech research and development lab will be within the means of many cultural groups who feel that their need to impose particular values (memes) warrants the violent abrogation of the life and the freedom of others. Their options are frightening, including diamondoid tanks, designer viruses, and unimaginably thorough surveillance. Despite the inherent dangers, open development seems the only viable course of action" [588, p.193].

[100] Such materials are a remarkable achievement of the Chelyabinsk-70 weapons laboratory [589].

engineering task. But it is not out of proportion with what has been achieved in the past decades in several areas of high technology. The danger is precisely that there are no obvious fundamental scientific obstacles,[101] and that the engineering problems might be overcome before a thorough discussion of the need and purpose of these weapons has taken place.

[101] In this relation we stress again the importance of the discovery of the superlaser. The fact that this device enables the production of *nuclear* reactions merely using a light source is emphasized in a recent comprehensive review of the scientific and technological potential of superlasers [570, 571].

Superlasers					
Name	Location	Energy [J]	Duration [ps]	Power [TW]	Intensity [W/cm^2]
USA					
Petawatt	LLNL	1000.00	20-0.500	1000.0	$> 10^{21}$
JanUSP	LLNL	15.00	0.085	200.0	$2\ 10^{21}$
	UM, Ann Arbor	3.00	0.400	4.0	$4\ 10^{18}$
Trident	LANL	1.50	0.300	5.0	$> 10^{19}$
	UC, San Diego	1.00	0.020	50.0	
LABS II	LANL	0.25	0.300	~ 1.0	$1\ 10^{19}$
	UM, Ann Arbor	0.07	0.025	3.0	
	WSU, Pullman	0.06	0.026	2.0	
UK					
Vulcan	RAL	1000.00	1.000	1000.0	Design
Vulcan	RAL	180.00	1.000	200.0	$1\ 10^{20}$
Astra	RAL	1.00	0.100	~ 10.0	
Titania	RAL	1.00	0.400	~ 2.5	
Sprite	RAL	0.25	0.380	~ 0.7	$4\ 10^{17}$
Japan					
Petawatt	ILE	1000.00	1.000	1000.0	Design
PW-M	ILE	50.00	0.500	100.0	$> 10^{17}$
Petawatt	APRC	30.00	0.030	1000.0	Design
	RIKEN	0.05	0.500	~ 0.1	$1\ 10^{17}$
France					
Petawatt	CESTA, Bordeaux	1000.00	1.000	1000.0	Design
P-102	CEL-V, Limeil	50.00	0.500	80.0	$> 10^{19}$
	LOA, Palaiseau	0.80	0.030	30.0	$5\ 10^{19}$
	LOA, Palaiseau	0.03	0.100	~ 0.3	$1\ 10^{18}$
ELIA	U. of Bordeaux	0.01	0.010	1.0	$1\ 10^{18}$
Germany					
PHELIX	GSI, Darmstadt	1300.00	0.420	~ 1000.0	Design
Ti-Nd	MBI, Berlin	10.00	0.100	~ 100.0	Constr.
ATLAS	MPQ, Garching	5.00	0.100	~ 100.0	Constr.
Ti	MBI, Berlin	0.30	0.032	~ 10.0	$< 10^{19}$
ATLAS	MPQ, Garching	0.80	0.130	~ 5.0	$< 10^{18}$
	IOQ, Jena	0.22	0.110	~ 2.2	$< 10^{18}$
Russia					
Progress-P	St. Petersburg	55.00	1.500	~ 30.0	$1\ 10^{19}$
China					
BM				~ 3.0	

Table 4.1: Major operating or planned superlaser facilities

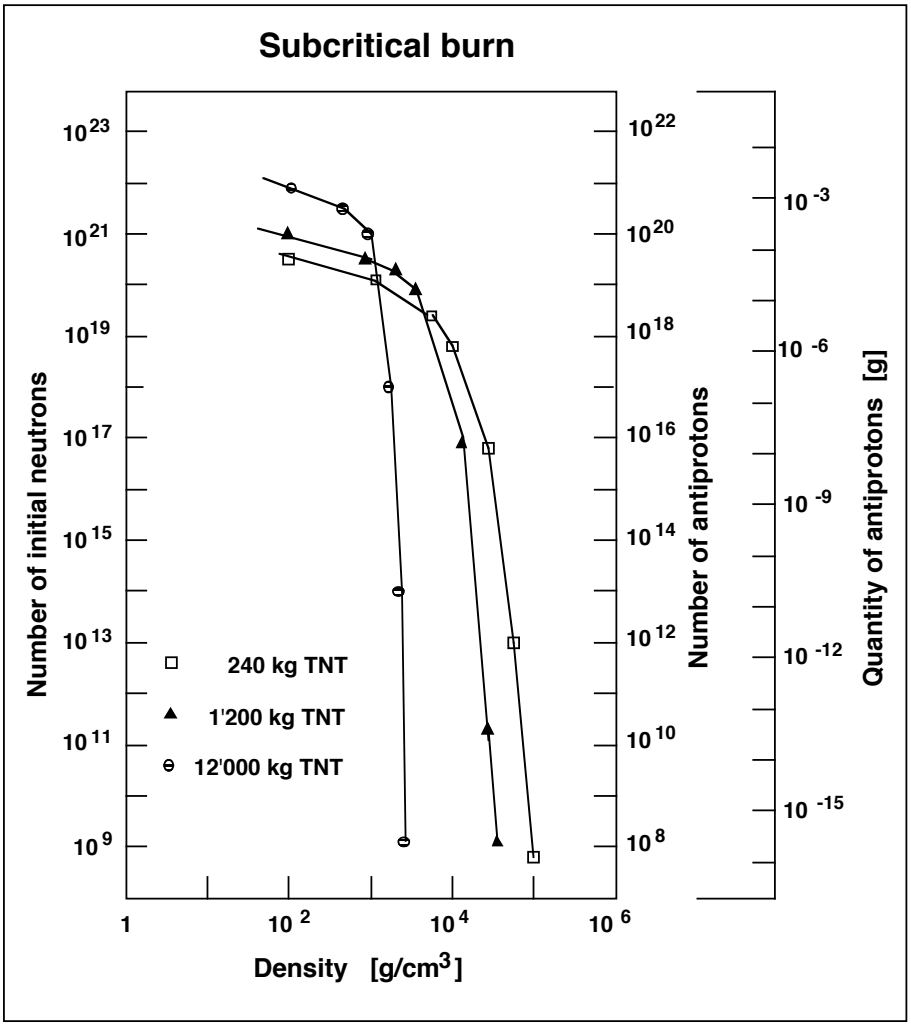

Figure 21 Dependence of the number of initial neutrons (or antiprotons) required for a 100% burn versus the final pellet density for three pellet sizes.
Adapted from R.A. Lewis et al., Nucl. Sci. Eng., Vol. 109 (1991) p. 413.

Figure 4.1: Figure 21

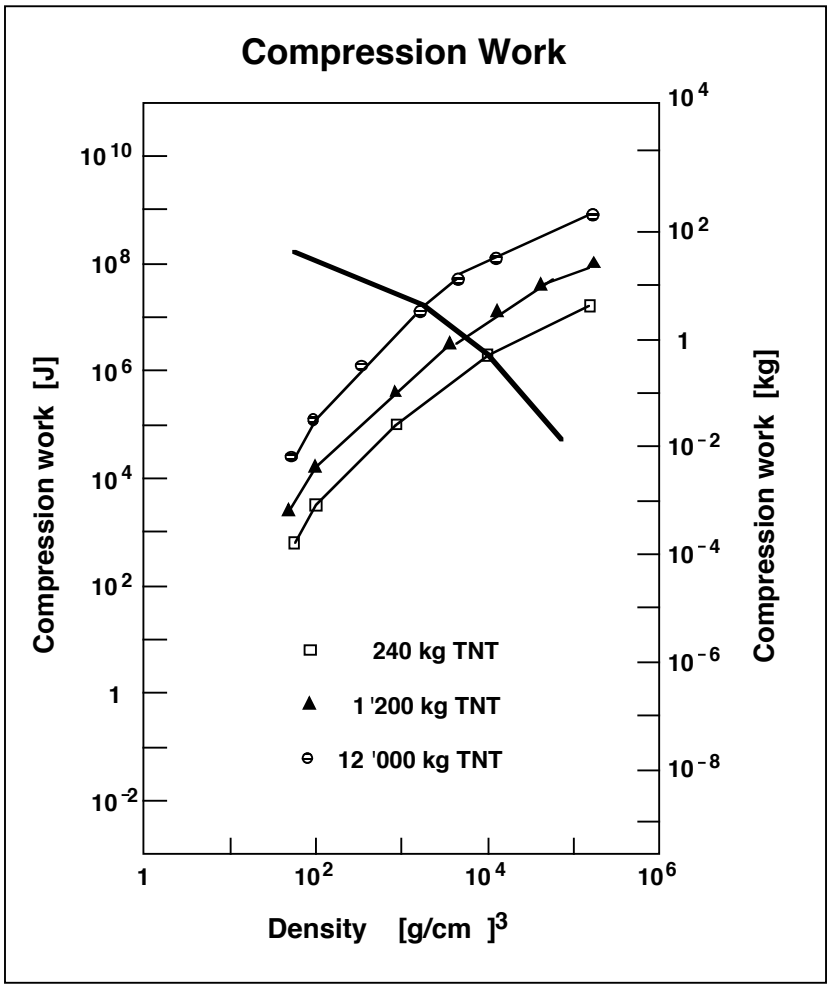

Figure 22 Compression work (in Joule or kilogram equivalent of high-explosives) related to the final pellet density for three pellet sizes (14, 70 and 700 milligrams of plutonium). The curve indicates the boundary between the critical and the subcritical regimes.

Figure 4.2: Figure 22

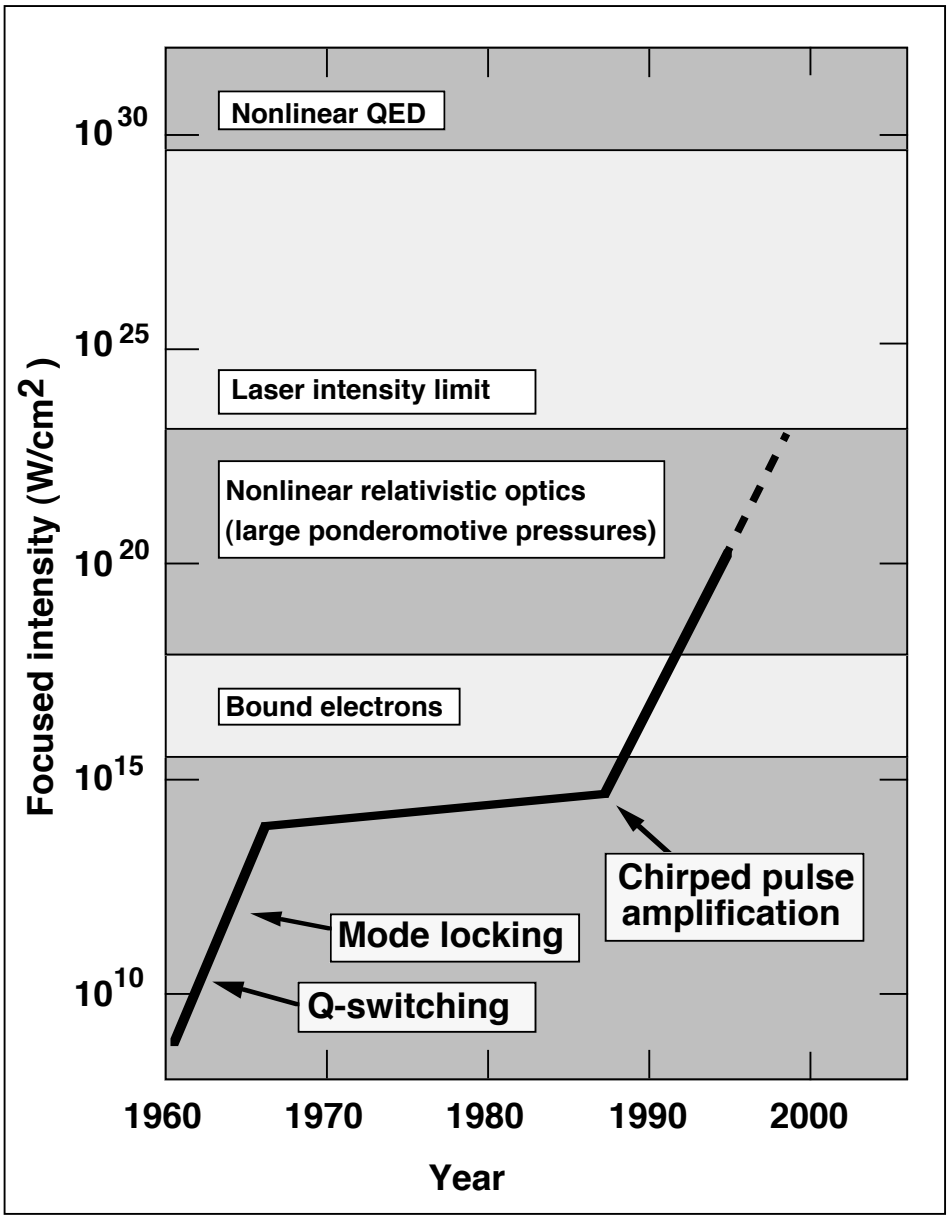

Figure 23 Laser intensity versus year for tabletop systems. Over the past decade the intensity has increased by a factor of one million. *Adapted from G. Mourou et al., Physics Today (January 1998) p. 25.*

Figure 4.3: Figure 23

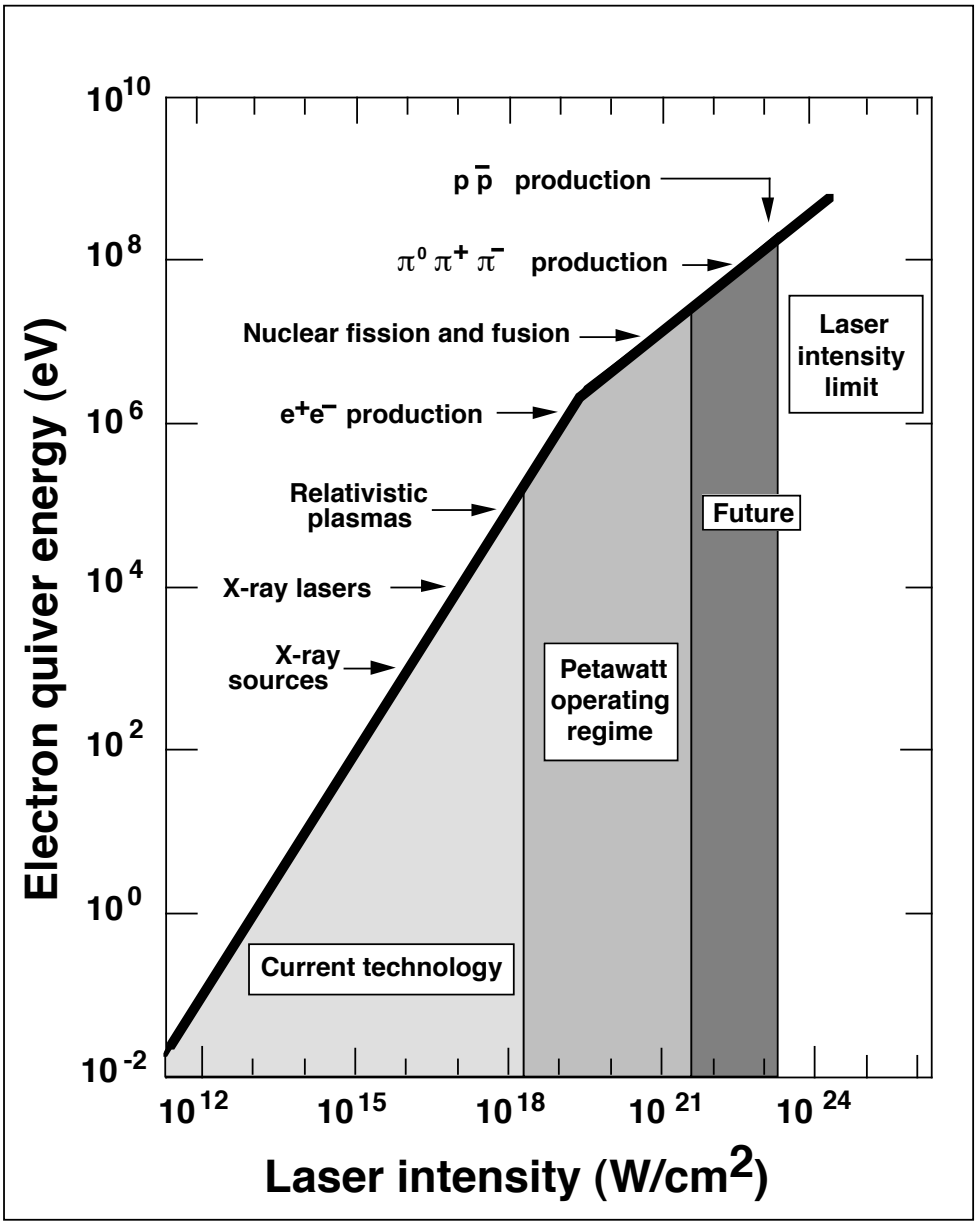

Figure 24 Electron quiver energy and accessible phenomena as a function of *Nd:glasss* laser intensity. The quiver energy is the cycle-averaged oscillatory energy of free electrons in the laser field. The break at 10^{19} W/cm^2 corresponds to quiver energies on the order of the electron mass, i.e., to the beginning of the relativistic regime characteristic of superlasers. The 10^{23} W/cm^2 threshold intensity for proton-antiproton pair production assumes a CO_2 laser. *Adapted from M.D. Perry and G. Mourou, Science (14 May 1994) p. 918.*

Figure 4.4: Figure 24

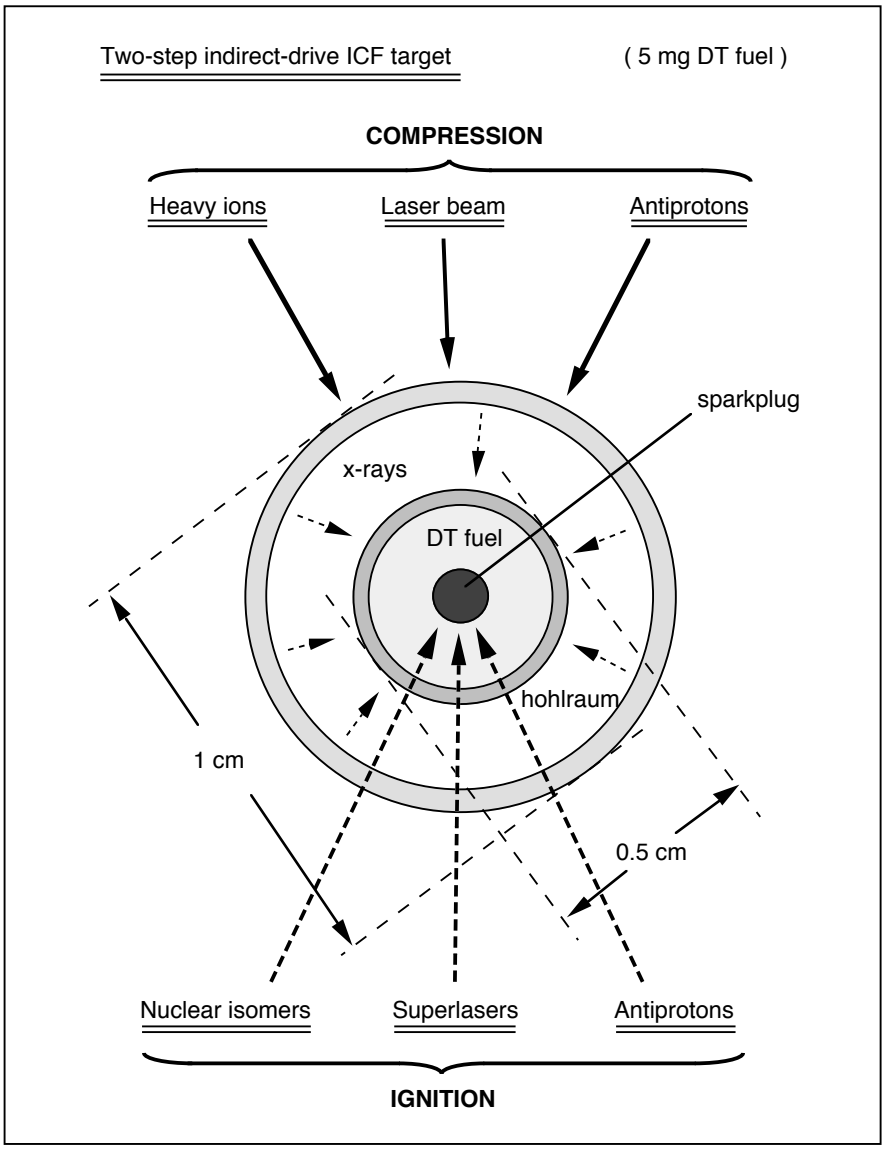

Figure 25 The most promising indirect-drive ICF targets achieve high compression and fast ignition by a two-steps process similar to the "sparkplug" ignition concept used in early hydrogen-bombs.

Figure 4.5: Figure 25

Chapter 5

Conclusion

According to Theodore B. Taylor, the 1950s have been the "Golden Age" of thermonuclear weapons *development*. The fundamental breakthroughs of "boosting" and "radiation driven implosion" led to the second generation of nuclear weapons which are today the backbone of the nuclear arsenals of all nuclear powers.

On the other hand, many developments initiated in the 1960s and pursued until the late 1980s, "the special-effect weapons — low fission yield, enhanced neutron, and hot x-ray devices — for possible use in peaceful activities (Plowshare), enhanced radiation effects (the neutron bomb), and antiballistic missile (ABM) systems" [20], never became part of a third generation of nuclear explosives because they never found any truly convincing civilian or military use.

Therefore, since 1965, nuclear arsenals evolved slowly, with a major trend towards increased safety and reliability [20], together with a considerable decrease in the number and yield of warheads deployed by the two superpowers.

In the meantime, despite the entry into force of treaties, such as the Nuclear Non-Proliferation Treaty (NPT), which prevent the spread of nuclear *materials* and sensitive equipment, the knowledge and skills of nuclear and thermonuclear weapons *science* and *technology* have spread dramatically[1]. The ultimate step in this direction is the current enthusiasm about ICF as a potential energy source,[2] a

[1]This can be seen by looking at the proceedings of the many international conferences where sensitive subjects on the borderline of classification are discussed. For example, in the 1993 *Laser interaction and related plasma phenomena workshop* [152], it is striking to see (in the section devoted to target physics, pages 325–361) how little could be said by scientists from U.S. weapons laboratories (before the Department of Energy "openness initiative of December 1993) compared with what was said by outsiders from Australia, China, Israel, or Spain.

[2]See, for example, the enthusiastic response [161] of a European Union-appointed working party to the U.S. Government declassification act of December 1993 [22, 23].

drive which in many ways resembles the 1950s optimism about nuclear energy[3] and "peaceful nuclear explosions."

As a result, many technologically sophisticated countries (and, in particular, Germany, India, Israel, Japan, and Pakistan which have highly developed nuclear infrastructures) are today in a good position to make not only atomic bombs but also hydrogen bombs that could be built and delivered with a very high probability of success. This is a first major conclusion of this report.[4] Indeed, in May 1998 (eight months after the first edition of this report was published), India claimed to have tested an advanced hydrogen bomb concept.

In effect, both the theoretical arguments presented in this report and the numerical results obtained by simulating some crucial phenomena with the ISRINEX computer program, clearly show that the principles of megaton-yield hydrogen bombs are much simpler and easier to implement than generally assumed. In fact, these principles are so simple that a country such as Japan, which has the second most powerful ICF facility in the world, is in a far better position today than the United States in 1952 to make a hydrogen bomb. There is little doubt that if Japan decides to build such a bomb, it would work without failure, even without any previous atomic test. This situation follows directly the possibility of studying thermonuclear weapons physics in the laboratory by means of ICF microexplosion systems, a widespread technology that is neither covered by the NPT nor the CTBT [8].

A similar analysis applies to "boosting." Indeed, numerical simulations with ISRINEX enabled us to find that *tritium-boosting* of fission bombs is far easier than is usually thought. In fact, the physics is such that the most difficult part of boosting is the implosion of a thin shell of fissile materials by means of chemical explosives. Thus, the most important aspects of boosting can be tested completely without actually starting fission or fusion reactions and can therefore be done outside of the scope of the CTBT.[5] In May 1998, both India and Pakistan showed

[3]One should keep in mind that the problems of building thermonuclear fusion power reactors, which are mostly of an engineering type, are considerably greater than those of building ordinary nuclear fission reactors.

[4]This conclusion is in agreement with the U.S. Department of Energy Office of Arms Control and Nonproliferation statement that: "Regardless of access to the NIF or any other ICF facility, one cannot rule out that a technologically advanced country would be able to field a very conservatively designed thermonuclear weapon that would present a credible threat without nuclear testing" [158, p.27].

[5]This is not in contradiction with the fact that experiments with an inert nonfissioning pit, which are allowed under a CTBT, would possibly not be sufficient to insure that an alteration of the primary of an *existing* device would remain adequate to trigger the secondary explosion [20, p.309].

that they had successfully developed boosted fission weapons.

Moreover, using tritium-boosting, it is possible to fabricate highly efficient, reliable, and safe nuclear weapons in which *reactor-grade plutonium* is the fissionable material. The main price to pay for using reactor-grade instead of weapon-grade plutonium is that weapons made with such low-grade plutonium are somewhat more difficult to fabricate and handle, and have a relatively shorter shelf-life, so that they cannot be assembled and kept in storage for long periods before deployment and use.[6] Otherwise, they are militarily as significant as any other fission weapons and clearly show again the dangerous links that exist between the civilian and military uses of nuclear energy. Two of the five devices tested by India in May 1998 are believed to have used plutonium that was not classified as weapons grade.

The relative ease of boosting and its possible use in conjunction with reactor-grade plutonium to make simple but highly effective fission weapons is a second major conclusion related to the *horizontal* proliferation implications of ICF technology. In effect, tritium-filled ICF target construction requires the mastering of tritium technology, and micro-explosion fusion ignition studies provide all the necessary physics background for detailed simulations of the fission weapon's boosting process.

Concerning the *vertical* proliferation impact of ICF, the first conclusion to emphasize is that laboratory scale thermonuclear explosions will enable the scientists to push the understanding of the physical processes on which thermonuclear explosives are based much beyond what would have been possible with continued full-scale testing alone. The technical reasons for this conclusion have been developed at length in chapter 3 of this report.

Another major conclusion related to both the vertical *and* horizontal proliferation impact of ICF is that the new insight gained with ICF is providing a way out of the "tyranny of the critical mass" — the fact that until recently, the only way to acquire a nuclear or thermonuclear weapon arsenal, was to first acquire a large stock of expensive fissile materials, a few kilograms of which is needed for every weapon.

The "tyranny of the critical mass" had one positive aspect: access to fissile materials was the biggest obstacle to horizontal proliferation of nuclear weapons. Its negative aspect, however, from a military point of view, was that existing nuclear weapons have proved far too powerful to be useful militarily — apart from providing some degree of deterrence against "rational" potential enemies.

[6]These problems are due to the higher radioactivity of reactor-grade plutonium relative to that of weapon-grade plutonium.

The new types of weapons that will result from extensive ICF research will be *fourth generation nuclear weapons*, i.e., explosive devices based on atomic and nuclear processes that are not restricted by the CTBT. Considering that existing high-yield thermonuclear weapons will remain the principal component of strategic arsenals for quite some time, it is likely that the first fourth-generation nuclear weapons to be developed will be highly miniaturized explosives with yields in the 1 *ton* to 1 *kiloton* range, i.e., within the gap that today separates *conventional* from *nuclear* weapons.

These new weapons will use either fusion or fission fuels as their main explosive charge. In the latter case, the fission process will be used in the *subcritical* mode, i.e., in a nuclear-fission yield-generation mode that is *not* forbidden by the CTBT. While subcritical fission-burn is not suitable for making high-yield (i.e., *kiloton* range fission weapons), it is adequate for making fourth generation nuclear weapons with yields in the 1 to 100 *tons* range. For this type of explosive, the currently preferred technique is to use magnetic compression to increase the density of the fissile material (which may consist of low-quality, reactor-grade plutonium) and a very small amount of antimatter to initiate the subcritical burn.

In the case of low-yield nuclear devices using a fusion fuel as the main explosive charge, high-explosive-driven magnetic compression is a rather near-term technology enabling one to realize a pure-fusion explosive with a reasonably good yield-to-weight ratio.

Much better performances may be expected for more sophisticated types of fourth generation nuclear weapons. Such types will make use of a full range of advanced nuclear processes that are currently vigorously being investigated: nuclear isomerism, superheavy elements, antimatter, metallic hydrogen, superlasers, etc. These processes have been reviewed in chapter 4, where it is shown that substantial progress has been made on all of them in the past few years. A particular reason for this progress is that, since the collapse of the Soviet Union there has been considerable synergetic interaction between Western scientists and scientists from the former communist States, both among those working in military laboratories and among those working at universities and non-military laboratories. Moreover, as is also the case with ICF, major industrialized countries such as Germany and Japan are investing considerable resources to remain at the forefront of the development of all advanced nuclear processes.

An important common factor in the research and development of these advanced nuclear processes is that they all rely on similar kinds of high-energy beam technologies, using high-intensity laser or particle beams to produce, manipulate, or implode all sorts of new nuclear species and materials.

Fourth generation nuclear weapons based on such processes, and with yields of 1 to 10 *tons* equivalents of TNT, may weigh less than a few kilograms. Their engineering will make extensive use of nanotechnologies and various miniaturization techniques being developed, for instance, for ICF target construction. Their mass production techniques will be similar to microcomputer manufacturing techniques. Since these weapons will contain only small amounts of expensive special materials, their cost will be low. Their small size and weight will make them suitable for delivery by artillery or tank shells, cluster bombs, small missiles, drones, mini cruise-missiles, etc. The convergence of this development with the decades long "change from the importance of the big bang to the importance of accuracy" was emphasized by Edward Teller in a question written shortly after the *1991 Gulf war*:

> "Shall one combine the newly acquired accuracy with smaller nuclear weapons (perhaps even of yields of a few tons) to be used against modern weapons such as tanks and submarines? " [E. Teller, American Journal of Physics, **59** (October 1991) page 873.]

Whereas current-generation nuclear weapons are one million times more powerful than conventional weapons, fourth generation nuclear weapons may only be a thousand times more powerful. This is more than enough to revolutionize the battlefield: the firepower of conventional weapons will be multiplied by a factor of a thousand or more. Moreover, these new nuclear weapons will *not* qualify as "weapons of *mass* destruction." Therefore, their use will not be in contradiction with the rules of war and with international humanitarian law.

Apparently, no fourth generation nuclear weapon based on non-standard nuclear technologies has been built yet. However, the considerable progress made in the whole field of nuclear physics in the past few years demonstrates that many possibilities that were long considered as speculative are becoming technically feasible. Radically new types of nuclear weapons in which advanced nuclear processes are used may soon become a reality.

In fact, one of the most important *strategic lesson of the 1999 war over Kosovo* is that while existing delivery systems are capable to strike any target with very high precision, the explosive yield of conventional warheads is such that many non-nuclear weapons are needed to destroy a single target. A least ten times less aircrafts, bombs and missiles could have been used in the war against Serbia if each warhead would have been made of an explosive a few hundred or thousand times more powerful than existing chemical explosives.

It is therefore likely that most military powers will continue equipping them-

selves with high precision guided weapons and delivery systems, and that they will at the same time continue developing the scientific and technological basis for making new types of nuclear explosives, which could be produced on short notice in case of need.

In conclusion, we stress that the signing of the CTBT and the implementation of politically-correct programs, such as the Science Based Stockpile Stewardship, might well correspond to the beginning of a new age, the "Golden age" of thermonuclear weapons *proliferation*. If the construction of large ICF simulation facilities (such as NIF in the USA, LMJ in France and others in Japan, Germany, Russia, China, etc.) are not stopped, we will soon witness the emergence of a growing number of "virtual"[7] thermonuclear-weapon States, as well as a proliferation of *fourth generation nuclear weapons*. During the last session of the CTBT negotiations at the Conference on Disarmament, the Ambassador of India, Ms Arundhati Ghose, made the following statement (emphasis added):

> "We have always believed that the objective of a CTBT was to bring about an end to nuclear weapons development. We are all aware that nuclear explosion technology is only one of the technologies available to the nuclear-weapon States. Technologies relating to subcritical testing, advanced computer simulation using extensive data relating to previous explosive testing, and weapon-related applications of laser ignition will lead to *fourth-generation nuclear weapons* even with a ban on explosive testing. It is a fact that weapons-related research and development in these technologies is being promoted. Our objective therefore was a truly comprehensive test-ban treaty, rather than merely a nuclear-test-explosion-ban treaty. For many years, we had been told that a CTBT was not possible because testing was required for the safety and reliability of existing nuclear weapons. We questioned it then and now we know that we were right. Today, underground explosion technology has the same relevance to halting development of new nuclear weapons by nuclear-weapon States as banning atmospheric tests did in 1963. A truly comprehensive treaty should have fossilized the technology of nuclear weapons" [40, p.6].

In this respect, the so-called *comprehensive* test ban treaty[8] will prove not to be a serious disarmament measure, but just an additional legal instrument legitimizing

[7] "Virtual" (or "latent") nuclear proliferation is the development of the technical and industrial *capability* (e.g., by means of "peaceful" nuclear activities) to manufacture nuclear or thermonuclear weapons components and to assemble them on short notice.

[8] The CTBT is not limiting nuclear weapon research and development but only nuclear weapon *yield* tests.

the endless possession and perfection of nuclear weapons by the nuclear-weapons States and a further ambiguous arms-control treaty whose quasi-universal acceptance[9] may be explained by the hope of an increasing number of States[10] to benefit from a possible redistribution of power enabled by further advances in science and technology.

In fact, the arms control problem of fourth generation nuclear weapons is not only that their development circumvents the limitations of the CTBT. The real challenge is that their development is even more closely related to purely *scientific* research than it was for weapons of previous generations. Just as military laboratories are opening themselves more and more to non-military research, fundamental research in most areas of modern science is becoming more and more ambivalent. In the case of fourth generation nuclear weapons, however, the military character of the "civilian" research on which they are based is clear. For instance, the fundamental research, whether in the fields of astrophysics, nuclear, plasma, superlaser, or elementary particle physics, is devoted to understanding extreme states of matter: very high pressures, very high energy densities, very high temperatures, very high powers, or very high energies. If no quantitative or qualitative limit is put on the fundamental research concerned with these asymptotic states of matter, the *dynamics* of technological innovation will make the development of new weapons based on the resulting knowledge unavoidable.

A necessary condition for avoiding such developments (and thus for achieving the true purpose of the CTBT, i.e., to fossilize the technology of nuclear weapons as a first step towards general and complete nuclear disarmament) would be to supplement the existing treaty regime by effective measures of *preventive arms control* [295, 15, 24, 25, 30, 45, 47]. These would include internationally binding restrictions in all relevant areas of research and development, whether they are claimed to be for military or civilian purposes. In particular, any pure or applied research that deals with nuclear fission, thermonuclear fusion, antimatter, or any other nuclear reaction, should be severely limited.

[9]The letter of the NPT only forbids the *manufacture* of nuclear weapons by non-nuclear-weapon States. Its almost-universal acceptance may therefore come in part from the fact that the status of "virtual"-nuclear-weapon-state is implicitly allowed by the NPT. However, as shown by the 1968 negotiating record of the NPT, more than the final assembly of an explosive device is prohibited. For instance, the production of components that could *only have relevance to* an explosive device would be prohibited [18, p.17]. Ambivalent nuclear-weapon related activities of non-nuclear-weapon States are therefore restricted to areas such as scientific research, development of nuclear energy, etc.

[10]Upon signing the CTBT on 24th of September 1996, Germany made the following declaration: "It is the understanding of the German Government that nothing in this Treaty shall ever be interpreted or applied in such a way as to prejudice or prevent research into and development of controlled thermonuclear fusion and its economic use" [41, p.5].

Chapter 6

Bibliography

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