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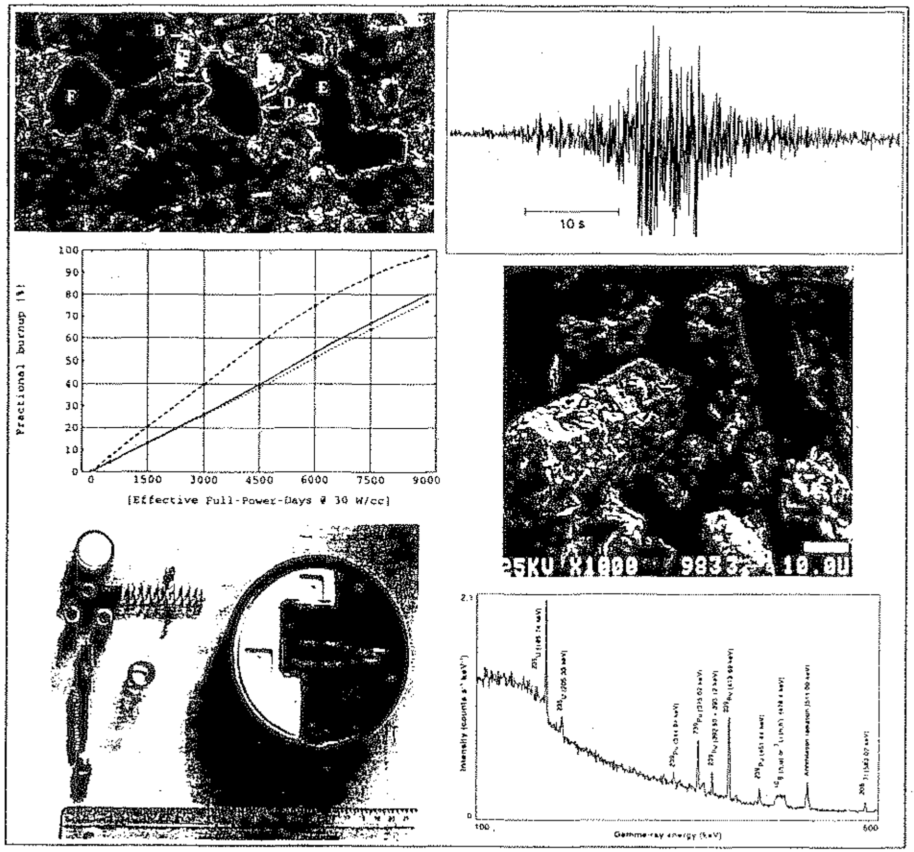
Nuklearwaffen - Neue Rüstungstechnologien - Verifikation von Abrüstung

Naturwissenschaftliche Beiträge zu Abrüstung und Verifikation II



Tagungsbeiträge der Frühjahrstagungen
in München und Regensburg

Inertial Confinement Fusion and Fourth Generation Nuclear Weapons

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1. H-bombs and boosting

Despite the tight secrecy that covers the technical details of how nuclear and thermonuclear weapons are built, their principles are sufficiently well known to be described fairly accurately [1]. Using the wording of the U.S. Department of Energy, Office of declassification, the fundamental idea is that, "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" [2, p.94]. This is the essence of the so-called "Teller-Ulam" principle which is used in all modern two-stage fusion explosives, i.e., in hydrogen bombs. Nuclear warheads based on this principle typically produce yields in the 100–300 *kt* range for a weight of about 200 kg. This corresponds to a yield to weight ratio of about one *kt*/kg, i.e., to an explosive power equivalent to 1000 times that of TNT.

Figure 1 is a simplified diagram of a hydrogen bomb. Its first stage is a fission bomb (also called the trigger, or the primary) producing the radiation (i.e., x-rays) necessary to compress and ignite the main stage (also called the secondary, or second-stage) that produces the major yield. The secondary consists of a U^{238} tamper containing the thermonuclear fuel (Li^6D) and possibly a "sparkplug" (a thin rod of U^{235} along its axis) to facilitate ignition. The radiation case enclosing the primary and the secondary is typically made of U^{238}. Its main characteristic is to be sufficiently heavy to contain long enough by its own inertia the x-rays emitted by the primary, in order that this radiation (accumulated in the hohlraum) has enough time to compress and ignite the secondary.

I practice, to make hydrogen bombs sufficiently small and lightweight to be deliverable by an ICBM, it was necessary to first miniaturize the primary. This miniaturization was achieved by putting a few grams of a deuterium-tritium mixture (*DT*), a thermonuclear fuel, in the center of a fission bomb to enhance its performance. This technique is called *boosting* because it was first developed in order to increase the yield of a fission bomb. Boosting is now primarily used to decrease the overall weight and size of nuclear bombs for a given yield, as well as to dramatically increase their safety. Boosting is used in all modern nuclear weapons, i.e., in all tactical or strategic weapons within the nuclear arsenals of the five nuclear-weapon States, as well as in those of India, Pakistan and Israel.

In a boosted weapon, before arming the device, the tritium is stored outside of the warhead in a separate reservoir. This facilitates maintenance and insures that boosting will not happen in case of an accidental detonation of the high-explosives. A boosted fission-weapon is therefore 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 years.

The very significant technical advantages of boosting underline the importance of an eventual cut-off in tritium production from the point of view of the non-proliferation of fission and fusion weapons.

Let us return to the design of a two-stage thermonuclear weapon. To operate successfully, two conditions have to be satisfied: (a) the thermonuclear fuel has to be sufficiently compressed for the fusion reaction to be fast enough, and (b) the thermonuclear fuel has to be brought to a sufficiently high temperature for the fusion fuel to be ignited. Condition (a) is satisfied by the strong compression resulting from the enormous pressure that is generated by the interactions of the x-rays filling the hohlraum with the surface of the secondary.

Condition (b), ignition, is achieved by the *sparkplug* at the center of the secondary. It consists of some fissile 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. 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 Edward Teller invented the sparkplug concept, soon after discovering with Stan Ulam in 1951 a means for achieving very high compressions, the whole scheme became thoroughly convincing. 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 feasible approach to thermonuclear weapons, *provided only the design work be done properly*." 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 of the five nuclear-weapon States worked the *first time*. Similarly, when India announced in May 1998 that it had successfully tested a two-stage hydrogen bomb, there was no technical reason to doubt that this success was true.

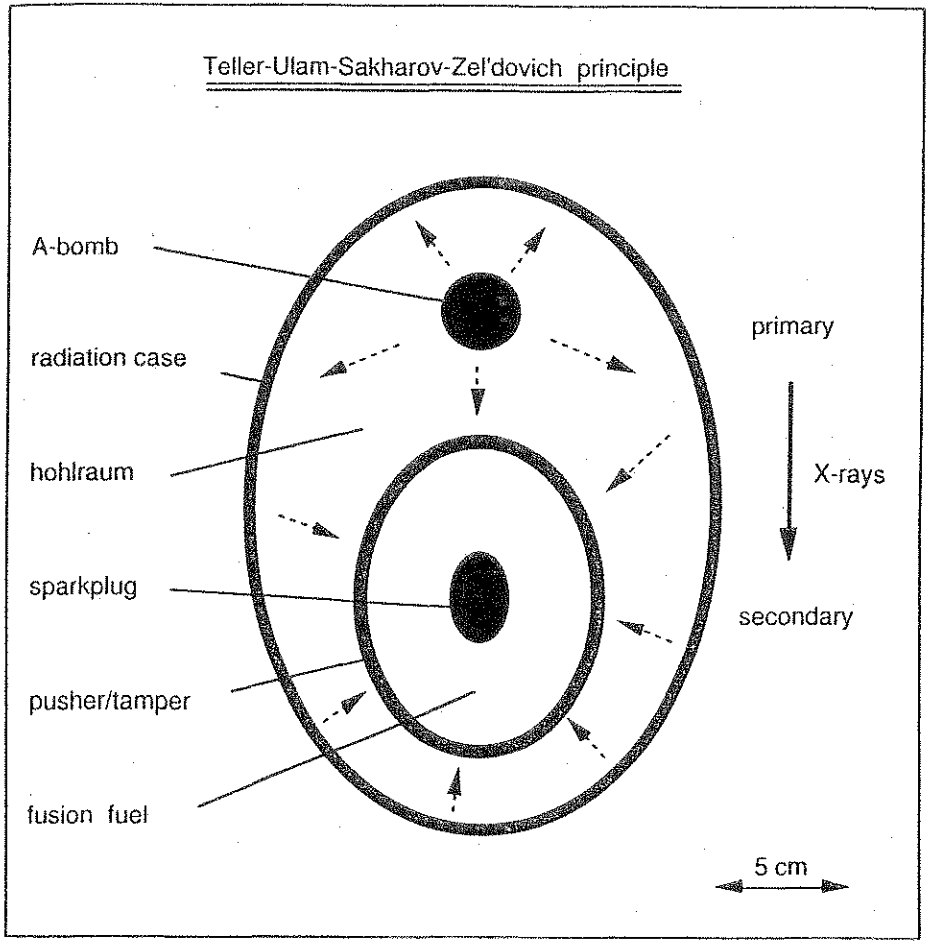

Figure 1: *"In thermonuclear weapons, radiation from a fission explosive can be contained and used to transfer energy to compress and ignite a physically separate component containing thermonuclear fuel" (U.S. DOE, 1979).*

The ignition mode in which a fissile 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 possible ignition concepts.

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. This is very difficult to achieve because the intrinsic characteristics of the fission explosion which is at the origin of the whole process are severely limiting the design options. In this respect, another concept, the so-called *volume ignition* or "Wheeler mode," is much less demanding: it consists of achieving compressions higher than those sufficient for the Teller mode, and let the fuel temperature rise by self-heating until it reaches a self-sustaining burn temperature.

Hence, while the Teller mode of ignition was used in the first thermonuclear explosives, the Wheeler mode is most probably 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 research with megajoule laser facilities may lead to further improvement in thermonuclear weapons technology.

2. Inertial confinement fusion and nuclear weapons

The concept of inertial confinement fusion (ICF) 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: $D + T \longrightarrow {}^4He + n + (2.8 \times 10^{-12} J)$. This energy is converted in an absorbing blanket into 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. 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.

Figure 2 is a simplified diagram of an advanced indirect-drive ICF target of the kind that is extensively studied for future ICF reactors. Such a target consists of a hohlraum containing a $1 - 10$ mg DT fuel pellet. 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 x-rays confined in a hohlraum. In the U.S., this concept was declassified in 1979 at the same time as the Teller-Ulam principle [2, p.103].

It is therefore not surprising that Fig.1 and Fig.2 are very similar, except for the technique used to generate the 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. With other drivers, e.g., ion beams or antiprotons, the details would be different, but the result the same: strong heating of some material 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.

The problem, of course, it to succeed in compressing the pellet to a very high density and in igniting the fuel, either by spark ignition, or by volume ignition, as for hydrogen bombs. The difficulty of this task is enormous, and it would be advantageous to find a technique similar to Teller's "sparkplug" concept that considerably simplified the design of early H-bombs. Apparently, such a technique has been found with the invention of the "superlaser": it will be discussed in the following section.

Ignition is therefore still an open question. Consequently, for many years to come, the main practical application of ICF will be the *simulation of nuclear explosions* , i.e., research in the domains of thermonuclear weapons physics and effects. Let us briefly review these topics, and then come back on the foreseeable implications of successful ignition.

- *Nuclear weapon-effects research.* Until the conclusion of the Comprehensive Test Ban Treaty (CTBT), underground explosions were the most effective method for nuclear weapon-effects studies. 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. 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 100 J/cm^2 x-rays, without completely destroying them.

- *Nuclear weapons physics research.* After the discovery of the Teller-Ulam principle, and some major improvements during the 1960s, progress on thermonuclear weapons slowed down dramatically. In fact, despite more than fifty years of research and development, and after almost two thousand test explosions, the scientific understanding of the details of the secondary system is still incomplete. If the CTBT would not have been concluded, 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.

A major problem with full-scale testing is that the secondary of an actual bomb is buried deep inside the weapon. Therefore, most experimental data on the thermonuclear part of the explosion is indirect. In comparison, an ICF pellet is an almost naked secondary, and many configurations can be tested at will, with much better diagnostic capabilities than with underground nuclear tests. The promise of ICF is a complete description of nuclear weapons physics from first principles.

The complexity of ICF target experiments requires that they be analysed by computer-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-weapon States, very sophisticated computer codes have been developed and published by scientists in such States. For instance, the two-dimensional hydrocode MULTI2D 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.

Considerable scientific data necessary for the design of fusion energy systems is also crucial for thermonuclear weapons. For example, the temperature- and pressure-dependent opacity functions for high atomic-number elements were classified until 1993 because this information is needed to make such weapons.

- *Ignition and new types of nuclear weapons.* Whatever the details, successful ignition of thermonuclear micro-explosions in the laboratory will enable the improvement of existing types of nuclear weapons [3].

Moreover, successful ignition will open the way to the development of radically new types of nuclear weapons. This is because ICF 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 is 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. For this purpose, current ICF technology may not be appropriate, even though a single-use device is usually much more compact and simple than a multi-purpose re-usable experimental facility. More probably, a solution will derive from the application of some very-high energy-density technology such as antimatter, nuclear isomers, or superlasers.

- *National ICF research programs.* At present, some kind of theoretical ICF research is under way in about twenty countries. But only seven countries, the five nuclear-weapon States, Japan [4] and Germany [5], have truely significant experimental ICF programs.

A rough idea of the magnitude of these efforts is provided by comparing the relative capabilities of the ICF-related high-energy beam facilities operating in these countries. This is not trivial because beam-target coupling is a function of a number of parameters. 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. 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 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., 1.8 MJ) 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.

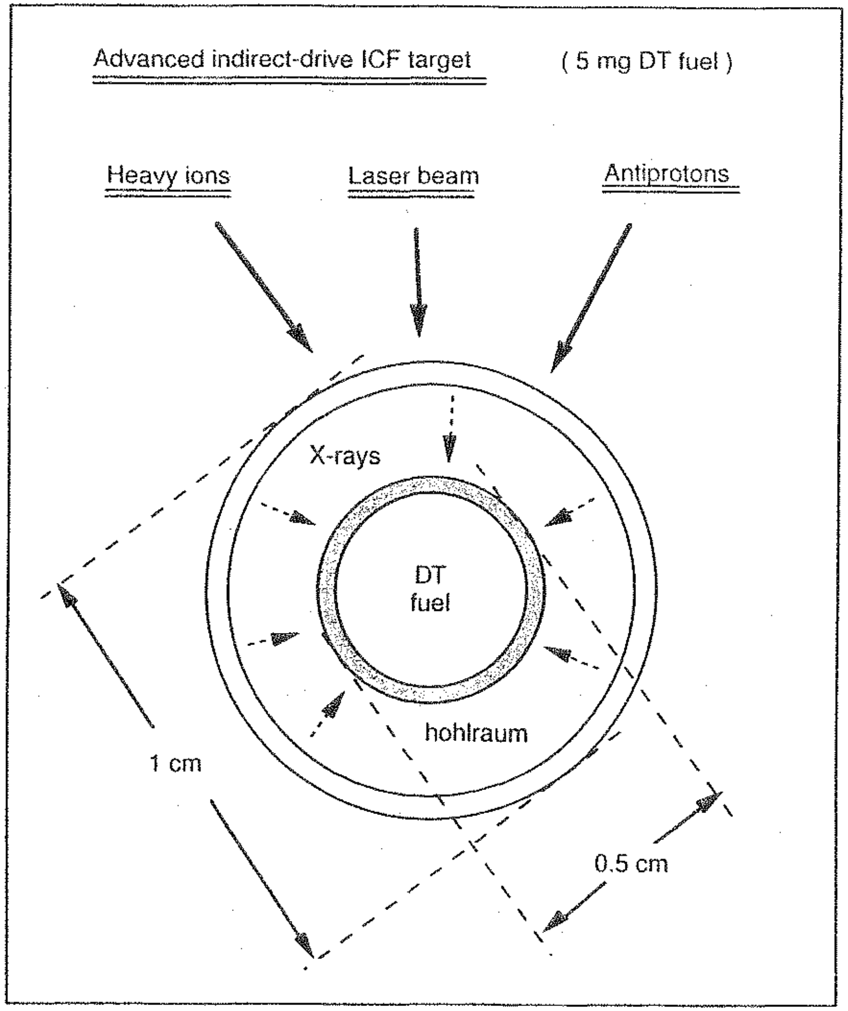

Figure 2: *"In some ICF targets, radiation from the conversion of the focussed energy (e.g., laser or particle beam) can be contained and used to transfer energy to compress and ignite a physically separate component containing thermonuclear fuel" (U.S. DOE, 1979).*

3. Technological breakthrough: the "superlaser"

"Superlasers" are ultra-short ultra-intense pulsed lasers with pulselengths in the range of 10^{-15} to 10^{-12} s, i.e., femtoseconds to picoseconds, and beam intensities on the order of 10^{20} W/cm^2. They are called *super*lasers because their interactions with matter are qualitatively very different from those of ordinary lasers. In particular, their intensity is sufficient to induce strong relativistic, multi-photon, nonlinear, and nuclear effects [7, 8]. Superlasers are the result of the combination of two inventions: a clever optical pulse compressor discovered in 1984, and a scheme called *chirped pulse amplification* invented in 1985. These inventions ended a twenty years long period over which laser intensity plateaued at a maximum of about 10^{14} W/cm^2, due to limitations caused by nonlinear effects.

The potential military applications of superlasers are so impressive that their principles have been implemented on existing large laser systems built for ICF and nuclear weapons simulation, pushing their peak power by three orders of magnitude from 1 TW to 1 PW. For example, the Lawrence Livermore laboratory *Petawatt* laser is the result of transforming one of the ten *Nova* laser beams into a superlaser beam [7, p.25]. It is now the World's most powerful laser, overtaking the French 55 TW laser which was leading until June 1996. Since then, Japan has put a 100 TW laser in operation in April 1997, the United Kingdom a 200 TW one in January 1998, and Germany will soon have its own 100 TW laser [8, p.7].

Superlasers enable a two step approach to ICF similar to the sparkplug ignition of a cold compressed fuel in H-bombs [9]. The proposed *fast ignition* scheme is as follows: First, a pellet is imploded as in the conventional approach to ICF to assemble a high-density fuel configuration. Second, a hole is bored by a superlaser through the pellet corona composed of ablated material. Finally, the fuel is ignited by fast electrons, produced in the superlaser-plasma interactions, which then propagate to the center of the pellet and heat the fuel. This new scheme enables a factor of 10–100 reduction in total driver energy; it also 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 [9, p.1626].

Fast ignition of ICF pellets is however only one of the many potential applications of superlasers with important military consequences. For instance, high energy electrons and x-rays generate by focusing a superlaser pulse on a fissile target can induce electro-fission and photo-fission reactions [10]. This process of *optically induced fission* 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.

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. The configuration would then be almost identical to that of the H-bomb depicted in Fig.1, with the sparkplug replaced by a small inclusion of fissile material.

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 d'Etude Lasers Intenses et Applications* (CELIA) in Bordeaux, or the *Advanced Photon Research Center* (APRC) near Osaka. All the most advanced industrialized countries have now superlasers with powers of at least 10 TW, and 100-1000 TW superlasers under construction.

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 using the superlaser *Atlas* at Garching were the first to report the unambiguous production of neutrons from fast deuterium-deuterium fusion reactions initiated by ultrashort laser pulses [11].

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.

The future will show if the development of the superlaser is really one of the most important inventions of the past decade. In any case, the increase in the instantaneous power of laser beams provided by superlasers is of the same magnitude as the factor of one million difference in energy density between chemical and nuclear energy. Therefore, as is suggested in a recent review, the superlaser may well be the signal that the industrial civilization has definitely entered, for better or for worse, the "Age of the photon" [8, p.7].

4. Fourth generation nuclear weapons and the CTBT

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. In the case of nuclear weapons, many different types have been studied over a very long time: pure-fusion bombs, antimatter bombs, laser-triggered bombs, thermonuclear shaped-charges, new explosives based on nuclear isomers, superheavy elements, metallic hydrogen, etc. 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. It is therefore important to review these concepts and analyse their potential for becoming part of a new generation of nuclear weapons.

First generation nuclear weapons are all uranium or plutonium A-bombs, and *second generation* nuclear weapons are fusion-boosted fission-explosives and two-stage H-bombs. *Third generation* nuclear weapons are "tailored" or "enhanced" effects weapons, such as the Enhanced Radiation Warhead (ERW), and nuclear-driven "directed energy" weapons producing beams or jets of x-rays, electromagnetic waves, particles, plasmas, etc. While the enhanced effect weapons never found any truly convincing military use, none of the nuclear-driven directed energy weapons appears to have been perfected to the point where it could be deployed. The third generation is therefore an aborted one, mainly because it did not lead to any practical weapon providing some truly decisive military or political advantage compared to those of the second generation.

Fourth generation nuclear weapons are new types of explosive devices based on atomic and nuclear processes that are not restricted by the CTBT. In contrast with the development of second generation nuclear weapons, which heavily relied on full-scale testing, 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. 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 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.

The development of these weapons is possible because the CTBT, which has put an end to *explosive testing* of nuclear weapons, does not forbid laboratory scale nuclear explosions and the use of a number of techniques perfected during the last forty years, which today can effectively replace explosive testing.

In fact, 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, a considerable insight is given by a report of the U.S. Department of State which includes an article-by-article analysis of the CTBT [12]. For instance, this analysis gives 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." [12, p.6].

None of these activities constitute a "nuclear explosion", implying that all possible kind of *microexplosions* and *subcritical experiments* (i.e., experiments in which no self-sustaining nuclear fission chain reaction occurs) are allowed by the Treaty.

Moreover, the Department of State analysis recalls the U.S. statement made at the 1975 Non-Proliferation Treaty (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" [13].

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.

To conclude this section, it is appropriate to give an overview of the main physical processes which are important to existing and possible future nuclear explosives. These processes can be classified according to the nature of the energy release, which is either of *atomic* or *nuclear* origin; and according to the level of technological sophistication, which is either *standard* for processes that are currently used in existing military explosives and for their development, *advanced* for those which may be used within a decade or two, or *exotic* for those which may become relevant in the more distant future:

	atomic processes	**nuclear processes**
standard processes	chemical detonation lasers particle acceleration	fission fusion spallation
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 plasmoids etc.	superheavy nuclei bubble nuclei halo nuclei etc.

It can seen 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.

5. Subcritical burn and microfission explosives

The explosive properties of a finite assembly containing fissile material is characterized by its effective neutron multiplication factor, or criticality factor, k, i.e., the average number of neutrons produced by fission per neutron absorbed in the assembly. When $k = 1$, 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. This does not mean, however, that a subcritical assembly cannot be used to produce nuclear energy or to make a nuclear explosive. In effect, since at each generation the number of neutrons is multiplied by k, the total number neutrons produced by an initial number $N(0)$ is $N = N(0)/(1-k)$. For k close to 1, N can be very large. Therefore, 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 method 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 [14], 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) 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).

In summary, subcritical fission burn is a potentially attractive method for making a low yield fission explosive. But, until recently, no practical techniques to produce the required compression, and to generate the large number of initial neutrons, were available.

The problem with compression is that the maximum pressure produced by existing chemical explosives is not high enough to compress fissile materials to the required densities [15, p.9–10]. Using a very sophisticated implosion technology, the maximum compression factor achievable is about 10. 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 will therefore require a system of laser or particle beams, or the use of magnetic compression [16]. Both techniques are under development since a long time and currently available systems are powerful enough to make decisive experiments. But existing lasers and particle accelerators will probably be too large to make a transportable weapon. Similarly, in the magnetic compression approach, the main difficulty will be to miniaturize the system converting the energy content of high-explosives into the energy of electrical currents and magnetic fields.

The problem with supplying the initial neutrons is the great difficulty of focusing a stream of neutrons on a very small target. However, by focusing a beam of *charged* particles on the pellet, fission reactions can be induced by various high-energy reactions. This requires a compact accelerator which could be built using a superlaser. Moreover, if sufficiently intense, the superlaser beam itself could be focussed directly on the pellet: high energy electrons and photons generated on the surface would cause electrofission and photofission in the material surrounding the focal volume [10]. Finally, a solution that directly leads to a very compact device is to direct a bunch of antiprotons at the pellet to generate the required number of initial neutrons .

At present, possibly the most ambitious microfission research program is at Phillips Laboratory (formerly, Air Force Weapons Laboratory, Kirtland Air Force Base, New Mexico) where antiprotons are planned to be used to initiate subcritical burn in magnetically compressed pellets [16]. Detailed computer simulations related to these experiments show that about one microgram of antiprotons is enough to produce explosive yields between 0.24 and 12 *tons* of TNT equivalent from magnetically compressed plutonium targets weighing between 14 and 700 milligrams [17].

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 [2, p.121].

6. Antimatter weapons

Matter-antimatter interaction produces more energy than any other means of energy production. For example, proton-antiproton annihilation releases 275 times more energy per unit mass 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 high-temperature and high-pressure 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, and that both Edward Teller and Andrei Sakharov, 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.

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. Using this method, antiprotons very produced for the the first time in 1955, although in very small quantities. 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 is at the European Center for Nuclear Research (CERN), at Geneva, Switzerland. Finally, it became possible to study, on a large scale, the interactions of antiprotons with nuclei.

Thanks to the results of CERN, it was possible 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 [18]. It turns out that it is possible to build an H-bomb in which the three to five kilograms of plutonium are replaced by one microgram of antihydrogen.

Since the summer of 1983, stimulated by the prospect of the imminent availability of antiprotons, 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" [19]. The report published in 1985 constitutes a serious evaluation of the development possibilities for such an undertaking in view of military applications. Four main categories of applications are mentioned: *propulsion* (fuel for 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 years that followed, 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, and then to form solid antihydrogen pellets which could be stored and manipulated with the help of various electromagnetic and optical levitation techniques. The first atoms of antihydrogen were synthesized at CERN in 1996. 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, the existence of metastable states of antiprotons in condensed matter cannot be ruled out *a priori*.

As low energy antiprotons became routinely available, a number of physical quantities of military interest could be precisely measured. For example, about 16 neutrons are produced by stopped annihilation in uranium. 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 [20] and Phillips laboratories [21].

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. Designed and constructed at the Los Alamos laboratory [20], this trap was successfully tested at CERN in 1996 [22].

Another important application of antimatter to fourth generation nuclear explosives is the triggering of ICF pellets [23, 24]. For this purpose, as we had found in 1985 [18], an important issue is to transfer as much of the annihilation-energy as possible to the DT or LiD fuel. A possible solution investigated at the Lawrence Livermore laboratory is to put a small, heavy metal or fissile material inclusion at the center of the pellet [25]. Using this technique, the estimated number of antiprotons required to initiate ignition of a typical ICF capsule is only 3×10^{13}.

At the end of 1996, CERN's antiproton 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. In order to continue its program of research on antimatter — which will be the only major physics research program at CERN in the years 2000 to 2005 — a new antiproton source is being constructed. Beginning in 1999, antimatter production will resume at CERN. There will be two main experiments, both with participants from the United States which are supported in part by the U.S. Air Force antimatter technology program. Moreover, using antiprotons produced and trapped at CERN, numerous other experiments will be conducted in various American and European laboratories. Apparently, the only competition will come from Japan, where low-energy antiprotons should become available around the year 2003.

7. Pure-fusion weapons

The concept of pure-fusion (or fission-free) weapons refers to thermonuclear explosives in which there is no atomic bomb to start the fusion reactions. Research on such explosives started during World War Two and has followed many different paths. Among them, ICF is probably the most advanced at present, and antimatter possibly the most promising for the future. It is nevertheless important to review the other main pure-fusion candidate technologies, especially because they are generally much more compact than laser or particle beam driven ICF systems:

- *Chemical high-explosives* can be used to implode small amounts of fusion fuel (e.g., DD or DT gas), resulting in measurable production of fusion neutrons. However, 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. At present, the largest published neutron yield from a chemical explosive driven device is $\approx 10^{13}$ [26]. This yield was obtained by Russian scientists with a spherical chemical explosive device of 375 mm in diameter imploding a multilayered medium in order to achieve a higher energy cumulation level (compared to a homogeneous media). The analysis of this experiments shows that the device was only two orders of magnitude below the ignition threshold. 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.

- *Impact fusion.* Instead of igniting a thermonuclear fuel by means of chemical explosives, or a set of converging beams, it is possible to take advantage of the possibility of accelerating a macroscopic object to high velocity and then to use its kinetic energy to compress and heat a target. This technique enables a number of variations: 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. 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. But 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 [27]. 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 potential applications for ballistic missile defence and other military applications.

- Some *Magnetic Confinement Fusion* schemes were long classified because it was thought that they could lead to pure-fusion explosives. For instance, in the *magnetic pinch device*, or in the *plasma focus* [28], 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 is only useful to make a pulsed machine, e.g., a powerfull x-ray generator. Therefore, its most promising application today is as an *indirect* driver for ICF [29]. For instance, at the Sandia laboratory, the *Saturn* and PBFA-Z pulsed-power machines produce between 0.5 and 1.5 MJ of x-rays in about 5-30 ns [29, p.1820]. This is very impressive considering that these pinch devices are much smaller and less costly than laser facilities of comparable energy, e.g., NIF or LMJ. Implosion experiments with simple ICF targets containig deuterium fuel are planned for 1998 at PBFA-Z. They are expected to yield about 10^{12} DD-fusion neutrons per shot [30, p.19].

- *Magnetized fuel and magnetic compression* devices are based on the old idea that magnetic fields can serve to thermally insulate the fuel from the walls during compression and heating, and to improve fusion energy deposition in the fuel after ignition. These effects are particularly pronounced when very strong magnetic fields are generated, either by mechanical compression of a liner (i.e., a metallic receptacle) containing a magnetized fuel, or by magnetic compression of such a liner.

Magnetic compression can be driven by a capacitor bank [31] or by chemical explosives [32]. In Russia, a concept called *MAGO* 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 [33].

In the United States, the technique of magnetic compression is under investigation using non-destructive devices, such as the *Shiva Star* facility at the Philips laboratory [34], or explosive devices, such as *Procyon* at Los Alamos. *Procyon* is an explosive pulsed-power system designed to drive 1-MJ pinch experiments [35]. In 1995, a *Shiva Star* experiment in which a 4 cm radius aluminum shell was compressed to 16.8 g/cm^3, demonstrated the feasibility of electromagnetically driven spherical liner implosion in the cm/μs regime [34]. This technique can be used to compress either fusion or fission fuels, and is particularly suited to antiproton-triggered microexplosion experiments.

The chemical explosive approach to magnetic compression is now the object of a major collaboration between Los Alamos and Arzamas-16 [32]. The first ever joint scientific publication of a team of American and Russian nuclear-weapon scientists was the result of this collaboration [36]: A hot plasma was produced and 10^{13} DT fusion reactions were observed. 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 a recent assessment of the arms-control implications of such type of pure-fusion devices [30].

8. Conclusions

The facts that ICF and pulsed power technologies are effective substitutes for underground nuclear tests, and that they may lead to the development of new types of nuclear explosives, are now acknowledged in a number of reports [1, 3, 30, 37, 38].

In this paper, we summarized some of the main technical evidence supporting these conclusions. In particular, we showed that the knowledged gained in ICF research will certainly be useful to improve the design of existing types of nuclear weapons. We also emphasized the possibility that radically new types of weapons, i.e., fourth generation nuclear weapons, could be designed and built in both nuclear-weapon and non-nuclear-weapon States.

At present, no fourth generation nuclear weapons has been built. But there appears to be no obstacle in the form of some fundamental physical limitation in the way of their development and subsequent deployment. This is because the physical properties of the very-high energy-density processes (magnetic compression, superlasers, antimatter, nuclear isomers, etc.) which could be used in such weapons are already sufficiently well known for the general characteristics of these new weapons to be evaluated fairly accurately.

For instance, fourth generation nuclear weapons could be highly miniaturized very-low-yield nuclear explosives: their yield could be measured in *tons* rather than in *kilotons* of high-explosive equivalent; their small size and weight could make them suitable for delivery by artillery or tank shells, cluster bombs, small rockets, cruise-missiles, etc. This would revolutionize the battlefield: the firepower of conventional weapons would be multiplied by a factor of a thousand or more. Moreover, such very-low-yield nuclear weapons would not qualify as weapons of *mass* destruction. Therefore, their use would not be in contradiction with the rules of war and with international humanitarian law.

Consequently, an important strategic and political implication of fourth generation nuclear weapons is that they could make high-yield nuclear weapons obsolete. However, these new weapons would also enable a redistribution of power among the most industrialized countries — something that would seriously challenge the military supremacy of the five nuclear-weapon States, and create a lot of tension in existing military and political alliances.

In practice, it is therefore likely that fourth generation nuclear weapons will remain "latent" or "virtual" as long as there is no compelling reason to build them [39]. In the short term, this might be in the interest of both nuclear-weapon and non-nuclear weapon States. But in the long term, this will result in a very fragile strategic environment.

Therefore, the two major conclusions of this paper are (1) that the possibility of fourth generations nuclear weapons should be taken very seriously, and (2) that discussions on ways to constrain the development of ICF and the military applications of all types of advanced nuclear processes should begin as soon as possible.

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[5] 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 [6] and at the *Forschungszentrum Karlsruhe* (FZK). Furthermore, there are significant ICF-related laser facilities at Garching and a project for 1 kJ laser at GSI. Germany has also an ambitious superlaser research and development program.

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[39] Technologically advanced countries such as Germany and Japan have since long acquired the technical and industrial *capability* (e.g., by means of "peaceful" nuclear activities) to manufacture nuclear weapons components and to assemble them on short notice. Furthermore, regardless of their access to ICF facilities, "one cannot rule out that technologically advanced countries would be able to field a very conservatively designed thermonuclear weapon that would present a credible threat without nuclear testing" [40, p.27]. Because such an approach to a nuclear weapon capability is inherently ambiguous and does not force a nation to signal or even decide in advance its actual intentions, it is termed *latent* proliferation [41]. Recently, the concept of *virtual nuclear arsenals* has been suggested to describe a world in which all assembled, ready-for-use nuclear weapons would be banned [42]. This would link *latent* proliferation to deterrence in a way that has been termed *factory deterrence* by political scientists [43], and *technical deterrence*, or *deterrence by competence*, by nuclear weapons designers [44].

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