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Arms Control at the Stage of Research and Development? —The Case of Inertial Confinement Fusion

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This paper discusses some of the essential aspects of arms control at the research and development (R&D) stage of a project, using the example of inertial confinement fusion (ICF). This is a large R&D program with many potential military and civilian applications. Early in a project's life, it may be unclear what its military and civilian benefits will be: such ambivalence is a major obstacle to arms control at this stage of development. We investigate the feasibility of several of ICF's potential applications and outline their respective scientific requirements. It is shown that goals with civilian or military emphases lead to different paths of further R&D. Ways to determine the most probable end intentions of an "ambivalent" R&D program are discussed.

INTRODUCTION

As is shown by history, arms control agreements have generally been achieved only under one of three situations: (a) after the deployment of well-tested weapon systems (INF treaty); (b) after the end of the research and development (R&D) phase but before deployment (ABM treaty); or (c) when the agreement governed futuristic weapons that seemed unlikely to be developed by any of the parties to the treaty in the near future (seabed treaty).

This paper addresses one of the central difficulties of early control of R&D, the problem of military–civilian ambivalence. It is widely held that this ambivalence is unavoidable because in most cases both civilian and military

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applications are imaginable. However, this view does not acknowledge that different applications often play different roles in the structuring of the R&D.

It is obvious that this method will be most successful on those R&D programs that are large, expensive, and centrally organized. Therefore we consider only this sort of R&D here.

We analyze in particular inertial confinement fusion (ICF), a typical example of "big science," a very costly and longstanding R&D program that shows the military–civilian ambivalence of basic research in a very clear way. From the beginning this program was shaped by ideas of potential applications, civilian and military.

This article first gives a short description of ICF, including its historical and political background. It then discusses the most important potential military and civilian applications and assesses the potential for realizing these applications. We then attempt to establish criteria for identifying the goals of R&D and consider how to apply the results to arms control.

ICF—AN EXAMPLE OF BIG SCIENCE

Inertial Confinement Fusion[1,2,3] is, like magnetic confinement fusion, a process that aims to harness the energy released by the fusion of light nuclei, which is currently released on a significant scale in thermonuclear weapon explosions. In the laboratory, ICF involves microexplosions, which can be regarded as tiny thermonuclear explosions. In nature, fusion takes place in the interior of stars ("gravitational confinement"). Some details of ICF physics are described in appendix A.

In hydrogen bombs, as well as in laboratory ICF, the thermonuclear fuel must first be compressed and then heated in order to generate conditions that allow fusion reactions to take place. The required pressures are so high (in the range of 10^{11} megapascals) that those that can be generated by chemical explosives (on the order of 10^5 megapascals) fall far short.* So far, the only energy source capable of providing enough energy together with the necessary energy density is a fission explosion. Hence all thermonuclear weapons have a *fission trigger* or *primary*.

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* 1 megapascal ≈ 10 atmospheres.

From the early days of nuclear-weapon development, scientists sought methods to compress and heat thermonuclear fuel that did not require the use of a fission explosion. One reason was the radioactive fallout from atmospheric nuclear tests. The invention of the laser in 1961 seemed to offer an alternative because its energy per area can reach adequate values. Since the amount of energy delivered by a laser is far less than the energy delivered by a nuclear bomb, only experiments on a miniaturized scale can be conducted. Promising calculations led to the initiation of a classified experimental laser fusion program at the Lawrence Livermore National Laboratory in 1963.

The development of high-powered neodymium–glass lasers and carbon dioxide lasers accelerated the interest in laser fusion. R&D programs of various scales started in several countries, among them the USSR, France, Japan, Israel, and West Germany. Although the first experimental efforts used high-powered lasers, interest in particle beams also grew during the 1970s. The energy source is often described as the *driver.*

The short-term scientific goal of the R&D consists in achieving a *gain*—fusion energy divided by driver energy—that is as high as possible. The best fusion fuel—and consequently the favorite for experimentation—is D–T (deuterium and tritium) undergoing the reaction $D + T \rightarrow He\text{-}4 + n + 17.6$ MeV. A gain $G = 1$ is called *ignition* or *scientific breakeven.* It is the major goal of present research to demonstrate the feasibility of achieving this threshold with ICF.

During the course of ICF R&D, however, the amount of driver energy theoretically estimated to be necessary for breakeven grew by three orders of magnitude. It was first calculated by Nuckolls as 1–10 kilojoules;[4] today it is estimated to be 1–10 megajoules. The result has been requirements for the construction of a series of increasingly large and expensive high-energy lasers and experimental devices. Appendix B gives some details of current R&D.

R&D on ICF depends on large and very expensive experimental equipment, requiring huge financial resources. The motivation for its funding is fed by potential applications. These are military (R&D on thermonuclear weapons) and civilian (energy reactors). In nonclassified scientific publications only civilian applications are usually mentioned. On the other hand almost all requests for financial support in the US are based upon potential military usefulness. Also, in US government documents, an important goal for ICF R&D is stated to be support for the defense programs of the Department of Energy.[5] In contrast, R&D on ICF in Germany is justified exclusively by potential civilian applications, mainly energy production. Because of the Nonproliferation Treaty, Germany has forgone the acquisition of nuclear weapons.

It is often claimed that it is impossible to distinguish between civilian and military applications of a technology still at a basic stage of R&D—a military or civilian application may arise that nobody had foreseen.

But this argument does not apply to expensive projects such as ICF that depend on massive financial support, justified by specific goals of potential applications. No costly program would be continued without such justification. This is the same with all large civilian or military scientific programs such as SDI or cancer research. Therefore, all potential applications of ICF will be examined in the following sections in respect to their feasibility.

POTENTIAL APPLICATIONS

A variety of civilian, military, and ambivalent applications of ICF are discussed:

(i) potential civilian applications:

- reactors for energy production
- obtaining new knowledge for astrophysics
- acceleration of spacecraft

(ii) potential military applications:

- research on the physics of nuclear weapons
- contributions to the development of new nuclear-weapon concepts
- maintaining the expertise of scientists in thermonuclear explosions in case of a comprehensive test ban treaty
- studying the effects of nuclear radiation on military equipment

(iii) potential ambivalent applications:

- breeding of fissile material
- powering laboratory x-ray lasers.

Potential Civilian Applications[6]

Reactor Systems For Energy Production

A reactor based on ICF (see [2], p.555) basically involves the transformation of a sufficient amount of the energy released by the microexplosions into a steady stream of heat driving the turbines. In addition it must offer the possibility of breeding the tritium fuel from lithium according to the reaction

$$\text{Li-6} + n \rightarrow \text{He-4} + \text{T} + 4.8\ \text{MeV}$$

The energy flow through an ICF electrical generating system is depicted in figure 1. Part of the energy gained from the turbines and generators would be used to feed the driver. Energy losses will occur within the turbine–generator system (efficiencies in transforming the heat into electrical energy would likely be below 40 percent) and within the driver (transforming electrical energy into driver energy might have an efficiency of only a few percent). Tak-

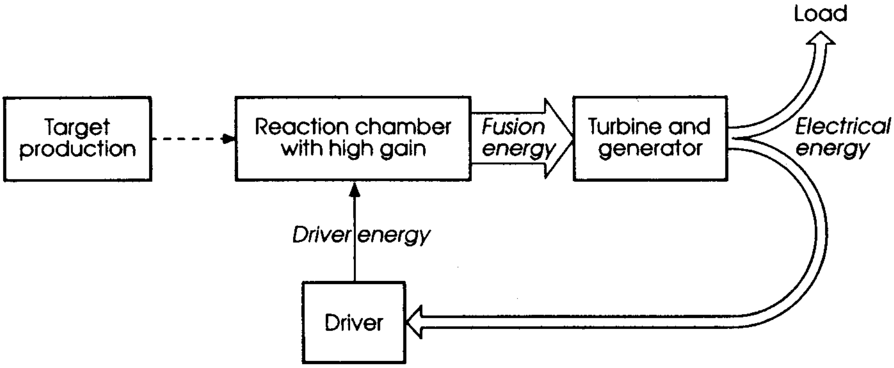

Figure 1: Energy circulation in an ICF reactor. Energy losses occur in several components of an ICF reactor. In order to operate such a reactor economically, a gain of $G \geq 100$ is required.

ing into account these losses, it can be estimated that the gain G required for an economic reactor is at least $G = 100$.

To have a sufficient power output to justify the great capital costs involved, a driver with pulse frequencies of at least 5–10 microexplosions per second is required.

These technical requirements, most of them still unsolved, are so high that the realization of a commercial reactor might not be expected within the next 30 to 50 years. Optimistic experts claim the feasibility of a demonstration fusion power plant by about 2020.[7]

Obtaining New Knowledge Relevant to Astrophysics

During a thermonuclear burn, pressures and temperatures reach values that are found only in the centers of stars. Therefore ICF offers the possibility of experimental investigations to learn more about processes in the center of stars.

Acceleration of Spacecraft

The energy from microexplosions could be used for the acceleration of spacecraft (see [8], p.7). The expanding plasma would be deflected by magnetic fields to produce a recoil in the desired direction. Since this requires microexplosions that release energy mainly as kinetic energy of the expanding plasma instead of kinetic energy of neutron, the deuterium–tritium reaction is inappropriate. However, all other fusion reactions require much higher temperatures and more effective confinement than the D–T reaction.

Potential Military Applications

While states not possessing nuclear weapons stress the potential civilian uses of ICF, R&D on ICF in nuclear-weapon states mainly concentrates on military applications. In the US, these applications are the principal justification for the ICF program. Micro-ICF involves quite similar physics to that of thermonuclear weapon explosions.

A thermonuclear weapon[9,10,11] (see figure 2) in principle consists of the fusion material (*secondary*), and a fission primary. The two parts, spatially separated, are arranged within a casing made of appropriate materials. The energy released by the primary will form an isotropic ***hohlraum*** (blackbody) radiation field in the interior of the casing. This will compress the fusion material causing ignition at its core, the origin of thermonuclear burn (see appendix A). The burn proceeds so rapidly that it is substantially complete before the secondary is disassembled by the expanding fission trigger.

Both thermonuclear weapons and laboratory ICF deal with the interaction of isotropic x-rays with matter. When particle beams or laser light in the visible region are used as drivers for micro-ICF, the heating of the outer layers of the pellet quickly converts the driver energy into x-rays, which then compress the pellet (see [12], p.2 and appendix A of this paper). The attainable temperature depends on the power of the driver and the conversion efficiency.[13]

Both micro- and macroexplosions (H-bombs) depend on the principle of compressing the fuel adiabatically in a first step and starting the thermonuclear reactions in an ignition core by local heating in a second step. In both cases the compression[14] and the propagation of the thermonuclear burn[11,15] are described by the same formulas. Yet there are some quantitative and qualitative differences. Quantitative differences relate to different densities, temperatures, and burning times. Qualitative differences mainly arise because the more experiments are miniaturized, the more troublesome are instabili-

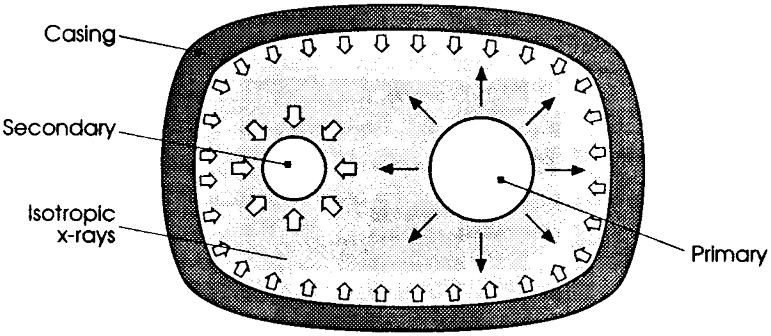

Figure 2: Simple depiction of the principle of a thermonuclear warhead, which consists essentially of a fission explosive (primary or fission trigger) and the fusion secondary. The fission explosion emits x-rays, which serve as driver energy. Multiple absorption and reemission of this driver energy causes the formation of an isotropic radiation field in the cavity (shaded central area) driving a symmetric implosion of the fusion material.

ties. This impedes scaling from macroexperimental results (underground nuclear explosions) down to microexperiments and vice versa.

The fusion materials used in weapons (for example $LiD_{0.5}T_{0.5}$ and LiD—see [11], p.84 ff.) also differ from the D–T used in ICF microexperiments. However, future microexperiments with other fusion materials, for example $LiD_{0.5}T_{0.5}$, which has an ignition temperature of about 30 keV, can be imagined as soon as ignition with D–T is achieved. In this case, the surrounding material may consist of $LiD_{0.5}T_{0.5}$ with the ignition core fuel still D–T. The outer region then would be heated by the traveling burning wave originating from the core (D–T), which still would be ignited at lower temperatures.

Another contrast between macroexplosions and microexperiments—at least thus far—is that secondaries of thermonuclear weapons may be constructed in nonspherical, e.g. cylindrical configurations.[10] But such configurations seem plausible in the future for microexperiments too.

The similarities—actual and potential—between ICF micro- and macroexplosions offer a number of potential military applications.

Research on Physics of Nuclear Weapons

Research on the physics of nuclear weapons deals mainly with the interaction of x-rays and neutrons with matter, implosion dynamics, equations of state at extreme pressures and temperatures, and the propagation of the thermonuclear burn. Micro-ICF offers the chance to measure data relevant to computer simulations of underground and laboratory explosions, such as cross sections of fusion reactions.

Contributions to the Development of New Nuclear-weapon Concepts[6]

Parts of the underground macroexperiments that are necessary for the development of new nuclear-weapon concepts could in principle be replaced by laboratory microexperiments. However, the development and testing of a prototype would involve much more design detail than could be simulated in ICF research. Therefore this research could not substitute for full-scale testing of new weapon designs.

Maintaining Design Expertise under a Comprehensive Test Ban Treaty

Banning micro-ICF research as part of a comprehensive test ban treaty

(CTBT) has never been considered. Therefore, to some extent, under a CTBT regime[7,16] much basic scientific knowledge could be maintained by R&D on ICF. Furthermore, ICF R&D could attract and keep creative people in the weapon laboratories—a major concern in the US.[*,6]

Studying the Effects of Nuclear Radiation on Military Equipment
A micro-ICF source with a high gain could simulate the energy output (x-rays, neutrons, gammas, expanding plasma) of nuclear weapons better than the other sources. If energy outputs of 100 to 1,000 megajoules were achieved, many experiments on military vulnerability and lethality now done in underground test sites could be carried out in the laboratory.

Potential Ambivalent Applications

Breeding of Tritium and Fissile Material
The D–T reaction releases fast neutrons that can be used for breeding tritium or fissile material. The gain of such a fusion breeder reactor need not be as high as for an energy production reactor because the breeder reactor would not necessarily have to produce net positive energy.

X-ray Laser for the Laboratory
An ICF microexplosion is a source of short-term intensive though incoherent x-rays. This radiation can be used as pumping energy for laser radiation in the x-ray band.[18] This would offer a laboratory source of intensive coherent x-rays, which would have many uses. In the field of biology, it is possible that molecular processes in living cells could be observed (see [8], p.5, [18], p.155). Very short wavelengths (about 3 nanometers) and short pulse durations (less than 1 nanosecond) would be required for this.

On the other hand, such experiments could also contribute to the R&D on the development of a nuclear-explosion–pumped x-ray laser, a substantial early component of the SDI program.

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[*] It has been suggested that experts might be retained for about five years longer in the US weapon laboratories.[17]

ARMS CONTROL AND ICF

Although control of ICF R&D is difficult, there are reasons to attempt it. Without controls, the effectiveness of a comprehensive test ban treaty could be degraded and the dangers of proliferation enhanced.

Impacts on a Test Ban

There are several reasons for a comprehensive test ban,* one of them being to block the development of new types of warhead, such as third-generation nuclear weapons.† This objective could be undermined to some degree by ICF research. Without high-yield (underground) tests, ICF alone would not suffice to enable the development of such weapons.However, it could significantly reduce the number of tests that would be necessary for the development of new nuclear weapons should the test ban break down.

Although US nuclear weapon laboratories claim that their responsibilities could not be met under restrictive test limits, they are taking steps to prepare in case limits on nuclear testing are imposed. These preparations include a high-gain ICF test facility named *Athena*.[22]

Proliferation Risks and ICF

R&D on ICF brings with it two proliferation risks: first, any D–T fusion reactor (ICF or magnetic fusion) offers the possibility of breeding plutonium or tritium in large quantities.‡

Secondly, micro-ICF could provide knowledge about the construction of fusion weapons. The first US hydrogen bomb was exploded only a year after Teller and Ulam realized how to compress and heat up the secondary. This is an idea that is also very important in the concept of hohlraum targets (see appendix A). It should be kept in mind in this connection that Germany, Israel, Canada, and Japan all have significant ICF programs.

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* For a critical evaluation of arguments given for continued testing see [19] or [20].

† For the role of the timing of a CTB aimed at preventing the development of third-generation nuclear weapons see [21].

‡ For a discussion of applications of fusion reactors see [23].

CRITERIA FOR IDENTIFYING THE MAIN GOALS OF R&D

Not all potential applications of ICF have the same technical requirements. An ICF power plant, for example, needs a gain of at least $G = 100$ and drivers with pulse frequencies over 5 per second, whereas for many military applications $G = 1$ or less and pulse frequencies of about 1 per day might be sufficient.

The emphasis of an ICF R&D program will, therefore, depend on the specific application sought. Consider, for example, R&D on ICF laser drivers and on target design.

A theoretical assessment,[24] which agrees with results obtained at Livermore using sophisticated and classified computer simulations,[25] shows that, in principle, a driver energy of about 1 megajoule will be necessary to achieve a gain greater than 1. The only laser that in the near future promises to deliver such a high energy at a low enough wavelength is the neodymium–glass laser. A gain of 100—the minimum requirement for a fusion power reactor—would require a driver energy of about 1–50 megajoules. Critical assumptions made in this assessment are that the outer fusion material is compressed with a minimum of early heating and without serious instabilities, and that about 5–15 percent of the driver energy contributes to heating the core.

Good progress has been made on these goals during the past few years. For example, at Livermore, a classified target design has been experimentally tested that fulfills the essential requirements. The results have been obtained within a classified underground target test program, called *Centurion/Halite* jointly conducted by Livermore (Halite) and Los Alamos National Laboratory (Centurion) (see [26], p.25 ff.). The radiation energy released by an underground nuclear explosion was used to provide driver energy.

It is claimed at Livermore that recent results, in particular with the Nova laser and *Centurion/Halite*, give high confidence that the goal of producing high gain using a 10-megajoule driver is indeed achievable. Plans for a laboratory microfusion facility using a new neodymium–glass laser system that can produce such high driver energies exist in the Livermore laboratory, but it is not clear if funding will be approved. The costs of this *Athena* project are estimated at about $750 million.[7,27] A disadvantage of neodymium–glass lasers is that their cooling time of several hours after each shot that makes high pulse frequencies impossible.

Table 1: Advantages and disadvantages of various drivers

Driver type	*Advantages*	*Disadvantages*
Laser	focusable to small spot size advanced technology variable pulse lengths and forms	low energy per pulse low pulse frequencies inefficient energy absorption
Light ions	large energy per pulse good energy deposition uses existing technologies high efficiencies inexpensive, small	uncertain focusability low intensity uncertain beam propagation at required current
Heavy ions	large energy per pulse low current beams compared to light ions high efficiency high repetition rate	very expensive uncertain focusability and beam transport high vacuum is required

Theoretical and experimental work with heavy-ion drivers has also gone forward in recent years in Germany (GSI Darmstadt, Kernforschungszentrum Karlsruhe, IPP Garching) and in the US (Lawrence Berkeley Laboratory, Los Alamos National Laboratory, Brookhaven National Laboratory).[28,29,30] Heavy ions offer high energies, powers, and pulse frequencies, high efficiencies and good energy deposition. However, heavy-ion driven research is still in its infancy.

Table 1 lists the advantages and disadvantages of different drivers,[1] and Table 2 outlines the main technical requirements of the potential applications most often discussed: military applications and energy production.

From these tables, it appears that there are clear differences in ICF R&D strategies with civilian and military objectives. For example, the power reactor requirement for a pulse frequency of at least 5 per second; this could never be achieved by a neodymium–glass laser driver such as is proposed by Livermore. Other lasers that might, in principle, achieve such frequencies at the high pulse energies required for ICF are highly unlikely within the foreseeable future. Therefore, any claim that an important goal of ICF R&D is energy production should be sceptically judged when the main focus of the R&D remains on laser drivers.

Heavy-ion drivers have the most promising prospect for the realization of high driver frequencies. In principle, it seems possible to develop heavy-ion drivers that fulfill all necessary requirements, although this is far from certain. The development of heavy-ion drivers is still in its infancy.

The difference between these two paths is depicted in figure 3. The laser path promises many military applications in a short time but is highly unlikely to contribute to the most important civilian applications. The heavy-ion path offers applications only in the long term, but leaves hope for the civilian options.

Table 2: Criteria for the assessment of ICF goals

Goal	*Main requirement for fulfilling the goal*	*Corresponding technical characteristics*
Power reactor	high pulse energy large maximum pulse power high pulse frequency high efficiency of driver good energy coupling	according to present knowledge possible only with heavy ions
	quick target fabrication	requires simple target design
Physics of thermonuclear weapons	good knowledge of physical processes	sophisticated diagnostic methods, hohlraum targets
	high pulse energy large maximum pulse power	neodymium–glass laser is the most promising
	flexible experimental facilities	flexibility in radiation geometry, target geometry, materials...

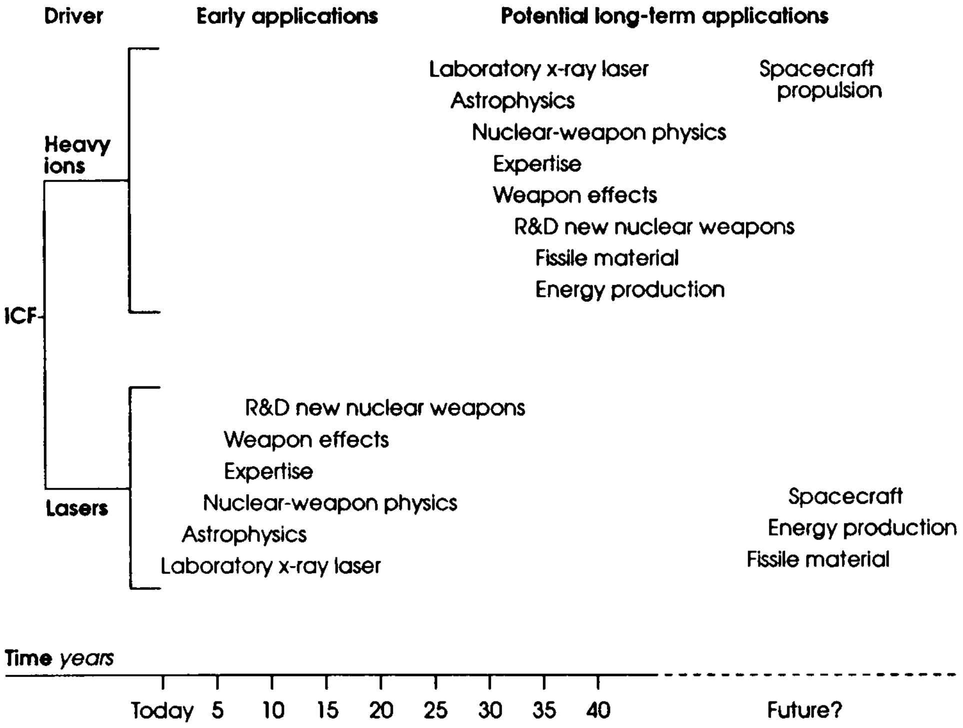

Figure 3: An example of an R&D bifurcation. Under the assumption that R&D projects are funded for practical reasons, the concentration of ICF R&D on laser drivers instead of on heavy ion drivers may be interpreted as a strong indicator that interest in military applications is paramount.

CONCLUSION: ARMS CONTROL ON AMBIVALENT R&D?

On the basis of this case study, we conclude that one of the indispensable prerequisites of any attempt to control weapon technology at the R&D stage—the identification of the true goals of the R&D—is not necessarily impossible if the program is large, centrally planned, and dependent on governmental funds. Thus for example the best indicator that the US ICF program is directed towards military applications is the emphasis that has been placed on laser drivers rather than heavy-ion drivers.

Open international cooperation appears the most promising and most realistic means of constraining big military R&D. The status of international cooperation in ICF is very different from that in magnetic confinement fusion (MCF). So far, international cooperation in ICF research has been on a small scale and limited in participation, because in some countries significant portions are classified. MCF, on the contrary, is an outstanding example of international cooperation, motivated mainly by civilian objectives—in this case, fusion energy power.* One way to ensure that ICF research follows a civilian path primarily would be to expose the research to open scientific exchange. Nations should strive to abolish all classification of scientific research, and to involve international staff in all big R&D science. But the political willingness to accept foreign scientists and inspectors in defense laboratories is still generally lacking. There are always fears that another country would gain some militarily useful knowledge. Therefore arms control constraints on R&D seem most promising when both sides are at the same stage of R&D.

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Appendix A

FUNDAMENTAL PRINCIPLES of INERTIAL CONFINEMENT FUSION

In ICF, a certain mass of themonuclear fuel is compressed by a rapid pulse of energy from the driver. This energy causes ablation of part of the fuel or of its containment (figure A-1). The remainder of the fuel implodes due to the recoil (ablation pressure). This must occur with as little preheating of the interior fuel as possible in order to achieve a high density, ideally as an adiabatic compression. At the end of the compression stage, the fuel in the center must be heated up to temperatures that enable fusion reactions. These fusion reactions then release energy in the form of kinetic energy of the reaction products. Part of this energy is deposited into the adjoined fuel, causing a *burn wave* to travel through the compressed fuel until it reexpands. During this time the fuel is confined by its own inertia.

In order to achieve a gain greater than 1 (ignition), the process requires very high temperatures and pressures and relatively long confinement times. The *confinement time* is the time during which the high temperatures and pressures can be maintained.

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* This aspect is also emphasized in the literature on fusion research. For example, see [31], p.1646.

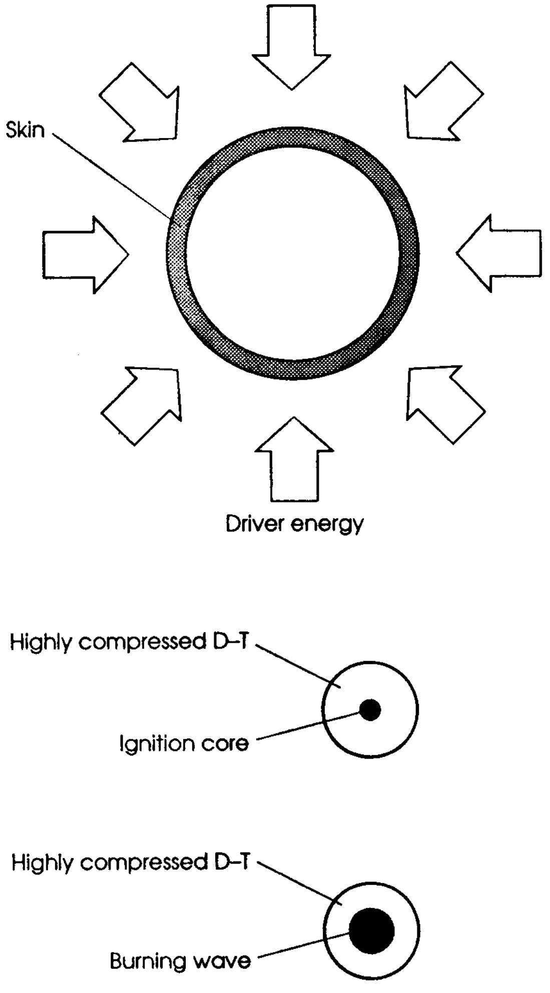
The easiest fuel to ignite in microexplosions is a mixture of deuterium and tritium, which react as follows:

$$D + T \rightarrow He + n + 17.6\ \text{MeV}$$

This reaction produces a helium nucleus and a neutron, both with kinetic energy.

The ignition condition for a given temperature T is described by the so-called *Lawson criterion*; for deuterium and tritium this criterion is

$$n\tau \geq 10^{14}\ \text{s cm}^{-3} \text{ for } T = 10\ \text{keV}$$



1. The outer part of the wall is evaporated by the driver energy, the rest of the pellet is imploded, compressing the D–T fuel.

2. Now the fuel is highly compressed. Its inner part ("core") is heated up to fusion temperatures.

3. The thermonuclear burn wave travels rapidly from the core to the outer regions before the compressed material starts expanding again.

Figure A-1: The stages of inertial confinement fusion (schematic representation).

where n is the density of the fuel and τ the minimal confinement time.

Thus the product of the density n and the confinement time τ (the so-called *confinement parameter*) must exceed a certain value in order to ignite the fuel. The minimum temperature at which the alpha particle production rate exceeds the radiation energy loss rate is $T = 4$ keV. Thus far, ignition has been achieved only using a fission bomb as driver.

The yields of ICF must be small enough to handle the explosions within a laboratory facility. A practical limit is 1 ton chemical explosive equivalent. Because of this energy release limit, the mass of an ICF fuel pellet must not exceed a few milligrams in laboratory experiments.

There are two different concepts for microexplosions, involving *directly* or *indirectly* driven targets. Directly driven targets must be spherically illuminated by intense laser light. A disadvantage of this method is that small asymmetries, inherently present in laser light, are amplified during the implosion of the pellet causing instabilities in the fusion process. The tolerance for spherical symmetry of the implosion is under 2 percent,[32] a requirement that has not as yet been fulfilled by direct drive.

The concept of indirectly driven targets (also called *hohlraum targets*) is more promising. Within this concept the fusion pellet is embedded in a cavity which is heated by laser or particle beams causing isotropic x-radiation in the cavity (see figure A-2).

This isotropic radiation is able to drive a very symmetric implosion. Unfortunately most US research on this subject is classified. However, most underground nuclear explosions have reportedly been used to heat hohlraum targets with x-rays.[33]

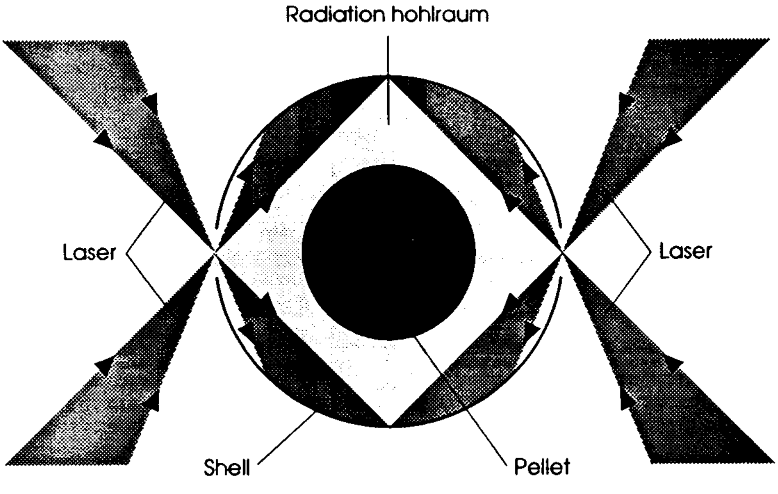


Figure A-2: Scheme for an indirectly driven pellet (25). The fusion pellet is centered in a radiation hohlraum, here being heated by laser beams that enter the hohlraum through two small holes. Part of the radiation is converted into x-rays at the inner surface of the cavity by multiple absorption and reemission processes. This creates an isotropic radiation field (light shading) in which the inner pellet is imploded in a very symmetric way. A major part of the US ICF program uses hohlraum targets (3).

Appendix B
STAGE OF R&D

The most important sites for ICF experiments[7,34,35,36] appear to be: Lawrence Livermore National Laboratory, Los Alamos National Laboratory,[37] Sandia National Laboratory,[38] University of Rochester,[39] Naval Research Laboratory, Osaka University,[40] Lebedev Physical Institute in Moscow,[41] and Limeil in France. Table B-1 provides a listing of the drivers used and their key parameters.

Some smaller, but nevertheless very important programs are under way in Germany, Great Britain, Israel, and Canada.

Table **B-1**: Some important ICF drivers

Facility	**Organization/ location**	**Driver type/ wavelength**	**Pulse**	
			energy	**duration**
		nanometers	*kilojoules*	*nanoseconds*
Nova	LLNL,	Nd–glass laser		2–3
	Livermore, US	1,054	125	
		527	80	
		351	55	
Aurora	LANL,	KrF laser		
	Los Alamos, US	248	10	5
PBFA II	Sandia National Lab.	Light ion	1 MJ	10–20
(goal)	Albuquerque, US	source		
OMEGA	University of	Nd–glass laser		
	Rochester, US	1,054, 527	3 or 2	0.5 or 1
		or 351		
Pharos	Naval Research	Nd–glass laser		
	Laboratory, US	1,054, 527	1.3	
GEKKO XII	Osaka University	Nd–glass laser		
	Japan	1,054	30 or 5	1 or 0.1
Delfin 1	Lebedev Institute	Nd–glass laser		
	Moscow, USSR	1,054	10	0.5–5
Phebus	Limeil,	Nd–glass laser		
	France	1,054	10	1
		527	4	1

NOTES AND REFERENCES

1. J. Duderstadt and A. Moses, *Inertial Confinement Fusion* (New York: John Wiley and Sons, 1982).

2. T.H. Johnson, "Inertial Confinement Fusion: Review and Perspective," *Proc. IEEE* **72** (1984), p.548.

3. J. Meyer-ter-Vehn, "Zur Physik des Fusionspellets" (On the Physics of the Fusion-pellet), *Phys. Blätter* **43** (1987), p.424.

4. A. J. Glass, "An Historic Overview of ICF: What Have We Learned?" *J. Vac. Sci. Techn.* **A4** (1986), p.1098.

5. "National Defense Authorization Act for Fiscal Year 1989," Report of the Armed Services Committee, House of Representatives on H.R. 4264, 100th Congress, second session, report 100-563, p.395.

6. W. Happer, ed., *Review of the DoE's Inertial Confinement Fusion Program*, (Washington DC: National Academy of Sciences, 1986).

7. E. Storm, J.D. Lindl, E.M. Campbell, T.P. Berrat, L.W. Coleman, J.L. Emmett, W.J. Hogan, J.T. Hunt, W.F. Krupke, and W.H. Lowdemilk, *Progress in Laboratory High Gain ICF: Prospects for the Future*, (Livermore, California: UCRL-99427, December 1989).

8. W.J. Hogan, "A Multiuser Development Scenario for ICF," in *Laser Interaction and Related Phenomena*, p.745.

9. T. Cochran, W.M. Arkin, and M.M. Hoenig, *Nuclear Weapons Databook Volume 1: U.S. Nuclear Forces and Capabilities*, (Cambridge, Massachusetts: Ballinger, 1984).

10. H. Morland, "The H-bomb Secret," *The Progressive*, November 1979.

11. W. Seifritz, *Nukleare Sprengkörper—Bedrohung oder Energieversorgung für die Menschheit?* (Nuclear Explosive Devices—Threat or Energy Supply for Mankind?), (Munich, Germany: Thiemig-Verlag, 1983).

12. J. Meyer-ter-Vehn and M. Murakami, "Analysis of Heavy Ion Fusion Targets," Invited talk given at the International Symposium on Heavy Ion Inertial Fusion, Monterey, California, 6–9 December 1990.

13. With the use of ion beams, temperatures up to 1 eV have been achieved so far; by 1992, temperatures are expected to reach 10–30 eV. J. Meyer-ter-Vehn, S. Witkowski, R. Bock, D.H.H. Hoffmann, I. Hofmann, R.W. Müller, R. Arnold, and P. Mulser, "Accelerator and Target Studies for Heavy Ion Fusion at the Gesellschaft für Schwerionenforschung," paper 214, *Bull. Am. Phys. Soc.* **34** (1989), p.1936.

14. J. Meyer-ter-Vehn and C. Schalk, "Selfsimilar Compression Waves in Gas Dynamics," *Zeitschrift f. Naturforsch.* **37a** (1982), p.955.

15. K.W. Brueckner and S. Jorna, "Laser-Driven Fusion," *Rev. Mod. Phys.* **46**, 325 (1974).

16. Arms Control and Disarmament Agency, Washington DC, Fiscal Year 1981 Arms Control Impact Statements, p.460 ff.

17. S. Younger, private communication 1987.

18. E.E. Fill, "Röntgenlaser für das Laboratorium" (X-ray Laser for the Laboratory), *Phys. Blätter* 44 (1988) p.155.

19. *Toward a Comprehensive Nuclear Warhead Test Ban*, (Washington DC: The International Foundation, January 1991).

20. R.E. Kidder, *Maintaining the U.S. Stockpile of Nuclear Weapons During a Low-Threshold or Comprehensive Test Ban*, (Livermore, California: LLNL report UCRL-53820, 1987).

21. D.L. Fenstermacher, "The Effects of Nuclear Test-ban Regimes on Third-generation-weapon Innovation," *Science & Global Security*, **1** (1990), p.187.

22. G.H. Miller, P.S. Brown, and C.T. Alonso, *Report to the Congress on Stockpile Reliability, Weapon Remanufacture, and the Role of Nuclear Testing* (Livermore, California: LLNL report UCRL-53822, 1987).

23. T. Umezu and V.F. Demichev, "Interactions with Other Fields," *Nucl. Fus.* **30**, p.1935.

24. J. Meyer-ter-Vehn, "On Energy Gain of Fusion Targets: The Model of Kidder and Bodner Improved," *Nucl. Fus.* **22** (1982), p.561.

25. J. H. Nuckolls, in *LLNL Laser Prog. Ann. Rep. 1979* **2**, p.3.

26. United States General Accounting Office, Briefing Report to the Chairman, Armed Services Committee, House of Representatives, "Performance of Participants in DOE's Inertial Confinement Fusion Program," GAO/RCED-90-113BR, March 1990.

27. E. Storm, "Progress Toward High-Gain Laser Fusion," (Livermore, California: LLNL Report UCRL-98828, 1989). Prepared for submission to *Proceedings of 19th ECLIM*, Madrid, 3–7 October 1988.

28. T.F. Goodlove, "Accelerator Research for Heavy Ion Inertial Fusion," *Nucl. Instr. Meth.* **B24/25** (1987), p.736.

29. R.C. Arnold and J. Meyer-ter-Vehn, "Inertial Confinement Fusion Driven by Heavy-Ion Beams," *Rep. Prog. Phys.* **50**, 559 (1987).

30. K.A. Long, "Range Shortening, Radiation Transport, and Raleigh–Taylor Instability Phenomena in Ion-Driven ICF-Reactor-Size Targets: Implosion, Ignition, and Burn Phases," *Phys. Rev.* **A35** (1987), p.2631.

31. International Fusion Research Council, "Status Report on Controlled Thermonuclear Fusion," *Nucl. Fus.* **30**, p.1641.

32. M. Murakami and J. Meyer-ter-Vehn, "Radiation Symmetrization in Indirectly Driven ICF Targets," submitted to *Nuclear Fusion*, January 1991.

33. William J. Broad, "Secret Advance in Nuclear Fusion Spurs a Dispute Among Scientists," *New York Times*, 21 March 1988, p.7.

34. S. Nakai, "Inertial Confinement," *Nucl. Fus.* **3**, p.2863.

35. Ibid., p.1779

36. W. Hogan, "Progress in ICF at Lawrence Livermore Laboratory," in *Laser Interaction and Related Phenomena*, p.689.

37. P.D. Goldstone, J.R. Ackerhalt, L.S. Blair, D.C. Cartwright, L.R. Foreman, C.A. Fenstermacher, A. Hauer, D.E. Hanson, J.K. Hoffer, R. Kristal, W.C. Mead, L.A. Rosocha, and D.C. Wolson, "ICF Research at Los Alamos," in Hora and Miley, eds., *Laser Interaction and Related Phenomena*, pp.469–482.

38. D.L. Cook, "PBFA II Progress and Plans," in Heinrich Hora and George H. Miley, eds., *Laser Interaction and Related Phenomena* **8** (New York: Plenum Press, 1988), pp.619–632.

39. R.L. McCrory and J.M. Soures, "Laser Fusion Experiments at the University of Rochester," *Nucl. Fus*, **25** (1985), p.1333.

40. C. Yamanaka, "Inertial Confinement Fusion at Ile Osaka," *Nucl. Fus.* **25**, (1985), p.1343.

41. N.G. Basov, G.V. Sklizov, W. Brunner, and K. Junge, "Untersuchung lasererzeugter Plasmen für die Kernfusion" (Investigation of Laser-produced Plasmas for Nuclear Fusion), *Ann. Phys*. **42**, 394 (1985).