Department of Energy
Washington, DC 20585

March 15, 2023

Subject: Mandatory Declassification Review Request 2020-0003

Dear

This is in final response to your request for Mandatory Declassification Review under section 3.5 of Executive Order 13526, *Classified National Security Information*. In your request, dated May 9, 2020, you requested the review and release of the following document:

"In the mid-1970s, Edward Teller compiled a book on fusion research at Lawrence Livermore National Laboratory (LLNL). The book was comprised of chapters written by several individuals including Dr. Teller, Dr. Gerald Yonas, and others."

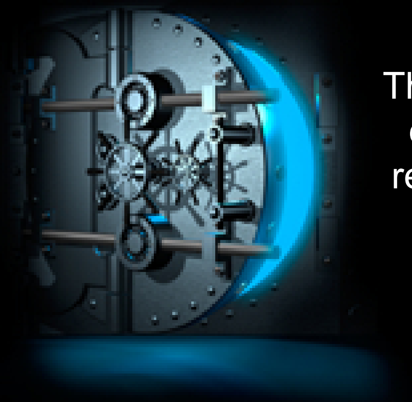
The Office of Classification forwarded a search request to organizations within the Department of Energy. Unfortunately, their records do not list or hold this document/book. Enclosed you will find declassified document R2D2 PHYS 78-3. This is the only responsive record we could locate that resembles information regarding your request. This document is provided in its entirety.

I appreciate the opportunity to assist you with this matter. If you have any questions about the request or this correspondence, please contact Mr. Nick Prospero of my staff, at (301) 903-9967.

Sincerely,

Edith A. Chalk
Director
Office of Classification
Office of Environment, Health,
Safety and Security

Enclosure



Lawrence Livermore National Laboratory

Review And Results Transmittal (R2D2) of Document Declassification/Downgrading

R2D2- PHYS 78-3
(Type document ID# here)

12-12-2022
(Effective Date)

Document Identification:

Fusion by Inertial Confinement
(Full Title, it title is classified, create an unclassified title and place here)
' All Titles Entered MUST Be Unclassified '

Edward Teller
(Name of the author, signer, or originator)

September 20, 1978
(Document date)

14
(# of pages in document

SRD
(The initial classification of the document)

PHYS 78-3
(Identification number or Cross-reference number)
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101.2.3, 101.3.1, 202.4.2, 203.2, 101.4.8

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Review Approval

Thom Scott Carm
Signature
12 Dec 2022
Date

R Grayson
Signature
12/12/2022
Date

Thomas Scott Carman
(Name of the DC or DD)
DC.
(Title)

RODNEY GRAYSON
(Name of DD)
Classification Adv
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September 20, 1978

WHEN SEPARATED FROM INCLOSURES, HANDLE
THIS DOCUMENT AS unclassified

Mr. Duane C. Sewell
Assistant Secretary
for Defense Programs
Department of Energy
Washington, D. C.

Dear Duane:

Enclosed you will find a few pages written by me and discussed within the Laboratory which I intend to use as an introduction of the second volume (Inertial Confinement Fusion) of the controlled fusion volumes. It is, of course, submitted in a properly classified form according to present rules. We believe that it can and should be declassified in a short time. I have incorporated in it the main statements whose declassification will make it possible to write the rest of the book in a reasonable manner.

You remember the arguments about the need for declassification. I, therefore, will not repeat them here. It is good of you to have taken an interest in this manner.

Hoping to see you in the near future.

Sincerely,

Edward

Edward Teller

P. S. Expert opinion, with which I tend to agree, claim that declassification of additional material will be highly desirable. We hope to submit this within a couple of months. At the same time, rapid declassification of the present material will remove many difficulties and will get us started on writing the volume.

Enc. Phys 78-3, 1/2A

~~RESTRICTED DATA~~

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PHYS 78-3

THIS DOCUMENT CONSISTS OF 13 PAGES
NO 2 OF 2 COPIES, SERIES A

FUSION BY INERTIAL CONFINEMENT

by Edward Teller

Sept. 20, 1978

Introduction

The main outlines of controlled fusion by inertial confinement are simple, logical and, indeed, are determined in an almost unique manner by the nature of the problem. The execution, in contrast with the principles, is complex, difficult and challenging. Here we emphasize the principles which have been clear for more than 15 years. For a number of reasons some of these principles have not been generally discussed.* The need for such a discussion has become ever more urgent with recent technical developments.

The basic idea is that inertially confined microexplosions can be produced in thermonuclear fuel, such as a mixture of deuterium and tritium, if the fuel is compressed to a density at least a thousand times greater than the density of the normal liquid. Indeed, according to an approximate similarity law, thousand-fold compression permits the use of one millionth of the mass of uncompressed fuel in an explosion; the result is a release of approximately a millionth of the explosive energy in a single event. Such explosions could be repeated in a power plant once a second, or more frequently. Even though each single explosion will release as much as 10^{16} ergs -- an energy approaching the yield of one ton of TNT -- power plant designs have been discussed which would permit the repetition of such an explosion

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*In the Lawrence Livermore Laboratory, John Nuckolls, Stirling Colgate, Ray Kidder and Lowell Wood have been particularly active in this discussion.

[redacted]

CLASSIFIED BY:
John H Nuckolls

[redacted]

a billion (10^9) times, with exploitation of the energy released.

A discussion of the approximate similarity law which makes such microexplosions possible also indicates the way in which the necessary compressions that precede the explosions may be produced. Therefore, we turn to the discussion of this similarity law.

Similarity holds if only hydrodynamic processes and binary collisions are taken into account. These binary processes include thermonuclear reactions, emission of radiation during collision of two participants, binary energy transfer between two particles -- which also is the main mechanism of heat conduction -- and also collision between light quanta and electrons. Non-binary processes will be mentioned below. The derivation of similarity becomes particularly obvious when a numerical example is considered.

We shall compare an explosion in an uncompressed fuel mass with one in thousand-fold compressed fuel having one millionth the mass. The linear dimensions in the latter case are decreased by a factor of thousand. Thus, in the compressed case the volume is reduced a billion (10^{-9}) fold, and therefore the amount of material is indeed a millionth (10^{-6}) of the uncompressed material, the density having been increased a thousand (10^3) fold.

In similar stages of the explosion, the energy per particle, and thus the temperature and the sound velocity, are the same. The time of disassembly is therefore reduced thousand-fold (10^{-3}). At the same time, the particles of the plasma interact with each other a 1000 times faster producing energy in each effective interaction. Energy loss and energy transfer also occur a thousand times more rapidly. Therefore the two explosions indeed occur in a similar manner, in that all processes are speeded up a thousand-fold over one-thousandth the time duration, in the compressed case.

In general, it is easy to see that n-fold compression leads to an n-fold reduction of the time scale and an n^2-fold reduction in the masses and total energies involved in the explosion. The fuel burn efficiency remains the same.

For two reasons the similarity relation is not precise. One is the Coulomb-Debye shielding effect in the processes of particle-particle energy transfer. Shielding necessarily implies interaction of more than two particles. The other is light absorption in which a light quantum is absorbed by the combined interaction of an electron and an ion, in which three particles participate. (In the relativistic approximation, a light quantum may also be absorbed by a pair of electrons.) Both of these effects tend to accelerate the fuel burn reaction in the compressed state.

In a thoroughly simplified description of a thermonuclear reaction, three processes must be considered (in addition to the hydrodynamic motion of the thermonuclear fuel). One is the thermonuclear reaction itself. This depends in excellent approximation on the collision of two fusile nuclei. The second is the energy loss of electrons to the ambient radiation field. This loss is cut down by re-absorption of light quanta, a three-body process which becomes important only at high densities. The third is the energy transfer from nuclei to electrons. After fuel ignition the temperature of the electrons is kept below that of the nuclei, since the electrons lose energy to radiation. In this electron-ion energy transfer term, a logarithmic factor appears: the argument of the logarithm is the ratio of the maximum electron collision parameter to the minimum collision parameter. At high fuel densities, the maximum collision parameter decreases, which means that distant collisions are becoming relatively ineffective. Thus the transfer of thermal energy from nuclei to electrons decreases, the nuclei retain more energy and the thermonuclear reaction proceeds rapidly.

For D-T fuel, the burn efficiency is increased with ion temperature if the ion temperature does not exceed 25 keV. (At higher temperatures, the sound speed increases and the inertial containment time decreases more rapidly than the burn rate increases.)

Below 25 keV the two corrections, photon absorption and shielding, both are helpful. These two effects help to determine the manner in which the microexplosion has to be engineered.

In the limiting case in which photon absorption occurs rapidly compared to escape of radiation from the plasma, a black-body temperature will eventually be reached in the plasma, whose temperature is equal to that of the plasma's electrons. However, if the fuel of the microexplosion is the highly reactive D-T mixture, this equilibrium may be established only at densities exceeding that of the normal liquid by more than a factor 10^5. Equilibrium with radiation may still be achieved by introducing a high-Z material into the fuel. This has the disadvantage of producing more radiation emission, and the corresponding advantage of engendering more radiation absorption. In addition, there is the disadvantage of increased ion-electron coupling. The advantage may be enhanced by adding a fissionable substance (U or Pu) to the system, which will add to its energy production. Whatever advantage may be gained in this manner has to be weighed against the drawback of the appearance of radioactive fission products. Since the containment of a long sequence of microexplosions will be a substantial power plant engineering problem in any case, it is preferable to avoid the appearance of fission products in the repetitive explosions. In the present volume we shall restrict ourselves to the discussion of pure fusion explosions, though the high energy neutrons emitted in the fusion process may also be utilized to interact with fissionable materials after the explosion has occurred. Thus we do not disregard the fusion-fission hybrid possibility as long as the fission process occurs in a non-explosive manner.

For the thermonuclear fuel we shall consider only essentially equimolar mixtures of D-T.

In connection with the energy transfer from the fuel's nuclei to its electrons, it is instructive to consider the case where the electrons are in a Fermi-degenerate state. In this case the energy transfer vanishes and so does the emission of photon energy by the electrons.

It is easy to verify in a formal way that the logarithm which occurs as a factor in the energy transfer from nuclei to electrons vanishes in the Fermi-degenerate case. The numerator in the argument of the logarithm, which is the maximum collision parameter, will become the velocity of the electrons v_F at the top of the Fermi sea divided by the plasma frequency ω. In the degenerate case the driving force in this frequency is not electrostatic, but is rather due to the energy increase caused by the density increase and the Exclusion Principle. This gives $\omega \approx \frac{\hbar n^{2/3}}{m}$ (m = mass of the electron, n = number of electrons per unit volume). The maximum collision parameter will become $\frac{m v_F}{\hbar n^{2/3}}$. The denominator in the argument of the logarithm is the minimum collision parameter, which is the de Broglie wavelength $\frac{\hbar}{m v_F}$. The ratio of the two parameters is $\frac{m^2 v_F^2}{\hbar^2 n^{2/3}}$. But $\frac{m^3 v_F^3}{\hbar^3 n} \approx 1$ is the condition for Fermi degeneracy. Therefore we see that in the degenerate case the argument of the logarithm approaches unity, and the energy exchange rate will vanish. It would seem then that the ignition of the fuel becomes easier. However, it is difficult -- if not completely impractical -- to achieve ignition temperatures in a Fermi-degenerate state: at temperatures of a few keV, the fuel density must be more than 10^5 x liquid. Furthermore, propagation of thermonuclear burn waves into degenerate D-T is not significantly easier, because fusion energy is deposited over longer distances.

When we try to create a microexplosion, a major difficulty is to achieve the required high compression. Of course, one may be satisfied with a lesser compression, but in this case the individual explosions will become larger and more difficult to repetitively contain, and the size of the laser or other driver required to initiate the explosion may become impractically large and expensive. The total energy required for the compression decreases as the fuel density becomes greater, and the amount of fuel to be compressed of course becomes less, in order to realize a given burn efficiency. In a n-fold compression (for the limiting case of big compression values), the energy per particle goes up as $n^{2/3}$ whereas the number of particles to be compressed decreases as n^{-2}. Thus the total compression energy required varies as $n^{-4/3}$. It is therefore clear that we must aim for high values of n -- but not too high -- since the required energy of compression must be sufficiently small compared to the fusion energy released so that the inefficiencies in the implosion, reactor, and driver may be accommodated. These considerations determine an optimal D-T density of 10^3 to 10^4 x liquid, providing the compression results in Fermi-degenerate electrons. If the D-T is not compressed to a degenerate state, then more energy will be required and even a megajoule-scale implosion driver system must have an efficiency ≥ 10%, in order to be practical.

The overall energy accounting also imposes the requirement that only a small fraction of the D-T can be compressed to ignition temperatures.

This condition and the degeneracy condition are simultaneously satisfied by an appropriate deviation from adiabatic compression in the central region of the compressed D-T fuel. The bulk of the highly compressed fuel is then ignited by the thermonuclear energy initially produced in this central region.

It is difficult to obtain these high compressions for two separate reasons. One is that, in order to accomplish the compression, energy must be made available in a small volume in an exceedingly short time interval, without causing significant entropy changes in the fuel due to shock or internal heating by long range particles. We shall discuss below the various plans for accomplishing this.

The second reason is that the compression must be applied in a highly symmetric fashion. Otherwise the fuel, instead of being compressed, will be fragmented into smaller portions. In order that spherical symmetry should be maintained, it is furthermore desirable that the required compression be accomplished in a single shock-like event. Reverberations in a dense system which is pushed inward by the higher pressure of a hotter, less dense material results in Taylor instability. Small deviations from sphericity grow exponentially and, as a result, the less dense material, instead of pushing the heavier material ahead of itself, will penetrate it. We are faced, therefore, with two seemingly irreconcilable requirements: compression by a rapidly applied impulse to high densities, but without significant entropy changes. However, detailed calculations support the intuitive notion that a sufficiently hydrodynamically stable and isentropic inward acceleration of the fuel is possible with a 'gradually' increasing pressure, provided the fuel capsule is enveloped by a spherically symmetric energy source without undue fuel 'preheat' by energetic particles.

There is one obvious, even rather compelling, way to accomplish our purposes: Collect and confine the energy which drives the implosion in a cavity or "hohlraum", in the form of electromagnetic radiation. A hollow spherical capsule, which may be made of low Z material such as Be, containing the thermonuclear fuel will be placed inside such a cavity, preferably but not necessarily at its center. In order to develop the required implosion pressures, radiation having a black body temperature of one hundred to a few hundred electron volts (T = several million °K) must be applied to the capsule. The electromagnetic radiation in this hohlraum will therefore consist of not very hard x-rays. The walls of the cavity should contain high-Z material to minimize the loss of heat energy into or through them. Repeated absorption and re-emission processes will produce a homogeneous radiation field in the cavity. Thus the fuel capsule will be exposed to highly isotropic, soft x-ray radiation. Sustained, spherically symmetric pressures required for adiabatic fuel compression are generated by subsonic ablation of the capsule surface by this radiation.

Our scaling law has a significant bearing on the proposed arrangement in that similarity scaling does <u>not</u> apply to radiation equilibrium. Indeed, equilibrium could not be established without the absorption process, which is not a binary process and for which the scaling law is not valid. In the high-Z material of the walls of the cavity, temperature equilibrium will, be attained. If the temperature of the radiation is made to be high enough, we have a means by which thermal energy concentration into the capsule's outer surface can be accomplished, particularly since the energy density in the cavity can be regulated in time in a way which is practically independent of other constraints on the system. If we had chosen another method to transfer energy to the fuel, the similarity scaling laws would usually apply to the transfer mechanism. The resultant restriction might well change the intrinsically challenging problem of strongly compressing the fuel into a virtually insoluble one.

Another approach that has been proposed is to use an intense laser beam to produce hot electrons whose heat conductivity is great enough to realize an isotropic pressure around the capsule. Except for the case of sufficiently short wavelength lasers, there are doubts whether this approach will succeed, since the deposition of laser energy brings about instabilities and superthermal electrons which prematurely deposit energy deep in the capsule (preheat). This approach has one common feature with the one we discussed above. In neither case does the similarity law apply to the system as a whole, and technical success may be achieved by adjusting the dimensions of the system. An important advantage of the use of thermal x-radiation is that by employing a low-Z shield in sufficient thickness, we can permit energy transfer by x-rays while we filter out fast electrons which may cause preheat problems.

Apart from the high degree of spherical symmetry with which the compressive push should be exercised, it is also important to deliver this push in an appropriately time-programmed manner. It is desirable to increase the pressure in such a manner that, due to the higher velocity of sound propagation in the already-compressed region within the fuel, an original, relatively weak inward-going shock will be followed by an adiabatic compression. If the fuel mass is not hollow, then in order to obtain ignition, it may be desirable to program the increase in pressure in such a way that the later portion of the compression wave should overtake and strengthen the original shock, before that shock reaches the center of the fuel sphere.

The question remains: by what technical means can this program be accomplished? There are, in principle, several solutions.

The best solution is to program the rate at which energy is supplied to the cavity so that the temperature in the cavity gradually increases in the optimal fashion.

An apparent method of influencing the density of radiation energy in the cavity is loss to the cavity walls. If the cavity wall is evaporated at a relatively low temperature and blown inward, it is possible to increase the energy density in the cavity. However since the energy density in the blackbody radiation is so small compared to that in matter at 200 eV temperatures, this approach is quantitatively totally insufficient.

Of course, what really matters is not the cavity's energy density but the pressure applied to implode the capsule. This pressure is generated by blowing off the outer surface of the capsule, thus accelerating the remainder toward the center, due to the reaction. Variation of the opacity of the capsule with radius could result in an increasing pressure. The difficulty is that all layers of the capsule must be strictly spherical if symmetric motion is to result. How to accomplish this at a small cost (capsules may in the end be consumed at the rate of one per second or more) may become a major engineering problem. Another difficulty is that to generate an increasing pressure, higher opacity material must be on the outside of the capsule. This material then impedes the flow of radiant energy to the inner layers, so that higher cavity temperatures are required to achieve the maximum required pressures.

Finally, we must introduce the Prince of Denmark into the performance of Hamlet. What is the origin of energy that enters the cavity? The variety of possible answers to this question is one of the most attractive features of the hohlraum approach.

The most popular contender at present is a laser beam. Efficient conversion of such a beam into x-rays has been observed. The development of laser technology is rapid. The focusing of the beam into a hole in the cavity does not present any great difficulty. In experiments beginning in 1975, laser-energized hohlraums have achieved radiation temperatures of 160 eV, and relatively simple capsules have been imploded to thermonuclear temperatures. Temporal shaping of the laser pulse to realize a time-programmed cavity temperature has been demonstrated. Lasers are now considered as the most probable driver energy source for realizing controlled fusion via the inertial confinement approach.

An alternate source is a heavy ion beam generated by a very powerful version of the equipment which is now used in high energy physics research. In this case much of the required technology is already available. The heavy ion beam may be readily focussed through a port in the thermonuclear combustion chamber's wall, and stopped in a not-too-massive structure inside the cavity, which is thus heated to several hundred volt temperatures, which radiates to fill and replenish the hohlraum against losses. It is not clear at present which of these two approaches will have a better engineering feasibility.

A further possibility is to use a beam of relativistic electrons as the energy source for the hohlraum. One might expect that in this case too much material is needed in which to deposit the beam energy effectively within the cavity. Fortunately, self-generated electric and magnetic fields and cooperative effects (of the type of two-stream instabilities) may greatly aid the process of deposition. Alternatively, protons (which have a suitably short deposition range) may be accelerated instead of electrons. In experiments, 50 eV hohlraums have been achieved by using the output of pulsed power machines to energize foils, or arrays of wires, confined in a hohlraum.

Finally, it is possible to use small, high-velocity projectiles as the hohlraum-heating energy source. This approach has received the least attention and development through the present time, but cannot be excluded as a practical possibility. It is the more attractive as the hohlraum heating could be made to occur purely hydrodynamically, and complications of plasma instabilities of any kind could thereby be avoided.

To develop thermonuclear microexplosions into a nuclear internal combustion engine is a possibility that is most challenging and intriguing. But it is also necessary to put the present state of development into perspective: imagine an internal combustion engine at a time when no individual explosion of the proper size has ever been performed. There is every reason to believe that the right kind of microexplosion will indeed be performed, understood, reproduced, optimized and developed. An explosion chamber has been devised which is potentially capable of confining 10^9 one-ton energy yield fusion microexplosions without unacceptable damage by shocks, high temperature, or nuclear radiation. This scheme has neutronically thick, continuously renewable walls formed by sheets or jets of liquid lithium. Uncertainties in reactor first wall designs in magnetic fusion systems involving radiation damage, durability, and economics of replacement are thus bypassed.

However, from the first really successful fusion microexplosion to a practical power system ready to deliver useful energy in the form of electricity or as artificial fuel, there stretches a long road.

It is not too early to discuss practical ways in which inertial confinement fusion may be practical and economical. It is of primary importance that the problem be attacked with the conviction that we shall succeed. It is of equal importance that every step in the proposed development be subjected to thoughtful criticism.

1/2A - D. Sewell, DOE
2/2A - E. Teller

1/1B - M. Rosenbluth