AN ADVANCED FUEL LASER FUSION AND VOLUME COMPRESSION OF p-^{11}B LASER-DRIVEN TARGETS

ADVANCED FUELS

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Progress in inertial confinement fusion development justifies an optimistic view of future concepts. The use of advanced fuels represents a key goal in obtaining future power plants. Prior work on such targets using a deuterium-tritium spark ignition is reviewed and evaluated via the conceptual reactor design LOTRIT. Preliminary calculations presented here also indicate that it may ultimately be possible to achieve a p-^{11}B burn using a volume ignition. However, the parameters required, e.g., 10^5 times solid density, are beyond the reach of present technology.

I. PRIOR DEVELOPMENTS

The advantages of using advanced fuels for fusion have been recognized for a number of years[1] and viewed as a long-range goal for fusion, which would enable this power source to assume its ultimate potential as a very clean and efficient energy supply. However, due to the increasing emphasis on safety and environmental issues,[2,3] advanced fuels assume more urgency and significance.

Two types of advanced fuels have been recognized: (a) deuterium-based reactions, e.g., deuterium-deuterium (D-D), catalyzed deuterium, semicatalyzed deuterium, and D-^{3}He; and (b) proton-based reactions, such as p-^{6}Li and p-^{11}B. The feasibility of burning p-^{11}B was first discussed in connection with its possible use in inertial confinement fusion (ICF) targets.[4] The energy balance required to burn p-^{11}B is very difficult to achieve. However, at that time it was argued that an ICF target would be best suited for such an operation (versus magnetic confinement) due to the elimination of synchrotron radiation energy losses. Further study, however, suggested that the energetics of a p-^{11}B ICF target were marginal at best. In this paper, we re-examine the issue based on new concepts, especially volume ignition.[5]

The p-^{11}B burns with no primary release and very few secondary neutrons; hence, it has received much attention as offering true "aneutronic" fusion. Another example of an aneutronic reaction is ^{3}He-^{3}He, but it is equally difficult to burn. The other fuel that verges on being aneutronic is D-^{3}He, and its energetics are much more favorable. Unfortunately, neutrons from D-D reactions that occur in the mixture result in $\sim$10% of the fusion energy going into neutrons. This might be reduced by polarization techniques,[6] combined with the use of a deuterium-lean mixture.[7] Thus, depending on one's definition of aneutronic, D-^{3}He will approach such an operation with $\sim$1% of the energy released going to neutrons.

While D-^{3}He offers many advantages, it suffers the difficulty of a lack of a "natural" source of ^{3}He. In 1987, however, the situation was radically changed with the revelation that ^{3}He is implanted in the lunar soil due to bombardment by the solar wind.[8] Subsequent studies indicated that mining of the ^{3}He on a relatively near-term basis should be taken as a serious option.[9] Three other sources of ^{3}He still remain feasible, namely, the breeding of ^{3}He in (a) a semicatalyzed deuterium reactor, (b) a special beam-target facility, or (c) the breeding and storing of excess tritium allowing it to decay to ^{3}He (Ref. 10). However, breeding is generally viewed as more complex and less economical than a natural source. How breeding compares with lunar mining from an economic point of view has not yet been studied. These issues require more evaluation; but, at any rate, the lunar ^{3}He discovery quickly revitalized interest in the possibility of D-^{3}He fusion.

II. ISSUES

Before considering possible approaches for burning advanced fuels with ICF, it is constructive to briefly review some of the issues involved in deuterium-tritium (D-T) versus advanced fuel fusion.

Fusion neutrons cause activation of materials associated with an ICF target itself, with the coolant, and with the chamber structure. This activation poses problems for maintenance operations and also greatly complicates the disposal of plant components and the ultimate decommissioning of the plant. Careful selection of materials can significantly minimize the neutron-induced activity. Reduction of neutrons by the use of advanced fuels would be an additional step in this direction. An ultimate goal is to achieve activity of such a low level that final disposal of power plant components as low-level radioactive waste becomes possible. However, conceptual design studies to date have had difficulty in achieving these goals with D-T plants.[2,3]

Tritium, which must be bred in the blanket to refuel a D-T reactor, poses yet another difficult environmental compatibility and safety problem. Tritium is difficult to contain because of its high rate of diffusion through many materials at elevated temperatures. Reactor design studies of D-T fusion plants have attempted to reduce the overall tritium leakage rate to <10 Ci/day. This appears possible, but it remains an open question whether, by the time that fusion becomes operational, even that release level might be viewed as unacceptable.

Due to the need to breed tritium in the blanket, a significant inventory of tritium (tens of kilograms) must be contained within the fusion plant. The resulting tritium release in the event of a major accident represents a serious safety issue for D-T fusion power plants. While the impact of a tritium release would be less than that of fission products released from a fission reactor, the question remains whether people will accept an energy source in the 20th century that involves this issue. Reactor studies to date have not completely resolved this question, although good progress has been made toward minimizing the potential for an accident, e.g., attempting designs that can withstand a loss-of-coolant accident without danger of the blanket components melting. Nevertheless, the magnitude of the tritium inventory leaves open the concern that some accident sequence could still occur that would have the potential for a significant tritium release.

Another issue is the overall plant efficiency. With a D-T fuel cycle, a conventional steam-type energy conversion cycle is normally envisioned. This is the natural choice since most of the energy released is carried by neutrons, which is best coupled to a thermal cycle. Although higher temperature blanket concepts might be feasible, a significant increase in efficiency requires an advanced conversion technique, e.g., direct conversion, which can couple directly to the fusion plasma energy. This becomes more practical with the use of advanced fuels where a larger fraction of energy goes into charged fusion products, which are generally retained in the plasma. Improved plant efficiencies are very important in many localities when waste heat rejection represents a severe limitation in plant siting.

III. ANEUTRONIC POSSIBILITIES

The p-^{11}B represents a speculative long term goal for ICF. However, before considering this, we first review some near-term possibilities, which use advanced fuels but would not go all the way to aneutronic operation. There appears to be several possible routes. If the minimization of the input energy, i.e., drive size, is a key consideration, a burn propagation technique seems crucial. One example is to use a D-T spark-ignited target of the advanced-fuel layered ignitor/pellet nurturing tritium (AFLINT) type to propagate burn into a region containing deuterium.[11] A second approach uses spark ignition, but arranges the target (see Fig. 1) to effectively achieve D-^{3}He operation.[12] In both cases, the objective is to eliminate the need for breeding tritium in the blanket. Tritium used in the spark core would ultimately be replaced by unburned tritium (generated in D-D reactions) recovered from debris from the outer region of the target. Similarly, such a target should be self-sufficient in ^{3}He for those concepts employing it.

This internal breeding target would still result in a significant neutron flux. Thus an activation problem would still be involved, but this approach would have a significant advantage in reducing the tritium inventory required. While this is a compromise that falls

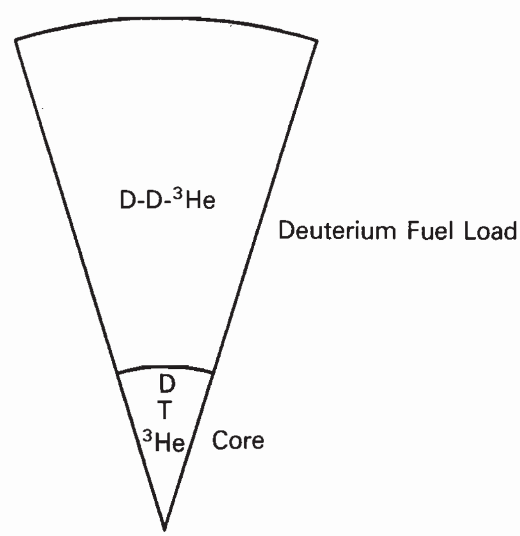

Fig. 1. Basic AFLINT concept for spark ignition.

short of the ultimate goal of a true aneutronic reaction, it could still offer a very attractive approach from the environmental/safety point of view. Furthermore, in contrast to aneutronic concepts, burning the AFLINT-type target (with a deuterium outer layer) appears to be feasible with some modest extension of present heavy ion beam fusion (HIBF) concepts. Thus, it offers a relatively near-term option.

The AFLINT approach was illustrated earlier in a conceptual design study of the LOTRIT reactor.[13,14] The study of a similar self-breeding target reactor design called TAKNAWA-I was conducted in Japan.[15] More recently, the authors considered an alternate approach to burning D-^{3}He, which would eliminate the need for a D-T spark.[5] This approach used volume ignition of a pure D-^{3}He target. The approach was found to be feasible, but resulted in lower gain target and lesser input energy requirements than an AFLINT design. This must be balanced against the advantage of eliminating the neutron and tritium involvement of the spark core.

IV. AFLINT TARGET FOR LOTRIT

Parameters for the AFLINT target used in LOTRIT are outlined in Table I. An important characteristic (ρ ~ density, R ~ capsule radius) is the large ρR required, which is typical of advanced fuel targets. The D-T spark plays an essential role in that it offsets the large energy input that is necessary to ignite such a target, although the ignition requirements are still a factor of 4 or more above that for an equivalent D-T design. This, incidentally, is one of the reasons that a heavy ion beam driver is well suited to such targets. Such an accelerator can readily access the largest energy input regime required. The performance characteristics for an AFLINT target are compared with a more conventional D-T design such as used in HIBALL in Table I. As expected, there is a significant increase in the charged-particle and X-ray output fractions, and a corresponding reduction in the neutron energy fraction compared to the D-T target.

It should be emphasized that this particular target is a "point" design, which has not in any way been optimized. Indeed, some variations on this concept are briefly described in Sec. V where the requirement of an internal breeding ratio of unity is relaxed. This allows some higher gain options but requires an external source of ^{3}He.

TABLE I

Comparison of Energy Splits for Internally Breeding and Nonbreeding Pellet Designs

	Fusion Pellet Type[a]	
	Tritium and ^{3}He Internally Bred	Nonbreeding
Conceptual design	AFLINT	HIBALL
Fusion yield (MJ/pulse)	1 000	400
Repetition rate (Hz)	4	5
Cavity power (MW_{fusion})	4 000	2000
Number of cavities	5	.4
Total power (MW_{fusion})	20 000	8000
Pellet data[a]		
Pellet gain	50	83
Deuterium (mg)	13.60	1.60
Tritium (mg)	0.10	2.40
^{3}He	0.72	---
Energy splits		
Neutrons and gamma rays (%)	10	72
X rays	56	22
Charged particles	34	6

[a]Core density radius produce is $\rho R = 8.9$ g/cm^2 at a core radius $r = 100$ μm for 2500 times solid density.

V. OTHER AFLINT CONCEPTS

Two variations of the basic AFLINT design (see Fig. 2) have been considered.[12] In the ^{3}He AFLINT design, a higher concentration of ^{3}He is used and the burn temperature is selected to favor D-^{3}He reactions over D-D in the outer region. The target is no longer ^{3}He self-sufficient, but tritium self-sufficiency is retained (partly via ^{3}He playing a larger role in the spark core). This concept requires ^{3}He from another "generator" reactor or, perhaps, from lunar mining. The main advantage of this design is an even larger energy fraction in charged particles. It has somewhat larger ρR and ignition energy requirements, however.

The high gain concept attempts to increase the gain of the AFLINT target by sacrificing complete tritium and ^{3}He self-sufficiency (70% or greater internal breeding was arbitrarily selected). The increased gain is achieved by adding a thin D-T layer in front of the tamper region. As in the other designs, it is assumed that the ^{3}He diffuses uniformly throughout this and the two inner zones, being confined by a barrier coating on the inner side of the tamper. When the center spark region ignites, the high temperature results in bremsstrahlung radiation that partly penetrates the fuel but is absorbed in the tamper. The resulting heating at the tamper-fuel interface is sufficient to ignite the outer D-T layer. This causes an inward moving compression wave, which, when combined with the outward moving wave from the spark, causes an effective burn in the D-^{3}He region. As seen from Table II, the driver energy required for this target is reduced somewhat while the gain is more than doubled compared to the other designs. The added D-T reactions in the outer

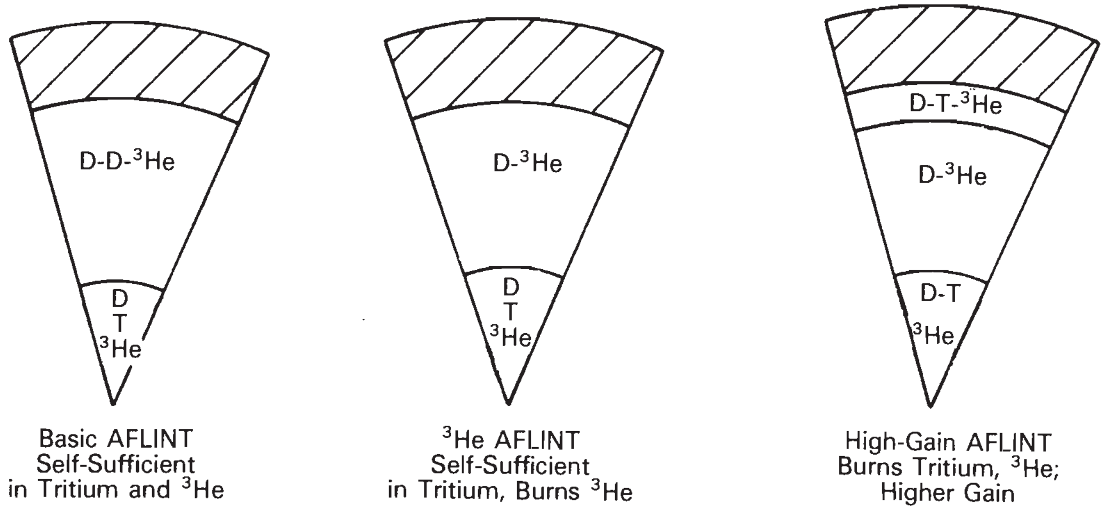

Fig. 2. Comparison of various AFLINT concepts.

TABLE II

Performance Estimates for Targets

Target Parameter	Type Target		
	Basic	^{3}He	High Gain
ρR	8.9	9.5	6.7
Target yield (MJ)	1000	1000	2000
Target gain	50	60	140
Driver energy (MJ)	20	24	15
Energy split			
Neutron/gammas	0.10	0.08	0.25
X rays	0.56	0.37	0.33
Charged particles	0.34	0.55	0.42

layer cause an increase in the neutron output energy fraction.

VI. VOLUME IGNITION OF D-^{3}He

In addition to the studies of AFLINT spark ignition to burn D-^{3}He, prior studies have also considered the use of volume ignition.[5] This was motivated by the encouraging volume compression experiments reported by Yamanaka and Nakai at Osaka.[16]

The application of volume compression and ignition has been investigated with emphasis on the burning of D-^{3}He (Ref. 5) and the role of the auxiliary D-D reaction. This problem is complicated since several components of the reheat are involved. A first result documenting the conditions of volume ignition of D-^{3}He is shown in Fig. 3. This figure gives a history of the temperature of the target for an input energy of 150 MJ where a gain of 18 is produced, corresponding to 47% fuel burn up. Contrary to prior D-T cases with volume ignition, where ignition occurs at densities as low as ten times solid state, for D-^{3}He in Fig. 3, a compression of 10 000× appears to be necessary. The fact that volume ignition occurs can be seen (as was

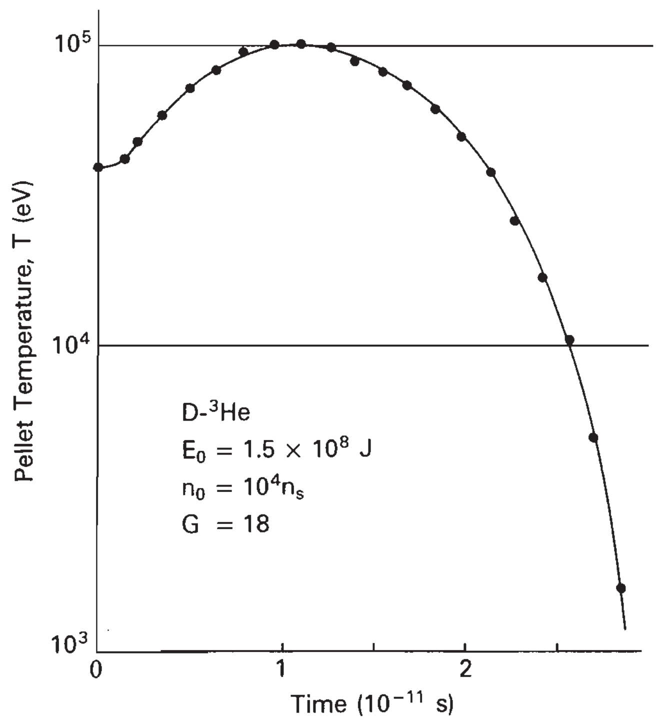

Fig. 3. Volume ignition of D-^{3}He reaction: time dependence of the temperature of a pellet compressed to 10 000 times the solid state density with an energy input of 150 MJ and a fusion gain G of 18.

observed in the prior cases of D-T) by the rapid increase to 100 keV starting from an initial temperature of 43 keV. Since the proton and alpha-particle fusion products from D-^{3}He have relatively high initial energies of 14.68 and 3.67 MeV, respectively, ignition at high densities is not unexpected.

VII. RECENT ADVANCES IN ICF

Since p-^{11}B is so difficult to burn, we must assume that highly advanced ICF systems will become available in the future in order to seriously consider its use. Fortunately, recent advances in the physics of ICF using laser drivers have been very encouraging. While technology studies for the development of an ICF reactor lag behind the technology for magnetic confinement, these advances in physics suggest rapid progress in ICF. This conclusion is based on continued achievements and some breakthroughs including

1. 5% measured D-T gains using direct drive
2. advancements in indirect drive experiments, in checking the recent high-gain underground experiment (Centurion-Halite)
3. the achievement of relatively uniform laser interactions also with an improved understanding of interaction physics
4. "Yamanaka" compression and volume ignition
5. an improved reactor design (Cascade) that avoids wall problems.

These points are elaborated further in the following paragraphs.

Experiments at Osaka University[16] using the GEKKO 12 laser with optimized conditions, and at the Lawrence Livermore National Laboratory using the NOVA (Ref. 17) (even without exhausting all possible optimizations), achieved fusion gains of 0.3 to 0.5% fusion energy out per absorbed laser energy. Directly driven D-T gas-filled glass balloons were employed. Thus, assuming that the hydrodynamic efficiency (~10%) can be improved in future targets, this corresponds to an effective efficiency as high as 3% (Ref. 18).

The gain cited above for D-T was achieved using a "direct" drive target where laser radiation was directly incident on the glass capsule containing the D-T fuel. The success of the GEKKO 12 experiments and of the enhanced gains with the OMEGA laser[19] was due to the use of a random phase plate for smooth laser irradiation. The mechanism for this smoothing can now be explained by hydrodynamics with a pulsating density rippling.[20]

Twenty years earlier, the field of laser-plasma interaction was frustrated with the appearance of various anomalies, nonlinearities, jet generation, a pulsation of reflectivity with 10-ps period,[21] and parametric instabilities.[22] To overcome these very confusing phenomena, John Nuckolls[23] proposed an ingenious approach to smooth the laser-surface interaction. By surrounding the target with an outer shell of high atomic number material, the laser radiation is converted into X rays, which then drive the compression and heating of the inner target of fusion fuel. This is called indirect drive. Although direct drive experiments produced impressive neutron yields [2×10^{13} n/shot (Ref. 16)], the main ICF program followed the indirect drive approach where better conditions for the future fusion reactors were believed to be possible. Indirect drive yields steadily increased compressed densities, but due to input energy, limits were restricted to $\sim 10^{11}$ n/shot even with the introduction of third harmonic neodymium glass laser pulses with 20-kJ energy.[24] The physical understanding gained from these experiments forms the basis for the present projections for the proposed laser microfusion facility, which would employ a 10-MJ laser to study high-gain targets.

Confidence that high-yield, high-gain indirect drive targets can be achieved has come from an entirely different series of experiments. X-ray driven compressions of D-T fuel targets have been studied in underground nuclear tests (the Centurion-Halite project) where ~100 kJ of X-ray energy was produced to drive the target compression. Based on these results, it is predicted that a laser-driven indirect-drive target can achieve high gain. Thus, using a very precisely established scheme[25] employing a 10-MJ neodymium glass laser, third harmonic pulses calculations predict 1000-MJ fusion energy per shot based on these underground tests.

In addition to improvements offered by indirect drive, there are other important advances in ICF experiments that promise advances in future performance, and there are indications that the presently achieved conditions may be even improved in the future. One indication is the use of a random phase plate,[26] or the induced spatial incoherence[27] or broad band laser radiation[28] to suppress most of the frustrating anomalies observed in early laser-plasma interaction experiments.

While it was long thought that these anomalies were due to stimulated Raman scattering or stimulated Brillouin scattering, recent experiments show that these mechanisms do not dominate the basic absorption processes.[29,30]

The history of events leading to this conclusion is instructive. At a time when attention was focused on instabilities,[22] it was observed numerically[31] that with an initially linear density ramp, the laser light was first reflected at the critical density in a 50 wavelength-long corona. The net reflection was low due to nonlinear dispersion effects. However, after 2 ps, more than 95% of the light was reflected at the outermost, low-density region of the corona, penetrating only a few wavelengths. (This interesting effect was recently confirmed experimentally.[32]) Then, Lubin[21] measured a pulsating reflectivity between a few percent and nearly 100% with a 10-ps period. The same pulsation of reflectivity was recently measured also by Maddever.[22] The same pulsation appeared from the 3/2nd harmonic[33] but was completely smoothed out when a random phase plate was inserted in the laser beam.

These observations can now be explained from a very general hydrodynamic computation using a two fluid model that includes all dynamic inhomogeneity fields and double layers.[34] Initially the absorption-modified total reflection of the laser light at the critical density causes a standing wave pattern. The plasma is pushed into the nodes of the standing wave field by nonlinear forces.[35] This ripple causes a Laue-Bragg reflection at the outermost low-density region of the corona.[21] In subsequent picoseconds, the unilluminated main part of the corona relaxes its density ripple hydrodynamically. Then, after 6 to 9 ps, the light again penetrates to the critical density until a new density ripple is produced, and the process repeats itself. A pulsation of the reflectivity between a few and nearly 100% with a period of ~8 ps is predicted.[30] If a random phase plate is used, the standing wave patterns are washed out and a smooth interaction is obtained. This result is especially important for direct drive targets and suggests that strong advances with this approach can also be expected.

A further point of potential improvement for the next steps in ICF development results from the shock-free, pusherless, stagnation-free compression of targets ("Yamanaka compression") verified experimentally in many experiments with GEKKO 12 using direct drive glass balloon targets. Without spark ignition, the highest fusion gains are achieved if an ideal adiabatic volume compression is used. For example, early computations[36] that followed the ideal adiabatic compression dynamics of D-T fuel resulted in high gains (>1000) and a high fuel depletion (>80%) when volume ignition occurred. A careful recalculation of the volume ignition scheme predicts a release of 1000-MJ fusion energy with a 10-MJ laser irradiation for 12% hydrodynamic efficiency. This is in good agreement with calculations by Storm et al.,[17] where only partial volume ignition was included. The Yamanaka compression has many advantages, and for illustrative purposes, we assume it is employed in subsequent p-^{11}B calculations in this paper.

In addition to strong advances in the physics understanding of ICF, advances in reactor design concept, such as the CASCADE concept,[37] indicate many advantages for ICF reactors. This concept can be easily extended to contain very high-yield targets such as would be expected from p-^{11}B operation. (The high yield is forced by the relatively large input energy required for ignition.)

In summary, the situation is similar to that which existed before landing a man on the moon; the basic physics problems are understood, and a feasible reactor scheme is available. The development of an improved driver with a high repetition rate and long durability remains a challenge but appears to be feasible. In view of these very promising results, it seems important to speculate on future advances that could lead to spectacular results such as burning p-^{11}B. Such a development is similar to that of using the diesel engine from a most primitive ship engine to use in aircraft motors.

VIII. VOLUME IGNITION OF p-^{11}B

For the reason stated above, we have recently extended our calculation of volume ignition by laser compression,[5,36] to this very difficult reaction, which has the ideal property of being essentially aneutronic. While some small amounts of radioactivity are produced, the overall result is comparable to burning coal (with respect to the part per million uranium in the coal).

The hydrogen-boron (H-B) reaction has such low cross sections that the results of a treatment of simple burn are most disappointing. The optimum temperatures are >150 keV, and the energies E_0 are in the range of terajoules. When the first estimations of this kind were discussed,[4] it was commented that H-B is not for the year 2000 but for the year 4000. Nevertheless, there were indications how the self-heat does reduce the optimum initial temperature, reducing the input energy and increasing the gain due to volume ignition,[4] as first seen following the result of volume ignition of D-T.

We report here on the recent results of volume ignition calculations for H-B where laser pulses of 1 GJ produce gains of 24 for compression to 100 000 times the solid state. These values are indeed far beyond the present technology; however, if laser fusion would be the main stream of large scale energy production with a huge amount of next century research and development, the missing numbers to today's physical-technical achievements in laser fusion[17] are nothing more than a factor of 100 in the density above the just reached experimental value, and a further factor of 100 above the value of laser pulses compared with the Athena project.[17]

When our volume ignition code was extended to the case of p-^{11}B, we found that an optimum temperature of ~150 keV was required, assuming adiabatic burning during compression and expansion. But, if self-heating of an exceedingly high-density target (10^5 times solid state) were possible, the optimum initial temperature for volume ignition and reheat is only 20 keV. The results of Fig. 4 show the conditions required for volume ignitions for H-B (Ref. 11) plasma compressed to 100 000 times the solid state. The time dependence of the plasma temperature during the reaction is shown. As before,[36] we have also illustrated

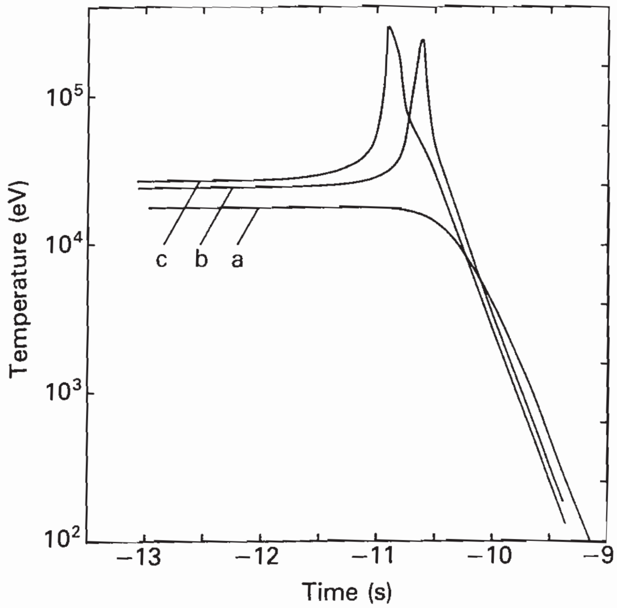

Fig. 4. Time dependence of the temperature of H-B pellets of 10^5 times solid state density with intake of the following laser energies E_0: (a) *Gj*, (b) 1.3 h *Gj*, and (c) 1.5 *Gj* resulting in gains of 0.07, 29.2, and 21.9, respectively, with a fuel burn of 0.18, 81.5, and 82.6%, respectively, and initial temperatures of 17.9, 29, and 26.9 keV, respectively.

the conditions at a slightly lower initial temperature that did not permit ignition so that the temperature dropped monotonously with time (curve a). With a little higher input energy (curve b), the temperature produced by a self-heat causing volume ignition is increased. The gain achieved was 24.2 with respect to the input energy. This is indeed a low value and could only be considered in the far future if much improved drivers with high efficiency are developed. At the same time, the methods used to obtain uniform irradiation must be drastically improved if there is to be any hope of achieving the enormous compressed density implied here.

Curve c in Fig. 4 shows a similar case, again for an enormous compression approaching 100 000 times solid state density, where a somewhat higher input energy results in a gain of 21.6. The conditions for the future would then be that a laser of 30% efficiency is needed, and that methods be found to achieve the ultra-high compression of 10^5 times solid state. The conversion of the output energy into electricity might be done with low thermal pollution using high-efficiency Mosely-type direct conversion.

The p-^{11}B parameters discussed here are indeed for quite futuristic designs. Still, these results should be of interest to identify directions and goals for future research.

IX. CONCLUSION

The review of progress in ICF development outlined here confirms that the rapid advances achieved justify optimism about futuristic, optimistic designs. This is particularly important for advanced fuels, which represent a key goal for achievement of highly attractive power plants with excellent environmental compatibility. A possible scenario for approaching this goal, which is considered here, would evolve from D-T targets to AFLINT-type spark ignited deuterium-based fuels. As illustrated by the LOTRIT conceptual reactor design, a significant advantage gained in that step would be reduction of tritium involvement by several orders of magnitude. The ultimate goal would still be to progress toward p-^{11}B targets. Our calculations presented here show that a modest gain might be obtained with a volume ignited p-^{11}B burn. However, the parameters required (e.g., 10^5 times solid density) place such an operation out of reach with present technology. The fact that a conceptual "window" for a p-^{11}B burn is even found must be viewed as a breakthrough, since prior p-^{11}B studies, especially for magnetic fusion, have concluded that such an operation is impossible. Assuming that improved methods can be found and advanced technology is developed, the present results suggest that ICF operation with p-^{11}B might be possible. Thus, while this goal still appears extremely demanding from all points of view, we conclude that research on this possibility should be intensified.

REFERENCES

1. G. H. MILEY, *Fusion Energy Conversion*, American Nuclear Society, La Grange Park, Illinois (1976).

2. J. P. HOLDREN et al., "Exploring the Competitive Potential of Magnetic Fusion Energy: The Interaction of Economics with Safety and Environmental Characteristics," *Fusion Technol.*, **13**, 7 (1988).

3. D. DICKSON, "Fusion Scientists Have Reacted Strongly to Charges That They Have Oversold Their Case," *Science*, **241**, 154 (1988).

4. T. WEAVER, G. ZIMMERMAN, and L. WOOD, "Exotic CTR Fuels: Non-Thermal Effects and Laser Fusion Applications," UCRL-4938, Lawrence Livermore National Laboratory (1973); see also H. HORA, *Nucl. Instrum. Methods*, **144**, 17 (1977).

5. L. CICCHITELLI et al., "Spark Ignition Distinguished from Ideal Adiabatic Compression and Volume Ignition of Nuclear Fusion in Pellets," *Laser Interaction and Related Plasma Phenomena*, Vol. 8, p. 565, H. HORA and G. MILEY, Eds., Plenum Publishing Corporation, New York (1988).

6. L. CICCHITELLI et al., "Pellet Fusion Gain Calculations Modified by Electrostatic Double Layers and Spin Polarized Nuclei," *Laser and Particle Beams*, **2**, 467 (1984).

7. W. KERNBICHLER, G. H. MILEY, and M. HEINDLER, "D-^{3}He Fuel Cycles for Neutron Lean Reactors," *Fusion Technol.*, **15**, 1142 (1989).

8. L. J. WITTENBERG et al., "Lunar Source of ^{3}He for Commercial Fusion Power," *Fusion Technol.*, **10**, 167 (1986).

9. Summary of Lunar ^{3}He/Fusion Power Workshop, NASA-Lewis, Cleveland, Ohio, 1988; see also *Fusion Technol.*, **15**, 67 (1989).

10. G. H. MILEY, "^{3}He Sources for D-^{3}He Fusion Power," *Nucl. Instrum. Methods*, **A271**, 197 (1988).

11. G. H. MILEY, "Potential Role of Advanced Fuels in Inertial Confinement Fusion," *Laser Interaction and Related Plasma Phenomena*, Vol. 5, p. 313, Plenum Press, New York (1981).

12. G. H. MILEY, "Advanced-Fuel Targets for Beam Fusion," *Proc. 6th Int. Conf. High Power Particle Beams*, Kobe, Japan, p. 309 (1986).

13. M. RAGHEB and G. H. MILEY, "Safety Aspects of Tritium in ICF Reactors with Internally-Breeding Targets," *Fusion Technol.*, **8**, 2061 (1985).

14. G. H. MILEY, "Advanced Fuels for Heavy Ion Beam Fusion," *Nucl. Instrum. Methods*, **A278**, 281 (1989).

15. T. TAZIMA et al., "Advanced ICF Reactor Takanawa-I with Low Radioactivity and Tritium Self-Breeding in the Pellet," *Proc. 11th Int. Conf. Plasma and Controlled Nucl. Fusion Research*, Kyoto, Japan, IAEA-CN-47/H-II-4, Vol. 3, p. 343, International Atomic Energy Agency (1986).

16. C. YAMANAKA and S. NAKAI, "Thermonuclear Neutron Yield of 10^{12} Achieved with GEKKO XII Green Laser," *Nature*, **319**, 757 (1986).

17. E. STORM, J. D. LINDL, E. M. CAMPBELL, T. P. BERNAT, L. W. COLEMAN, J. L. EMMETT, W. J. HOGAN, Y. T. HORST, W. F. KRUPKE, and W. H. LOWDERMILK, "Progress in Laboratory High Gain ICF: Prospects for the Future," Report 47312, Lawrence Livermore National Laboratory (Aug. 1988).

18. K. R. MANES, "Multi-Megajoule Nd: Glass Fusion Laser Design," *Laser Interaction and Related Plasma Phenomena*, Vol. 7, p. 21, H. HORA and G. H. MILEY, Eds., Plenum Press, New York (1986).

19. R. L. McCRORY, "2×10^{11} Neutron Yield with 2.4 kJ Laser Energy on Target," *ILE Rev. Quarterly*, p. iii (Apr./June 1985); see also *Phys. Today*, **39**, S-61 (1986).

20. GU MIN and H. HORA, "Generation and Relaxation of Density Ripples in Laser Produced Plasmas," *Chinese J. Lasers*, **16**, 656 (1989).

21. M. LUBIN, "10 psec Pulsation of Reflectivity of Laser Irradiated Targets," ECLIM 1974 Conf. Digest, Garching (1974); see also R. A. M. MADDEVER, "Temporal and Spectral Characteristics of the Fundamental and Second Harmonic Emission from Laser-Produced Plasmas," PhD Thesis, Australian National University (1988).

22. F. F. CHEN, "Physical Mechanisms of Laser-Plasma Parametric Instabilities," *Laser Interaction and Related Plasma Phenomena*, Vol. 3A, p. 291, H. SCHWARZ and H. HORA, Eds., Plenum Press, New York (1974).

23. J. NUCKOLLS, "The Feasibility of Inertial Confinement Fusion," *Physics Today*, **35**, *9*, 24 (1982).

24. J. D. LINDL, "Progress in Inertial Confinement Fusion," *Bull. Am. Phys. Soc.*, **32**, 1765 (Oct. 1987); see also "Achieving Spherically Symmetric Implosion in Ion Targets with Axially-Symmetric Beams Illumination by Controlling the Motion of the Deposition Radius," *Proc. 16th European Conf. Controlled Fusion and Plasma Physics*, Venice, Italy, March 13–17, 1989, p. 1787.

25. E. STORM, "Progress Toward High-Gain Laser Fusion," *Laser Interaction with Matter*, p. 85, G. VELARDE, Ed., World Scientific, Singapore (1989).

26. Y. KATO et al., "Random Phasing of High-Power Lasers for Uniform Target Acceleration and Plasma-Instability Suppression," *Phys. Rev. Lett.*, **53**, 1057 (1984).

27. S. P. OBENSCHAIN et al., "Laser Target Interaction with Induced Spacial Coherence," *Phys. Rev. Lett.*, **56**, 2807 (1986).

28. LIN ZUNGI et al., "Temporal and Spectral Features of the (3/2) ω_0 Spatial Fine Structure in Laser Irradiated Planar Targets," *Laser and Particle Beams*, **4**, 223 (1986).

29. C. LABAUNE et al., "Evidence of Stimulated Brillouin Backscattering from a Plasma at Short Laser Wavelengths," *Phys. Rev.*, **32A**, 577 (1985).

30. P. DRAKE, "Laser-Plasma-Interaction Experiments Using Multi Kilojoule Lasers," *Laser and Particle Beams*, **6**, 235 (1988).

31. H. HORA, *Laser Plasmas and Nuclear Energy*, Fig. 7.7a, Plenum Press, New York (1975).

32. R. A. M. MADDEVER, B. LUTHER-DAVIES, and R. DRAGILA, "Pulsation of $1\omega_0$ and $2\omega_0$ Emission from Laser-Produced Plasmas. I. Experiment," *Phys. Rev.*, **A41**, 2154 (1990).

33. A. GIULIETTI et al., "Study of Scattering of an Intense Laser Beam Smoothed by a Random Phase Plate," *Laser Interaction with Matter*, p. 208, G. VELARDE, E. MINGUEZ, and J. M. PERLADO, Eds., World Scientific, Singapore (1989).

34. H. HORA, GU MIN, S. ELIEZER, P. LALOUSIS, R. S. PEASE, and H. SCHIZMAN, "On the Surface Tension of Plasmas," *IEEE Trans. Plasma Sci.*, **17**, 284 (1989).

35. H. HORA, "Nonlinear Confining and Deconfining Associated with the Interaction of Laser Radiation with Plasma," *Phys. Fluids*, **12**, 182 (1969); see also H. HORA, *Physics of Laser Driven Plasmas*, John Wiley, New York (1981).

36. G. KASOTAKIS et al., "Volume Ignition in Pellet Fusion," *Nucl. Instrum. Methods*, **A278**, 110 (1989); see also "Volume Compression and Volume Ignition of Laser Driven Pellets," *Laser and Particle Beams*, **7**, 511 (1989).

37. J. PITTS et al., "Preventing Vaporization and Destructive Shock Waves in ICF Target-Chamber First Walls," *Fusion Technol.*, **15**, 563 (1989).