CONF-771126--30

PREPRINT UCRL-79856

Lawrence Livermore Laboratory

INERTIAL CONFINEMENT FUSION (ICF)

John Nuckolls

October 12, 1977

Invited Review paper to be presented at the 19th Annual Meeting, Division of Plasma Physics, American Physical Society, Atlanta, Georgia, November 7-11, 1977.

RECEIVED BY TIC MAR 21 1978

Form ERDA 426
ERDM 3201

U.S. ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

MAJOR CONTRACTOR'S RECOMMENDATION FOR DISPOSITION OF SCIENTIFIC AND TECHNICAL DOCUMENT

See Instructions on Reverse

1. ERDA Report No. UCRL-79856
2. Subject Category No.
3. Title INERTIAL CONFINEMENT FUSION (ICF)

4. Type of Document ("X" one)
   - ☐ a. Scientific and Technical Report
   - ☒ b. Conference Paper 19th Annual Meeting, Division of Plasma Physics
     - Title of conference American Physical Society
     - Date of conference November 7-11, 1977
     - Exact location of conference Atlanta, Georgia
   - ☐ c. Other (*Specify, Thesis, Translation, etc.*)*

5. Copies Transmitted ("X" one or more)
   - ☐ a. Copies being transmitted for standard distribution by ERDA-TIC.
   - ☐ b. Copies being transmitted for special distribution per attached complete address list.*
   - ☒ c. Two completely legible, reproducible copies being transmitted to ERDA-TIC.

6. Recommended Distribution ("X" one)
   - ☒ a. Normal handling (after patent clearance): no restraint on distribution except as may be required by the security classification.
   - ☐ b. Make available only to U.S. Government agencies and their contractors.
   - ☐ c. Make available only within ERDA and to ERDA contractors.
   - ☐ d. Make available only within ERDA.
   - ☐ e. Make available only to those listed in item 12 below.
   - ☐ f. Other (*Specify*)*

7. Recommended Announcement ("X" one)
   - ☒ a. Normal procedure may be followed.*
   - ☐ b. Recommended following announcement limitations:

8. Reason for Restrictions Recommended in 6 or 7 above.
   - ☐ a. Preliminary information.
   - ☐ b. Prepared primarily for internal use.
   - ☐ c. Other (*Explain*)

9. Patent Clearance ("X" one)
   - ☒ a. ERDA patent clearance has been granted by responsible ERDA patent group.
   - ☐ b. Document has been sent to responsible ERDA patent group for clearance.

10. National Security Information (*For classified document only; "X" one*)
    - ☐ a. Document does contain national security information other than restricted data.
    - ☐ b. Document does not contain national security information other than restricted data.

11. Copy Reproduction and Distribution
    - a. Total number of copies reproduced
    - b. Number of copies distributed outside originating organization

12. Additional Information or Remarks (*Continue on separate sheet, if necessary*)

13. Submitted by (*Name and Position*) (*Please print or type*)*
Jack L. King, Technical Information Department

14. Organization
Lawrence Livermore Laboratory, Livermore, California

15. Signature Rose Kenealy

16. Date 3-15-78

INERTIAL CONFINEMENT FUSION (ICF)*

John Nuckolls

University of California, Lawrence Livermore Laboratory
Livermore, California 94550

ABSTRACT/INTRODUCTION

The principal goal of the inertial confinement fusion program is the development of a practical fusion power plant in this century. Rapid progress has been made in the four major areas of ICF - targets, drivers, fusion experiments, and reactors. High gain targets have been designed. Laser, electron beam, and heavy ion accelerator drivers appear to be feasible. Record-breaking thermonuclear conditions have been experimentally achieved. Detailed diagnostics of laser implosions have confirmed predictions of the LASNEX computer program. Experimental facilities are being planned and constructed capable of igniting high gain fusion microexplosions in the mid 1980's. A low cost long lifetime reactor design has been developed.

Targets have been designed which have calculated gains of 500-1000 with 1 MJ/100 TW drivers.[1] This relaxes the 1 GWe fusion reactor driver efficiency to 1-2% and the allowed target cost to ~ 50 cents. Results of thousands of LASNEX simulations of implosion-fusion experiments with possible target designs have been used to determine which experiments to perform, which drivers to construct, and to find optimum target designs. Techniques are being developed for fabrication of targets at sufficiently low costs and high rates for fusion reactors.

In the driver area, several types of lasers, heavy ion accelerators, and relativistic electron beam machines are being developed which may be suitable for use in fusion reactors. Contrary to recent assertions,[2] focusing by lasers is feasible from such great distances (~ 100 meters to a several mm target) that the perturbation of the optical system by the fusion explosion is negligible. Heavy ion accelerator magnetic focusing elements are easily shielded. Progress has been made in focusing electron beams across the reactor chamber. This multiplicity of driver options greatly increases the chances of success for ICF.

In experiments with multi-terrawatt Nd glass lasers, exploding pusher targets have achieved record-breaking thermonuclear conditions,[3] including 8 keV ion temperatures, and DT gain $\approx 10^{-2}$. Measurements with an array of remarkable diagnostic instruments have recorded the detailed history of laser implosions and confirmed predictions of the LASNEX MHD-fusion-transport computer code and the ZOHAR plasma simulation code. Experiments are now underway to compress DT to 100 times liquid density. Implosion-fusion experiments have also been conducted with relativistic electron beam machines and magnetically insulated targets.

Several 10 TW class and at least two 100 TW class drivers will be completed in the 1977-1983 time period. Targets are being designed which may approach and possibly equal scientific breakeven with (one or more of) the 10 TW drivers, and achieve gains of 10-100 with (one or more of)

---

*Research performed under the auspices of the U.S. Energy Research and Development Administration under Contract No. W-7405-Eng-48.

the 100 TW drivers. Most of these 10-100 TW drivers are Nd glass lasers because they are the most advanced, powerful and versatile fusion drivers now available. Consequently Nd lasers will play a key role in first achieving implosion to high densities, scientific breakeven, and high gain fusion microexplosions.

A relatively low cost reactor design has been developed which solves the first wall problems.[4] Complete shielding from cyclical thermal stresses and fusion radiation is achieved by a thick wall of falling liquid lithium. Experimental power reactors are projected for the late 1980's and demonstration power reactors for the late 1990's.

at density 10^5 g/cm^3 in a Fermi degenerate state.[*] At 1000 g/cm^3 densities, thermonuclear burning occurs in tens of picoseconds - comparable to inertial confinement times[†] for 10^{-3}g pellets.

An implosion driven by a high power beam is used to isentropically compress DT to very high densities.[5] Material ablated from the pellet surface drives a spherical implosion rocket. In spherical compression, the rate of thermonuclear burn (proportional to the density) increases more rapidly than the inertial confinement time (proportional to the radius) decreases. Consequently spherical implosion to high densities makes possible efficient fusion microexplosions. Most of the DT is *ignited by a thermonuclear burn wave propagated outward from a small* region surrounding the center of convergence which is driven to thermonuclear temperatures. By exploiting propagation and isentropic compression the average specific energy required to achieve efficient burn of the DT is typically 2 x 10^7 J/g, only 2% of the specific energy at 10 keV. Fig. 1a. This conceptual approach to controlled fusion was developed by the author and simulated via computer calculations in 1960-61.

The performance potential of ICF targets may be limited by entropy changes, fluid instabilities, asymmetries, poor absorption, or poor implosion efficiency.[5] Optimum target designs incorporate methods of controlling these processes.

---

[*] The electron degeneracy conditions for DT fuel are $\rho \gg 20\ Z^2$ g/cm^3 and $\frac{5\pi^2}{12}\left(\frac{\theta}{\varepsilon_{\mathrm{Fermi}}}\right)^2 \ll 1$, where θ is the DT electron temperature and $\varepsilon_{\mathrm{Fermi}}$ is the Fermi energy.[5] For $\rho \approx 1000$ g/cm^3, $\varepsilon_{\mathrm{Fermi}} \sim 1$ keV and $\theta \lesssim 100$ eV.

[†] Time for the fuel to accelerate from rest to thermal velocities and significantly decompress and cool.

and Monte Carlo.[7] Typically the trajectories of a million individual electrons and ions in a small region of space are calculated for a short time via Newton's laws, Maxwell's equations, and the Lorentz force. These calculations show that in absorption of intense laser light there is density profile steepening, critical surface rippling, formation of bubbles and filaments, strong plasma turbulence, polarization and angle dependent absorption, fast ion generation, non-Maxwellian electron distributions, magnetic fields, and stimulated scattering. Experiments show evidence of these effects. The calculated absorption vs. angle and polarization, and superthermal electron spectra are shown in Figures 2 and 3 .[8] These predictions have been confirmed experimentally.

Heavy ion beam energy is absorbed classically by plasma electrons. Superthermal electrons are generated by ion electron collisions.[9] A few percent of the beam energy is released via nuclear reactions as neutrons and nuclear fragments. The absorption of relativistic electron beams in dense targets is complicated by self-generated magnetic and electric fields, reflexing phenomena, fast ion generation, and bremsstrahlung radiation.[10] Unlike the heavy ions which are very rigid, the electrons are strongly scattered.

Four classes of targets are being designed for ICF experiments and applications.

and high gain targets. The laser temporal pulse shape may be Gaussian and the illumination may be relatively asymmetric (with some degradation in neutron yield). A variety of emissions from the imploding target make detailed diagnostics possible, including x-rays, neutrons, alpha particles, ions, and scattered light.

Extensive LASNEX parameter studies have been made of exploding pusher targets.[13] Some of these results are shown in Figure 6. For each laser power there is a set of target/pulse parameters which give near maximum neutron yield.[14] The maximum neutron yields vary approximately with the power squared.

In exploding pusher targets driven by REB - relativistic electron beam - machines, magnetic fields have been used to reduce electron conduction so that thermonuclear temperatures can be reached with smaller implosion velocities.[15] REB driven implosions do not reach as high a velocity as laser driven implosions because the focal area is larger and the deposition length is greater.

HIGH DENSITY TARGETS:[16] The principal differences between the single shell high density targets and exploding pusher targets are: the initial DT density is increased from 2.5 to 10 milligram/cm^3, the pusher is made relatively thick compared to its radius (~ 0.3), the outer surface of the pusher is made smooth to 3000 Å, and a longer duration two step laser pulse is used. The two step pulse shape generates a more isentropic implosion so that higher densities may be achieved for the same maximum DT pressure. Figure 7 compares the calculated implosion histories in pressure-density space of the exploding pusher, high density, and high gain targets to the isentropic Fermi degenerate limit.

In general high voltage charged particles are efficiently absorbed. For short wavelength lasers, efficient absorption occurs via inverse bremsstrahlung in intermediate Z absorbers. Efficient implosions are achieved with short wavelength lasers because the blowoff velocity is well matched to the implosion velocity and relatively lightweight pushers and preheat shields may be used. Implosions directly driven by relativistic electrons are inefficient because relatively massive high Z shells must be used for preheat shielding. However, if the pulsed power machines are used to accelerate ions, the deposition length of these ions is greatly reduced and efficient implosion is possible.

Concerning fluid instabilities, in electron driven implosions favorable density gradients are formed which greatly relax the surface smoothness requirements. Similar gradients may also be generated in laser and ion implosions by introducing an energy spread in the beam.[18] Even with favorable density gradients relatively thick shells must be used ($\frac{\Delta R}{R} \sim 0.1$), in order to avoid extreme surface smoothness requirements (<< 1000 Å). Consequently, any inert material in the target should have as low a density as possible in order to minimize its mass relative to that of the DT fuel. Inert mass in the target must be imploded at nearly the same velocity as the DT, so that the target gain will be degraded. High Z materials for preheat shielding may be seeded into these low density shells.

Efficient fuel compression depends on pulse shaping and preheat suppression in order to achieve a Fermi degenerate state. Figure 8 freezing out uniform layers, Figure 11; for coating the capsule with a diversity of pusher and ablator materials having surface finishes better than 3000 Å; for automatically characterizing the entire outer surface to find "Mount Everest," and inspecting the shell interior to find bubbles and other defects; and for mounting the capsule on plastic films so as not to induce disastrous growth of fluid instabilities. Potentially these techniques could be used to manufacture targets at sufficiently high rates and low costs for fusion reactor applications. For a ton yield target the maximum allowed fabrication cost is ~ 50 cents, not including cost of the tritium which is regenerated in the lithium blanket. For a 1 GWe power plant the production rate is four quarter-ton yield targets per second.

population inverted excited states of atoms and molecules and exploits stimulated emission. Heavy ion accelerators store kinetic energy of near relativistic, low temperature charged particle beams guided by magnetic fields. The required high powers and currents are achieved without violating limits imposed by space charge and phase space considerations by bunching a beam of heavy ions in a low ionization state either in a circular ring or in a linear accelerator. Relativistic electron beam machines store energy in large volume, high voltage electrostatic fields (Blumleins).

Using the high gain targets described above, the driver characteristics suitable for a 1 GWe fusion power plant are

	ELECTRON BEAM	ION BEAM	LASER
ENERGY	2 MJ	1 MJ	1 MJ
POWER	200 TW	100 TW	100 TW
VOLTAGE/ WAVELENGTH	< 3 MeV	< 30 GeV U or 5 MeV P	< 2 μM
REP RATE	4/s	4/s	4/s
EFFICIENCY	2%	2%	2%
COST	~ $\$10^8$	~ $\$10^8$	~ $\$10^8$

Both lasers and heavy ion accelerators have demonstrated a capability of focusing across a 5-10 meter reactor chamber to a few mm size target. In fact lasers can focus to this size target from up to 100 meters using *meter optics and 1 μm wavelength light, so that there is no problem with*

10 TW Nd glass lasers are also scheduled for completion in 1978 at Lebedev, the DELPHIN,[22] Figure 14 and the UMI 35,[23] Figure 15. Finally the Rochester OMEGA 10 TW glass laser is expected to be completed by 1980.[24] Figure 16. Targets are being designed which may approach and possibly equal scientific breakeven with the SHIVA laser. However much larger lasers are required to demonstrate high gain microexplosions. The multi-100 TW Livermore NOVA Nd glass laser is designed to achieve this goal by 1985.[25] Figure 17.

The potential performance levels which may be achieved with Nd glass lasers have greatly increased to beyond the 100 TW level due to a series of important technological advances[25]: computer optimized disc amplifiers and staging chains, spatial filters, automatically aligned many beam systems, and improved laser glasses and optical components. Consequently glass lasers will be the most powerful and versatile fusion drivers for the next decade, and will have a lead role in demonstrating the feasibility of efficient, high gain fusion microexplosions. Although existing Nd glass lasers have too low an efficiency ($\lesssim 0.1\%$) and too small a rep rate for fusion reactor applications, recent innovations may lead to sufficient improvements in these areas so that these lasers become a contender for reactor drivers.

At Los Alamos, a 10 TW CO_2 laser will be completed in 1978 and the HEGLF 100 TW CO_2 laser in the early 1980's.[26] Figures 18, 19. Recent experiments and theoretical advances have improved the prospects for CO_2 as a fusion driver.[26a]

early-mid eighties.[28] Figures 21, 22, 23, 24.

A recent conference at Brookhaven addressed the feasibility of constructing a heavy ion demonstration facility, of order 50 TW/100 KJ/10 GeV by 1985. Several approaches are being considered including various combinations of pulsed linacs, RF linacs, synchrotrons, storage rings, and accumulator rings.[29,30,31] Figure 25.

More radical driver technologies may also be possible - for example multiple BB's moving at 2 x 10^7 cm/s may be used to drive the target implosion.[1] These BB's might be accelerated over distances of several hundred meters by GW power lasers, or over kilometers by magnetic guns.

The multiplicity of fusion driver options greatly increases the chances of a successful ICF reactor.

pusher targets were imploded to fusion conditions by a Sandia REB machine,[36] and a ball in disc exploding pusher target was imploded to fusion conditions with a LASL CO_2 laser.[37] Figure 26.

Implosion/fusion experiments with exploding pusher targets have been performed at a dozen laboratories throughout the world, using Nd lasers, CO_2 lasers, and REB machines.

LABORATORY	DRIVER	POWER	MAXIMUM NEUTRONS
LEBEDEV	Nd laser	0.5 TW?	~ 10^7?
KURCHATOV	REB	~ 0.1 TW	~ 10^6 (DD)
OSAKA	Nd laser	0.5 TW?	~ 10^7?
LEMEIL	Nd laser	0.5 TW?	~ 10^7?
RUTHERFORD	Nd laser	0.5 TW?	~ 10^7?
LIVERMORE	Nd laser	3-5 TW	~ 10^9
LOS ALAMOS	CO_2 laser	0.4 TW	10^5-10^6
KMSF	Nd laser	1 TW	~ 10^8
ROCHESTER	Nd laser	0.5 TW?	~ 10^7?
SANDIA	REB	1 TW	~ 10^6 (DD)
NRL	Nd laser	1 TW	?
GARCHING	I_2 laser	1 TW	?

Many of these drivers - and other smaller drivers - have also been used to irradiate simple discs or planar targets in order to explore beam-matter interactions. In laser experiments measurements have been

These diagnostic instruments have also been used to explore in detail the operation of laser driven exploding pusher targets. Some of the most remarkable results are shown: an x-ray microscope image, an x-ray streaking/pinhole image, and a zone plate image of the thermonuclear alpha particles. Figures 31, 32, 33. Again the results confirm predictions of the LASNEX computer program, not only as to neutron yield but also implosion velocity, DT ion temperature and density, x-ray emission and spectra, and laser light absorption and scattering. Figure 34 compares predictions and measurements of key parameters of exploding pusher targets.

The picture that emerges from this remarkable array of measurements and the detailed comparison with computer calculations is surprisingly good agreement over such a broad range of parameters that the agreement cannot be accidental. The successful prediction of these complex processes is indeed a triumph for the theorists and for computational physics. The LASNEX computer program is a powerful and unprecedented breakthrough in fusion research.

Laser fusion experiments are now underway to implode DT to 100 times solid density. New types of diagnostics are being developed to measure the DT density. (X-ray microscopes and pinhole cameras have marginal spatial resolution.) In particular it appears that radiochemistry is one of the best density diagnostics, and that it will play an increasingly important role as even higher densities are reached.

In the REB driven implosion experiments which have been conducted, the diagnostic results are less advanced. It has not been demonstrated

REACTORS

Fusion explosions of 0.1-1 ton yield will generate cyclic pressure and temperature stresses and also plasma and x-ray damage of the first wall, and neutron damage of the first wall and the structure beyond. Figure 35. Adequate experimental data on degradation of first wall lifetime by these effects do not exist. Consequently it is a major technological challenge to design a first wall and reactor which costs ~ $\$10^8$ (for 1 GWe) and which has a lifetime equal to that of the power plant (30 years). However during the past year a reactor design has been developed which solves these potentially critical problems.[4] The key idea is a continuously renewable first wall of liquid lithium sufficiently thick to attenuate the neutron flux as much as necessary to protect the underlying structural materials. Shielding is also provided by the falling lithium - which is separated from the wall by a gap - from the transient x-ray, blast, and thermal effects. The lithium is so massive, and the impulse generated by the low mass fusion pellet so small, that the reactor structure is essentially completely shielded from explosive effects. Figure 36.

Calculations show that laser light may be propagated through the lithium vapor in equilibrium with the liquid at reactor temperatures and that the energy required to pump the lithium is not excessive.

Computer codes are being developed to calculate the propagation of charged particle beams through this vapor. Based on calculations and experiments with electron beams it is believed that propagation is feasible

SUMMARY

The development logic, milestones, and projected time scales for ICF are summarized in Figure 37. While a number of reactor driver options are developed in parallel, Nd glass lasers are used to demonstrate the feasibility of high gain fusion microexplosions by the mid-1980's. The best driver options are then selected to make an experimental reactor by 1990, and finally to build a demonstration reactor by the end of this century.

16. W. Mead, 1976 Laser Fusion Annual Report, Lawrence Livermore Laboratory (in publication).

17. J. Lindl, Lawrence Livermore Laboratory Report UCRL 80104, Proceedings of Topical ICF Meeting, February 1978.

18. J. Lindl et al., Lawrence Livermore Laboratory Report UCRL 78470 (1976).

19. C. Hendricks, Lawrence Livermore Laboratory Report UCRL , Proceedings of Topical ICF Meeting, February 1978.

20. ARGUS Laser

21. SHIVA Laser

22. DELPHIN Laser

23. UMI 35 Laser

24. OMEGA Laser

25. NOVA Laser

26. HEGLE Laser

26a. CO_2 experiments, theory

27. W. Krupke, Lawrence Livermore Laboratory Report UCRL

28. Sandia Technology 2, 3 (1976) - SAND 76-0615.

29. A. Moshke - accumulators

30. R. Martin - Hearthfire

31. D. Keefe - Linear Induction Accelerator

32. G. Charactis et al., Plasma Physics and Controlled Nuclear Fusion Research IAEA, Vol. II, 1975, p. 317.

33. J. Nuckolls, Lawrence Livermore Laboratory Report UCRL 76395; also *Progress in Laser Fusion*, Plenum Press, New York, 1975, p. 105.

FUSION CONCEPTS/TARGETS

The efficiency of thermonuclear burn, ϕ, is related to the density, n, time τ, and Maxwell velocity averaged reaction rate, $\overline{\sigma v}$, by

$$\frac{\phi}{1 - \phi} \sim (n\tau)\overline{\sigma v}$$

where the $(1 - \phi)^{-1}$ factor corrects for fuel depletion.[5] For the most reactive thermonuclear fuel, DT (deuterium-tritium), $\overline{\sigma v}$ increases very rapidly with ion temperature and peaks at temperatures of ~ 30-100 keV. Typical ignition temperatures are 5-10 keV. The quality of thermonuclear burn in various inertial and magnetic fusion machines may be represented on a plot of $n\tau$, the Lawson number, vs. θ_i the DT ion temperature, Figure one. Contours of constant DT gain may then be constructed (DT gain $\equiv \frac{\text{fusion energy}}{\text{DT thermal energy}}$).

Both the magnetic and the inertial approaches must achieve thermonuclear temperatures and sufficiently great $n\tau$. However in magnetic fusion machines n is relatively small and is limited by the properties of materials, so that the objective is to maximize τ; whereas in inertial fusion machines τ is relatively small and is limited by the inertia of matter, so that the objective is to maximize n. The feasibility of inertial fusion rests on the fact that compression of DT to thousands of times solid density is energetically cheap compared to heating of DT to ignition temperatures; the specific energy of DT is 10^7 joules/gram at 10 keV temperature, and also

- Entropy changes - controlled by pulse shaping, beam wavelength or voltage and Z, and electron and x-ray preheat suppression and shields.
- Fluid instabilities - controlled by surface smoothness, shell thickness, and density gradients.
- Asymmetries - controlled by multiple beams, complex focusing systems, electron conduction smoothing in a low density atmosphere, and shimming.
- Absorption - controlled by beam wavelength or voltage and Z, absorber Z, focused intensity, and density gradients.
- Implosion efficiency - controlled by beam wavelength or voltage and Z, focused intensity, absorber Z, and relative pusher mass.

A highly sophisticated computer program, LASNEX, has been developed to calculate ICF experiments, implosions, and fusion microexplosions.[6] LASNEX is a Lagrangian finite difference code which calculates the space time evolution of an axially symmetric plasma containing thermal electrons and ions, superthermal electrons, x-rays, thermonuclear reaction products, and the associated electric and magnetic fields. The plasma may be driven by a laser, electron, or ion beam. The beam generates a multigroup electron distribution. The x-ray and thermonuclear reaction product physics is also multigroup. Transport is flux limited diffusion.

Non-linear plasma processes in LASNEX are calculated with approximations to results of parameter studies with plasma simulation codes. At Livermore, the principal plasma code is ZOHAR, which is two dimensional, relativistic,

- Targets which implode DT fuel to thermonuclear temperatures at normal densities. These targets have been tested in laser and electron beam experiments.
- Targets designed to compress DT to high densities (~ 100 times liquid density).
- Targets designed to achieve scientific breakeven (fusion energy equals laser energy, gain = 1).
- Targets designed to achieve high gains (up to 1000).

Examples of these four classes of targets are shown in Figure Four.

THERMONUCLEAR TARGETS: These targets which utilize the exploding pusher principle were invented at Livermore in 1970 for use in initial experiments.[11] The simplest exploding pusher target consists of a spherical hollow glass microsphere filled with low density DT gas and mounted on a stalk. Typical microsphere parameters are 80 μm diameter, 1 μm wall thickness, and 2 mg/cm^3 DT density. Many variations have been developed including those in which the microsphere fusion capsule is enclosed in foam or mounted with a glass or plastic sheet.[12]

Exploding pusher targets are particularly well suited to early ICF implosion experiments. Because the pusher (glass shell) is suddenly heated and exploded by a short duration ($\leq$ 100 ps) high power pulse, the implosion is relatively insensitive to preheat by superthermal electrons and x-rays and fluid instabilities grow relatively slowly. Figure 5 shows calculations of the characteristic decrease of the exploding pusher density during implosion and for comparison the behavior of high density

Fluid instabilities are sufficiently controlled by the 3000 Å surface smoothness and use of a relatively thick pusher. This pusher also reduces preheat.

The high density target performance may be improved by adding a second outer concentric pusher. This outer pusher enhances preheat sheilding and increases the implosion velocity upon collision with the inner pusher.

SCIENTIFIC BREAKEVEN TARGETS:[17] Double shell targets are the most promising candidates for achieving scientific breakeven with 10-100 TW drivers. The principal differences between these double shell targets and those being used to achieve high densities is that the inner pusher is made of high density, high Z materials, the surface of this pusher is smooth to better than 1000 Å, and the fuel is a cryogenic liquid or a frozen shell. The DT fuel is imploded to densities of ~ 1000 g/cm^3, and to temperatures $\gtrsim 10$ keV. Although the symmetry requirements are extreme (velocities must be uniform to $\sim 1\%$) gas between the inner and outer pushers is compressed and heated to temperatures of several hundred eV, and additional smoothing occurs due to electron conduction in this gas. A two step shape is required, similar to that used for high density targets.

HIGH GAIN TARGETS:[1,17] In order to achieve maximum gains, the driver energy must be used very efficiently. Ideally, all the energy should be *absorbed, and a target consisting entirely of fuel should be imploded and* burned efficiently.

compares the pulse shapes required to implode single shell thermonuclear (exploding pusher), high density, and high gain targets. However, for single shell hollow targets it is not possible to simultaneously achieve maximum efficiency compression and ignition. If the pulse shape is varied to put the inner edge of the shell on a drastically different isentrope than the outside, then the inside will implode and ignite prematurely. If the inner edge is shocked to a higher adiabat late in the implosion, then much higher driver powers are required. Consequently, much higher gains can be achieved at low power if an ignitor capsule is positioned at the implosion center. The fusion energy from this ignitor is then used to ignite the fuel in the outer shell. Since the ignitor mass is so small compared to that of the outer shell, the ignitor pusher may be high density. This target is very similar to that to be used for scientific breakeven. The principal difference is the second fuel region on the inside surface of the outer pusher. Calculations predict that with 1 MJ/100 TW drivers* gains of 1000 may be achieved with central ignitor target designs and gains of ≈ 300 with single shell designs.

The strategy for progressing across the $n\tau$, θ_i space in Figure 1, with this series of targets and a sequence of increasingly powerful Nd glass lasers is shown in Figure 9.

Significant progress has been made in fabricating ICF targets.[19] Techniques have been developed for manufacturing glass microspheres with droplet generators and drop towers having carefully controlled temperature gradients, Figure 10; for filling these microspheres with DT gas and

---

*having sufficiently short wavelength or voltage

FUSION DRIVERS

Energy densities of 10^7-10^8 J/g are required to drive microimplosions to the density and temperature conditions of efficient thermonuclear burn. These energy densities are more than 10^3 fold higher than those generated by chemical reactions. The bond energies corresponding to ordinary solids and phase changes are orders of magnitude smaller than those corresponding to matter at thousands of times ordinary solid densities. These super energy densities may be generated by absorption of high power photon or charged particle beams focused to high intensities, providing the absorption length is sufficiently short. Driver damage by the 0.1-1 ton fusion explosion in a reactor is avoided by focusing the beam across a distance of 5-10 meters from the reactor wall to the target, typically several mm in diameter. In order to avoid preheating of the target by the beam, and by the superthermal electrons and x-rays generated by absorption of the beam - which would preclude efficient, isentropic compression - the wavelength or voltage of the beam is limited. The efficiency of the driver is high enough - a few percent so that substantial net energy is generated by the reactor.

The three leading driver candidates for inertial fusion reactors are lasers, heavy ion accelerators, and relativistic electron beam machines. In each of these drivers, energy is stored in a relatively large volume at a density small compared to chemical energy densities, but in a low entropy state. This energy is suddenly released in a beam or wave moving at or near the velocity of light. The laser stores radiation energy in damaging the focusing optics or jarring it out of alignment. Complete shielding of the heavy ion magnetic focusing system is feasible. Progress is being made in the focusing of relativistic electron beams and light ions generated by REB machines.

A dozen or so 0.1-1 TW fusion drivers - including Nd lasers, CO_2 lasers, I_2 lasers, and REB machines - are being used to conduct fusion experiments at Laboratories throughout the world. The most powerful driver now being used for fusion experiments is the Livermore ARGUS 2 beam, 20 cm aperture, Nd glass laser.[20] Figure 12.This laser has focused 5 TW of power on targets. Two oscillators are used, one capable of providing pulses as short as 25 ps and another capable of producing pulses from 120 ps to 2 nanoseconds. This second super stable oscillator is used in conjunction with an interferometric pulse stacker to produce a two step pulse shape. The two laser chains contain a series of rod and disk amplifiers sequentially spatially filtered in vacuum to remove high frequency noise generated by small scale beam breakup due to the propagation of an intense laser beam. The ARGUS system is mounted on a 70 meter long, 12 meter wide, 1 meter deep concrete slab which is in turn supported by 96 columns - the world's largest optical table. The irradiation optics are two diffraction limited f/1 lenses.

A series of increasingly powerful drivers will be completed in the 1977-85 time period. The first of these, the Livermore Nd glass SHIVA laser, will achieve powers up to 30 TW in 1978.[21] Figure 13. Two Soviet

However the decisive experiments will be those with high density and high gain targets. Even if the outcome of these experiments is negative for CO_2 compared to shorter wavelength lasers, it is still possible that complex and ingenious target designs will be successful. Based on our present understanding and target designs, I have estimated the probabilities of achieving various target performance levels with the Livermore Nd lasers and the Los Alamos CO_2 lasers. These results are shown in Figure 20. Largely because 10 μm CO_2 light generates three times hotter electrons with 10 fold greater range than does 1 μm Nd light in the intensity range of interest ($< 10^{14}$ w/cm^2), I believe that the SHIVA and HEGLF lasers have comparable chances of reaching scientific breakeven. However if positive results are achieved in the critical CO_2 experiments, or if coupling difficulties are made tolerable by new target designs, then CO_2 will be a prime contender to drive fusion reactors, since it has a sufficiently high efficiency and rep rate.

Because of uncertainties in the utility of Nd and CO_2 lasers for reactor applications, other shorter wavelength lasers are being developed.[27] A number of promising candidates have been identified. A particularly attractive example is krypton-fluoride because of its short wavelength (< 0.3 μm), and adequate efficiency (> 3%). It is expected that a 10-100 TW laser using one of these candidates may be constructed by 1985.

More powerful REB machines are also under construction: the Sandia PROTO II, 10 TW, 1978, and EBFA I-II, 40-100 TW, early-mid 1980's[28]; and the Soviet Kurchatov ANGARA series of machines, reaching 50 TW by the

FUSION EXPERIMENTS

Many of the basic inertial fusion concepts have been experimentally demonstrated

1945 Implosion, inertial confinement (fission explosions)
1952 Thermonuclear explosion
1968 Laser induced fusion
1974 Fusion via laser driven implosion
1975 Thermonuclear burn via laser implosion
1976 Fusion via REB driven implosion

The simple glass microsphere exploding pusher targets first yielded DT neutrons in tests at KMSF in May 1974.[32] A two beam confocal ellipse illumination system was used in these experiments. Advanced exploding pusher targets first generated detectable neutrons in single beams. JANUS laser experiments performed at LLL in December 1974.[33] The first experimental demonstration of thermonuclear fusion in a laser implosion was achieved with advanced two beam targets at LLL in May 1975.[34] An f/1 lens illumination system was used in these experiments. In September 1976 ARGUS two beam experiments, advanced two beam targets achieved record-breaking thermonuclear conditions for all laboratory fusion machines, including 8 keV ion temperatures, 10^{12} $cm^{-3}s$ Lawson numbers and 10^{-2} DT gains (fusion energy/DT thermal energy).[3] Figure one. The first successful REB implosion/fusion experiment was achieved at Kurchatov in Spring 1976 using a conical target.[35] In early 1977 spherical magnetically insulated exploding made of the variation of absorption with angle, polarization, intensity, pulse length, spot size, and target material and thickness. In addition, the x-ray emission has been resolved spatially, temporally, and in frequency including line widths and intensities; the density gradients have been measured; and the angular distribution and frequency shift of scattered light, and generation of fast ions, electrons, and magnetic fields, have been diagnosed.[38]

An extensive array of diagnostic instruments including several newly developed have been used to diagnose these experiments and also fusion-implosion experiments.[38] These advanced diagnostics include optical and x-ray streaking cameras, x-ray microscopes, combined x-ray pinhole-streaking cameras, UV holographic interferometers, time resolved multi-channel x-ray spectrometers, zone plate coded x-ray imaging, alpha particle pinhole cameras, alpha particle zone plate imaging, and high resolution optical spectrometers. Figure 27. Resolution of these instruments is as high as a few ps for the optical streaking camera and 10 ps for the x-ray streaking camera, a few microns for the x-ray microscope, an angstrom* for the x-ray line spectrometer, 10 ps/10 μm for the combined x-ray pinhole/streaking camera, and 500 ps/200 eV for the time resolved x-ray spectra.

The results of these laser-matter experiments have in general confirmed the predictions of the plasma simulation codes. For example, Figure 28 compares the measured and predicted absorption vs. angle and polarization. Figure 29 shows the calculated and predicted x-ray spectra. Figure 30 shows the radiation pressure steepened density profile.

---

*wavelength

that the fusion is thermonuclear. However there is some evidence for enhanced absorption, presumably by reflexing in self-generated magnetic or electrostatic fields.[10]

Ion driven implosion experiments have not been conducted because sufficiently powerful drivers do not yet exist.

for both heavy ions and electrons. Because the vapor density is so high this reactor design is not suitable for magnetic fusion systems.

The economics of ICF power plants are favorable. Cost estimates for most driver options, the targets, and the reactor total << $\$10^9$ for a 1 GWe plant. Some heavy ion accelerators have already demonstrated a highly reliable long lifetime capability. With intensive development other driver options could achieve these characteristics. A principal factor in the cost of fission LWR's is related to the long delays associated with siting, environmental considerations, etc. It is believed that this factor could be substantially reduced for fusion reactors.

Compared to other inexhaustibles, ICF fusion has more than a factor of two cost advantage over solar, many order of magnitude cleanliness and safety advantage over breeders, and potential technological and cost advantages over magnetic (because of the lithium fall reactor option). Coal is not inexhaustible, and sustained high level consumption may trigger unacceptable changes in the earth's climate.

REFERENCES

1. J. Nuckolls et al., Lawrence Livermore Laboratory Report UCRL 79373, European Conference on Laser Matter Interaction, Oxford, England, September 1977.
2. D. Rose, M. Feirtag, Tech. Rev. 79, 2, p. 20, December 1976.
3. E. Storm, et al., Lawrence Livermore Laboratory Report UCRL-79031 (1976).
4. J. Maniscalco, Lawrence Livermore Laboratory Report UCRL-
5. J. Nuckolls, Laser Interaction and Related Phenomena, Vol. 3, Plenum Press (1974, pp. 399 ff; J. Nuckolls et al., Nature 239 , 139, 1972.
6. G. Zimmerman, Lawrence Livermore Laboratory Report UCRL
7. B. Langdon, Lawrence Livermore Laboratory Report UCRL
8. W. Kruer, Lawrence Livermore Laboratory Report UCRL
9. R. Bangerter, Lawrence Livermore Laboratory Report UCRL
10. M. Clauser, private communication.
11. J. Nuckolls, Lawrence Livermore Laboratory Report UCRL 50000 71-5 (1971) SRD.
12. G. McCall, R. Morse, Laser Focus Magazine, December 1974.
13. J. Larsen, 1976 Laser Fusion Annual Report, Lawrence Livermore Laboratory (in publication).
14. J. Nuckolls, Lawrence Livermore Laboratory Report UCRL 79834, European Conference on Laser Matter Interaction, Oxford, England, September 1977.
15. J. Yonas, private communication. D. Meeker, et al., Lawrence Livermore Laboratory Report UCRL

34. V. Slivinsky et al., Phys. Rev. Lett. 35, 1083 (1975).

35. Rudakov

36. J. Yonas

37. G. McCall

38. See for example H. Ahlstrom, Lawrence Livermore Laboratory Report UCRL 79819, European Conference on Laser Matter Interaction, Oxford, England, September 1977.