CLM-P310

UKAEA RESEARCH GROUP

Preprint

REACTOR IMPLICATIONS OF LASER IGNITED FUSION

R HANCOX
I J SPALDING

CULHAM LABORATORY
Abingdon Berkshire

1972

CLM-P 310

REACTOR IMPLICATIONS OF LASER IGNITED FUSION

by

R. Hancox
I.J. Spalding

ABSTRACT

Some technological and economic aspects of a super-high density inertially-confined laser-ignited thermonuclear reactor are discussed. Consideration of the economics of the system shows the importance of minimising circulating power by using efficient lasers ($\eta_\ell \sim 0.15$-0.3) and achieving a high burn-up in the compressed core. The importance of a high repetition rate ($f \sim 50$ Hz) to permit an adequate margin in the capital cost of laser components is demonstrated. An estimate of typical costs for a 530 MW(e) deuterium-tritium fuelled system which might compete with a fast fission reactor is presented. Economic operation of a deuterium fuelled system is shown to be much more difficult to achieve. Some physical factors which might affect the thermonuclear gain but which are not included in published computer predictions are discussed, including relativistic effects and topological problems which arise if the incident radiation is polarized.

UKAEA Research Group
Culham Laboratory
Abingdon, Berks

December 1972

CONTENTS

1. INTRODUCTION

Several inertially-confined laser-ignited thermonuclear reactor (ICLITR) appraisals have appeared in the last year(1-8). The conclusions of these studies range from pessimism to optimism, and it therefore seems worthwhile reviewing differences in the underlying assumptions. In particular it is instructive to anticipate some general characteristics of an ICLITR assuming that the very promising thermonuclear gains recently predicted by the Livermore Group(5), using relatively low laser energies to produce superhigh density targets, can be substantiated by subsequent experiments at laser wavelengths of practical interest. The most probable competitors for an ICLITR are the fast breeder fission reactor or a magnetically confined fusion reactor. Since generating costs for the fast breeder reactor can already be assessed quite closely these have been adopted as the basis for an economic criterion, and it has been assumed that fusion generating costs should not be greater than these anticipated fast breeder costs in order to provide a sufficient incentive for fusion to displace fission. This criterion may prove to be rather conservative since no allowance is made for any environmental advantage which may accrue to fusion.

2. TECHNOLOGICAL ASPECTS OF AN ICLITR

2.1 Reactor Vessel

In the Blascon device(3) a free-standing vortex is formed by rotating a lithium pool about a vertical axis. The neutron flux and energy seen by the stationary structure will be very low because of the thick lithium inner layer, with the advantages that the radiation damage and build-up of radioactive impurities normally expected in the structure are reduced. Access to the pellet is very restricted, however, so that it seems impossible to ensure that the incident laser intensity approximates to the desired spherical symmetry, and the frequency of operation is limited by the time required to re-establish the lithium vortex to 1 pulse per 10 seconds.

A slightly more conventional design, which is compatible with a laser input approximating to spherical symmetry, has been discussed in detail by the Los Alamos Group(4). A thin ablative layer of lithium protects the inner wall of the reactor vessel, which is porous. Approximately 1.6 kg of lithium are vaporised per pulse and it is estimated that approximately 1 second is required to achieve an adequate vacuum between the micro-explosions. Two further concentric spherical walls contain lithium coolant and withstand the shock from the explosion. Finally, the feasibility of a 'dry wall' design has been indicated by the Livermore group(5).

The parameters for these proposed systems are summarised in Table I. The implication of these designs is encouraging since they suggest that not only can thermonuclear explosions of energy 10^9 joules be contained in specially designed reactor vessels, but that explosions of energy 5×10^7 joules which are typical of an ICLITR operating at superhigh densities can be absorbed without significant wear and tear in a relatively simple reactor vessel. This is important because the low value of the electricity produced per shot places severe economic restraints on the permissible capital cost of the reactor vessel and on the cost of replacing damaged components.

2.2 Repetition Rate

Another important economic constraint on an ICLITR is likely to be the capital cost of a suitable laser, or of the capacitor store required for pumping it (assuming, for the present, electrical excitation). It is therefore desirable to operate the laser at as high a repetition rate as possible. When the nuclear output energy (E_f) is large this leads to impracticably high mean powers, as has already been noted(1). With a nuclear output energy of 10^8 joules, however, repetition rates (f) of 1 to 100 Hz may be quite practicable.

Four principal technological problems are likely to determine the optimum repetition rate:

TABLE I

System	Blascon(3) (Oak Ridge)	Wetted wall(4) (Los Alamos)	Dry wall(5) (Livermore)
Thermonuclear energy per pulse	1500 MJ	200 MJ	10-80 MJ
Repetition rate of laser	0.1 Hz	1 Hz	~ 100 Hz
Mean power	150 MW(th)	200 MW(th)	~ 1000-8000 MW(th)
Inner wall	Lithium vortex (with bubbles)	Porous wall wetted by 2 mm of Li	10 chambers?
Inner wall diameter	4.5 m	2 m	-

(i) The life-time of the laser and/or capacitor bank.
(ii) The time required to evacuate the reactor vessel between explosions.
(iii) The cost of the reactor vessel(s) as a function of mean power.
(iv) The cooling of the laser and associated optical components.

Pulse rates of order 50 Hz imply the need for reliable operation of components for approximately 4×10^{10} pulses, assuming a reactor life-time (τ) of 25 years, which is an exacting requirement. The life of present experimental capacitor banks is typically 10^5 to 10^6 pulses. The reliable life-time of most laser or electrical components can be economically increased, however, by under-rating them. As a specific example, present experience with energy storage capacitors at Culham(9) suggests that their life scales as

$$(\tau f) = A(Vo/V)^6 \qquad \dots (1)$$

where V is the peak operating voltage, Vo is the maximum rated voltage, and A is a constant characteristic of the capacitor design. Assuming a capital cost B £/joule at the full rated voltage, it follows that the cost when derated to give the same life at a higher operating frequency is

$$\begin{aligned} B' &= (\tfrac{1}{2}CV_0^2)/(\tfrac{1}{2}CV^2)B \\ &= B(\tau/A)^{1/3} f^{1/3} \end{aligned} \qquad \dots (2)$$

where C is the capacity. This cost increases much more slowly with repetition rate than the thermonuclear output, which is directly proportional to f, so that there is a distinct economic advantage in operating at higher frequencies. It is concluded that the upper limit to the frequency of operation is unlikely to be determined by component life-time considerations, provided that strong power-laws of the type given in equation 1 are valid. The operating frequency is therefore more likely to be determined by the requirement to evacuate the reactor vessel between explosions, so that the focussed laser beam can be efficiently transmitted to the target. If this evacuation time is estimated to be of order 1 second(4) a high operating frequency implies a requirement for several reaction chambers within one reactor vessel. Whilst it would be perfectly feasible to use one capacitor bank to energise sequentially such an assembly of reaction chambers, each of which is surrounded by its own spherical array of laser amplifiers, beam-splitting and other problems make it less convenient to switch a single laser output to each of the reactor chambers in turn. It is therefore concluded that the choice of the number of reaction chambers, and hence the operating frequency, will be determined primarily by the capital cost of a multiplicity of efficiently pumped chambers with their surrounding laser assemblies. For practical reasons, it seems desirable to restrict the number of reactor vessels to a low number. The operating frequency is arbitrarily set at 50 Hz in the following economic assessments, and it is noted that the optimization of the reactor vessel design to permit rapid repetition rates within one chamber may prove to be a problem of major technological importance.

3. ECONOMIC CONSTRAINTS

An energy flow diagram typical of ICLITR systems is shown in figure 1; the possibility of direct conversion is neglected. Assuming a repetition rate of 50 Hz, but taking a thermonuclear gain A (ratio of fusion energy E_f to laser light energy E_r) intermediate between the low value (A = 10) discussed by Rosenbluth(7) and the higher values (A ∿ 80) predicted by the Livermore Group(5), it will be shown that costs could be comparable with alternative fission reactors.

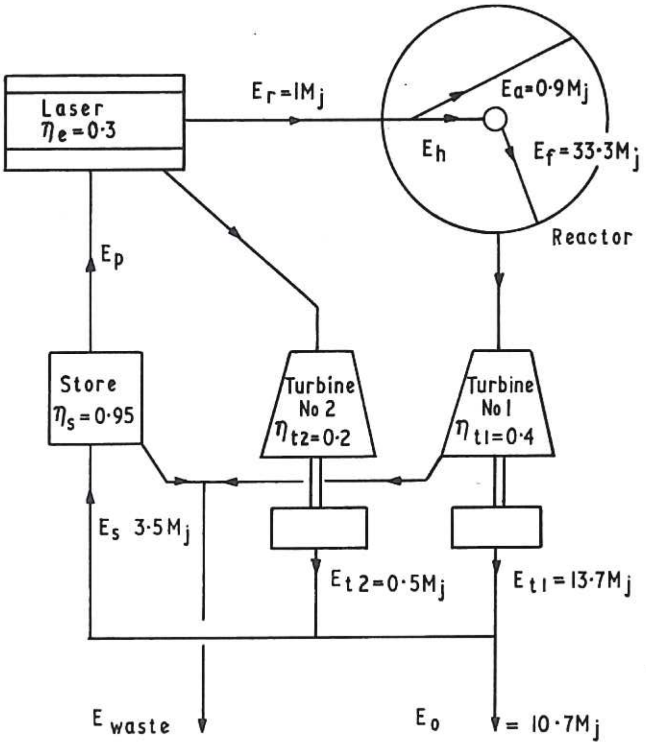

Fig.1 Typical Energy Flow Diagram. At a repetition rate of 50 Hz the mean station output is 530 MW(e). If total laser costs amount to 8% of capital plant costs the laser could cost £3.3M, i.e. £3.3/laser joule or £1/pump joule.

3.1 Component Costs

The reference fast breeder (fission) reactor will be a fully developed commercial 2 × 1250 MW(e) sodium-cooled reactor operating with carbide fuel at a load factor of 65% and with a life of 25 years. It is assumed that the fuel inventory, fuel replacement costs, and the refuelling penalty, can be reduced by a factor four for the fusion system. On this basis the allowable plant costs, excluding buildings and civil works, are £80/kW(e) at 1971 prices. It could be argued that the reactor vessel design is simpler than that of the equivalent fission reactor, and the cost per kW(e) of the reaction chambers is therefore arbitrarily set at two thirds of the breeder vessel. Most of the reactor auxiliary costs will be similar in the two systems, with liquid sodium replaced by liquid lithium in the cooling system and the fission fuel handling equipment replaced by a tritium separation plant and fuel pellet manufacture and injection system.

The saving already outlined will be offset by the cost of a laser and its energy storage capacitors. The cost of capacitors will probably lie between the present cost of £0.2/joule for capacitors of limited life and £0.5/joule for long-life (power factor) capacitors; a figure of £1/joule is therefore tentatively assigned to cover capacitors having a life of the order of 4×10^{10} discharges and the laser. This may be compared with total laser costs for present one-off, limited-life, experimental neodymium or carbon dioxide facilities, which are of order £1 to £4/pump joule.

In calculating the total system cost the unit cost of each component is multiplied by the local circulating energy.

3.2 Maximum Economic Level of Circulating Energy

The economic criteria and component costs are closely related to the circulating energy ratio R. The inverse of this ratio is defined as the net electrical output of the system divided by the thermonuclear power available after conversion by the main turbo-alternator. Thus

$$
\begin{aligned}
R^{-1} &= E_0/E_f\,\eta_{t1} \\
&= 1 - \frac{1}{A}\left[\frac{1}{\eta_s\eta_\ell\eta_{t1}} - \frac{(1-\eta_\ell)}{\eta_\ell}\,\frac{\eta_{t2}}{\eta_{t1}} - 1\right] \\
&\approx E_0/E_{t1} \quad \text{when} \quad A \gg 1 \qquad \ldots (3)
\end{aligned}
$$

Typical values of this inverse ratio (R^{-1}) are plotted in figure 2 as a function of the thermonuclear gain (A) for various values of the laser efficiency η_ℓ (assuming $\eta_s = 0.95$, $\eta_{t1} = 0.4$, $\eta_{t2} = 0.2$). The minimum value of the gain required to satisfy the economic criterion is given by the intercepts with the lines of constant laser costs, assuming the operating frequency of 50 Hz.

3.3 Burn-up Required

In order to meet the economic criterion the thermonuclear gain in the reacting core must be high. This requirement can be expressed more vividly in terms of the 'burn-up' required in the compressed core. Elementary computations of the ignition phase in the compressed core suggest that ignition with deuterium-tritium (D-T) fuel is obtained when the initial temperature approaches 5 keV, after which the ion temperature rises very rapidly to greater than 100 keV. Taking the mean energy from each reaction as 22.4 MeV, which includes the exothermic reactions of neutrons in lithium but neglecting deuterium-deuterium (D-D) reactions, the energy gain is approximately

$$A_{DT} \sim 750\,F\,\eta_a \qquad \ldots (4)$$

where F is the fraction of fuel ions consumed in the compressed core and η_a is the efficiency with which the core is heated by the laser i.e. $\eta_a = (E_r - E_a)/E_r$, where E_a is the energy wasted by ablation of the non-reacting outer corona. η_a is sensitive to a variety of physical factors, some of which are discussed in section 4; with various simplifying assumptions η_a has been calculated to vary between 5%(6) and 10%(5). Taking $\eta_a = 0.1$, an approximate burn-up scale for D-T is indicated on Fig.2.

With deuterium (D-D) fuel the ignition energy is nearer 50 keV, and the achievement of an 'economic' energy gain appears much more difficult, even assuming direct conversion of both the charged particle and the neutron energy, since

$$A_{DD} \sim 75\,F\,\eta_a \qquad \ldots (5)$$

in a D-D system in which the mean energy released for each primary reaction is 34.2 MeV(10).

The economic criteria of section 3.1 are illustrated in slightly different manner in figure 3, where the repetition rate (f) required to permit 'economic' plant costs of £80/kW(e) are plotted as a function of burn-up for various values of the total laser costs, expressed in £ per (pump) joule for a laser system operating with $\eta_\ell = 0.3$, $\eta_{t1} = 0.4$, $\eta_{t2} = 0.2$, $\eta_s = 0.95$. The tentative estimate of £1/pump joule for laser costs and an assumed frequency of 50 Hz would permit economic operation with D-T fuel for burn-ups greater than 45%. A typical breakdown of costs for this system is given in Table II.

3.4 Economic Limitations

Two potential economic limitations can be identified from figures 2 and 3:

(i) The necessity for a sufficiently high thermonuclear gain (A), equivalent to a sufficiently high burn-up (F). This requirement arises primarily because of the high capital cost of the steam generating plant and turbines, which makes it essential for the power handled by these components to be comparable with the output power.

(ii) The need for lasers of adequate efficiency and reasonably low capital cost.

Provided possible technological problems associated with a reactor vessel operating at repetition rates of the order of 50 Hz can be overcome, a reasonable financial margin appears to exist for the (unspecified) laser capital costs, even if the thermonuclear gain does not reach values approaching 80 because of departures from spherical symmetry or for other physical reasons discussed in section 4.

The criteria discussed above are approximately equivalent to the requirement

$$A_{DT} > \{3 + 38(C_\ell/f)\}/\eta_\ell\eta_{t1}\eta_s \qquad \ldots (6)$$

where C_ℓ is the cost of the laser and its associated capacitors in £/pump joule and f is the operating frequency of the reactor. This is more restrictive

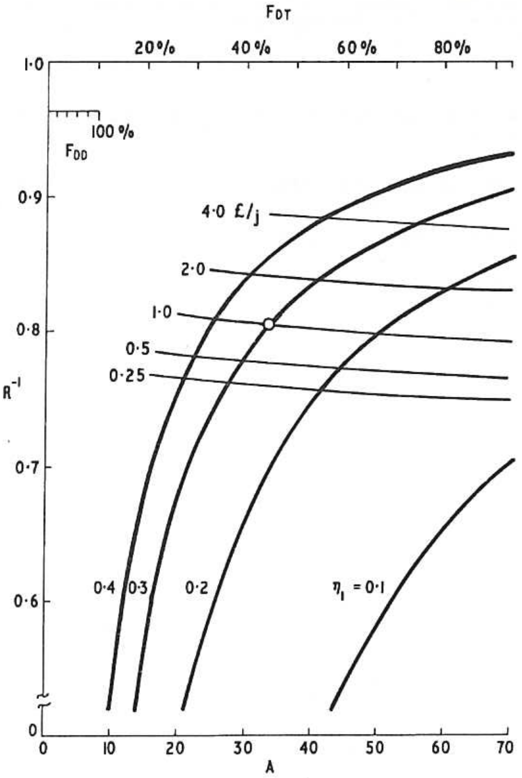

Fig.2 Variation of the reciprocal of the circulating energy ratio (R^{-1}) with thermonuclear gain (A) plotted for laser efficiencies (η_ℓ) of 0.1 to 0.4. The minimum value of the gain which would satisfy the economic criterion at an operating frequency of 50 Hz is given by the intercepts with the lines corresponding to laser costs of £0.25 to £4.0 per pump joule. The core burn-up (F) appropriate to the D-T and D-D reactions (assuming $\eta_a = 0.1$) are also indicated on the abscissa. The point indicated by a circle corresponds to the reactor parameters given in figure 1 and Table II.

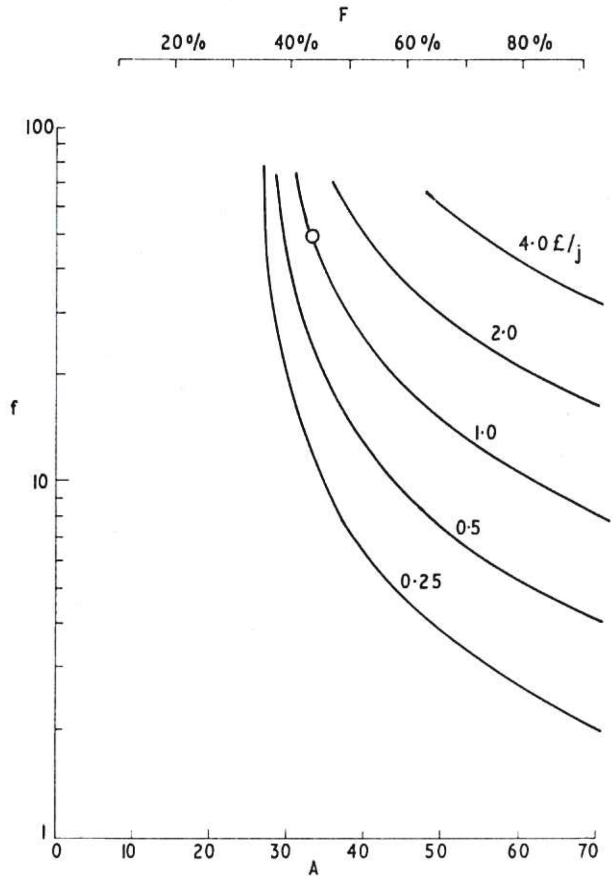

Fig.3 Required operating frequency (f) as a function of the thermonuclear gain (A) to meet the economic criterion with a laser efficiency (η_ℓ) of 0.3 and laser costs of £0.25 to £4.0 per pump joule. The core burn-up (F) appropriate to the D-T reaction (assuming $\eta_a = 0.1$) is also indicated on the abscissa. The point indicated by a circle corresponds to the reactor parameters given in figure 1 and Table II.

than the criterion for marginal operation given by Nuckolls et al(5).

4. SOME FACTORS AFFECTING THE THERMONUCLEAR GAIN

Several important physical effects which may adversely influence the high predicted thermonuclear gain have been mentioned by Nuckolls et al(5), in particular the possible generation at longer laser wavelengths, and at intensities of reactor interest, of supra-thermal electrons with a consequent danger of prematurely heating the compressed core. Rosenbluth(7) has discussed an additional possibility that at the highest laser intensities strong stimulated back-scatter of the incident radiation might also occur, so lowering the efficiency (η_a) with which the laser radiation is used to form the compressed core.

Other processes which have not yet been fully simulated in published numerical work, and which may also affect the overall efficiency, include the effect of density gradients on plasma instabilities(11), absorption of radiation at sub-critical frequencies due to stimulated compton scattering(12), self-focussing, and harmonic generation due to density gradients and relativistic effects. Perhaps of particular interest is the possibility of relativistic over-dense propagation in the presence of density gradients(13); neglecting attenuation, circularly-polarized $\lambda = 10.6$ μm radiation might propagate into a plasma having a density as high as $7 \times 10^{20}/\text{cm}^3$ assuming a density scale length of 1 mm and an incident intensity of 10^{17} W/cm^2. Propagation therefore occurs, in this particular example, up to densities which are 70 times greater than the non-relativistic, low intensity, 'critical' density.

The significance of the state of polarization of the laser beam has not been widely discussed. Two effects are of importance:

(i) Stamper(14) has discussed polarization-induced velocity anisotropy and radiation pressure sources of asymmetry which can generate magnetic fields. Thus, circularly polarized beams can generate strong magnetic fields through the inverse Faraday effect(15). Such magnetic fields may cause unwanted departures from spherical symmetry during the density compression.

(ii) These are symptoms of a more general problem that topological considerations preclude the possibility of perfect spherical symmetry of any polarized intensity distribution , see figure 4. This may prove to be a significant practical problem, since relatively few techniques exist for pulse shaping an unpolarized laser beam at the present time; moreover the polarisation of the laser beam is often useful in protective devices, such as Faraday isolators. (Note that cylindrical symmetry is topologically possible using plane-polarized radiation in infinitely long systems; however, thermo-electric effects will occur at the ends of real cylinders, just as they will in spherical experiments which lack perfect symmetry in the intensity distribution).

5. POTENTIAL ADVANTAGES OF ICLITR

An inertially confined thermonuclear reactor has several potential advantages over a magnetically confined fusion reactor.

(i) In common with all nuclear reactors, the structure will become radio-active and the fuel handling equipment will contain active materials, so that nuclear shielding and secondary containment vessels will restrict access to the reactor. The escape from the toroidal geometries preferred in magnetically confined fusion systems therefore provides a significant topological advantage for the spherical ICLITR geometry, since maintenance and replacement of sections of the structure are possible using simple modifications of present remote handling methods.

(ii) The abandonment of magnetic confinement not only removes the item of highest capital cost but also greatly simplifies the reactor design. (The support structure which is required to withstand the large forces between sections of the magnet tends to dominate the reactor, and the need to cool the magnet and this massive structure to liquid helium temperatures will severly limit access for the blanket coolant pipes and other necessary auxiliaries.)

TABLE II

Breakdown of costs for a D-T reactor operating with a laser efficiency $\eta_\ell = 0.3$. (Assumptions: $\eta_{t1} = 0.4$, $\eta_{t2} = 0.2$, $\eta_s = 0.95$, f = 50 Hz, A = 33.3, R = 1.25)

Reactor vessel	11.8 £/kW(e)
Reactor auxiliaries	4.5 £/kW(e)
Liquid lithium	2.0 £/kW(e)
Control	4.5 £/kW(e)
Fuel processing	0.6 £/kW(e)
Steam generation	12.8 £/kW(e)
Turbines	27.8 £/kW(e)
Electrical plant	9.4 £/kW(e)
Capacitors and lasers	6.6 £/kW(e)
	80.0 £/kW(e)

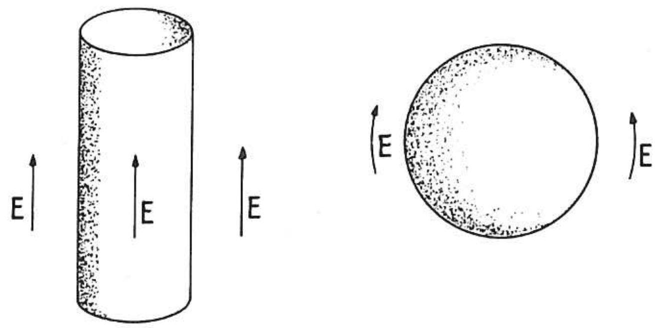

Fig.4 Polarization-induced deviations from spherical symmetry. (a) Plane-polarized wave, having true (infinite) cylindrical symmetry. (b) The topological problem associated with a polarized spherical intensity distribution; regions of zero over-lap are required to approximate to perfect spherical symmetry.

(iii) A relatively modest vacuum is required, relative to most fusion approaches.

(iv) Means of ignition, refuelling, and fusion-product removal, which still have to be developed for most magnetically confined fusion reactor concepts are automatically provided in this approach.

(v) The mean power output of the reactor can be readily controlled.

(vi) The various components can be developed and proved independently of the reactor itself. Thus, the lasers and fuel injection system can be developed separately, and scientific feasibility can be demonstrated on a single-shot basis in the equivalent of a very low power reactor.

Against these potential advantages must be balanced certain technological problems which are specific to laser fusion. These currently include the development of:

(a) Highly efficient, pulse-shaped lasers, working at appropriate wavelengths and operating at approximately 50 MW mean power.

(b) High repetition rate (50 Hz), long life (4×10^{10} pulse) pumping systems having costs of order £1 to 10/joule.

(c) High repetition rate (5 to 50 Hz) reaction chambers compatible with high peak and mean power loadings, and capable of thermal cycling for more than 10^{10} pulses.

(d) Windows compatible with the nuclear environment, and capable of working with minimum distortion at high laser intensities, and at mean powers in the megawatt region.

(e) Means of generating and positioning spherical pellets of controlled size, and of ensuring adequate symmetry of the incident laser flux.

6. CONCLUSIONS

Some technological and economic aspects of a super-high density ICLITR have been discussed. Consideration of the economics of the system shows the importance of minimizing the circulating power by using highly efficient lasers and achieving high burn-up in the compressed core. The importance of a high repetition rate (of order 50 Hz), to allow adequate flexibility in the capital cost of (electrically-pumped) laser components, has been demonstrated. An estimate of typical costs have been presented for a D-T system which might compete with competitive fission systems, assuming that the high thermonuclear gains which have been predicted(5,6) can be achieved in practice. Economic operation of a D-D system is shown to be much more difficult to achieve. Some factors which might affect the thermonuclear gain, and which are not yet included in the computer predictions, have been discussed. The most important of these may be relativistic effects, and topological departures from spherical symmetry which occur if the incident radiation is polarized.

ACKNOWLEDGEMENTS

The authors wish to thank Dr R J Bickerton for helpful comments on the text of this paper, and to acknowledge subsequent interesting discussions with Drs K Boyer, R Kidder, J Nuckolls and P Pashinin.

REFERENCES

1. Report of a consultants meeting on fusion power and the environment. 15-17 December, 1971, IAEA Headquarters, Vienna.

2. LUBIN, M.J. and FRAAS, A.P. Scientific American, 224, 21, (1971).

3. FRAAS, A.P., ORNL-TM-3231, (1971).

4. BOOTH, L.A. et al. Los Alamos Report, LA-4858, I, (February, 1972.)

5. NUCKOLLS, J. et al. Nature, 239, 139, September, 1972, (and VII International Quantum Electronics Conference, Montreal, May, 1972).

6. BREUCKNER, K.A. KMS preprint, KMSF-NP5, April, 1972, - part of the compilation in Doublekay-7521, July 27th, 1972, Basel. Switzerland.

7. ROSENBLUTH, M. 5th European Conference on Controlled Fusion and Plasma Physics, Grenoble, (August, 1972).

8. EDEN, M.J. and SAUNDERS, P.A.H. Nucl. Fusion 11, 37, (1971).

9. JAMES, T.E. and BARNES, P.M. Culham Laboratory, private communication (1972).

10. KOFOED-HANSEN, O. Riso Report No.18, pp.347-365, (1960.)

11. ROSENBLUTH, M.N. Phys. Rev. Lett, 29, 565 (1972).

12. ZELDOVICH, et al, Zh. Eksp. Teor. Fiz 62, 1392, (1972).

13. MAX, C. and PERKINS, F. Phys. Rev. Lett 27, 1342, (1971).

14. STAMPER, J.A. Naval Research Laboratory Report NRL 7411, (1972), and 'Laser Interaction and related phenomena', vol.2, Ed. H.J. Schwarz and H. Hora, Plenum, New York (1972).

15. STEIGER, D.A. and WOODS, C.H. Phys Rev. A5, 1467, (1972).