A Comparison of Lasers and Relativistic Electron Beams (or Light Ion Beams) as Drivers for Inertial Confinement Fusion Reactors

G.A. Moses, G.W. Cooper

March 1979

UWFDM-296

FUSION TECHNOLOGY INSTITUTE

UNIVERSITY OF WISCONSIN

MADISON WISCONSIN

A Comparison of Lasers and Relativistic Electron Beams (or Light Ion Beams) as Drivers for Inertial Confinement Fusion Reactors

G.A. Moses, G.W. Cooper

Fusion Technology Institute
University of Wisconsin
1500 Engineering Drive
Madison, WI 53706

http://fti.neep.wisc.edu

March 1979

UWFDM-296

"LEGAL NOTICE"

A Comparison of Lasers and Relativistic Electron Beams (or Light Ion Beams) as Drivers for Inertial Confinement Fusion Reactors

G. A. Moses

G. W. Cooper*

UWFDM-296

March 1979

*Chemical and Nuclear Engineering Department,
University of New Mexico, Albuquerque NM 87131

Abstract

There are many questions that remain to be answered before the viability of either laser or REB fusion reactors can be accurately determined. At this stage of development the U.S. program is devoting about 80% of its support to the laser fusion approach. Consequently its progress has been more rapid than the REB fusion approach and more is understood about its technical problems. However, there are potential advantages of REBs as drivers in ICF reactors and therefore this approach to fusion must continue to be given serious consideration.

Lasers are capable of delivering very high power pulses (∿1000 TW) to a target in vacuum. Electron beams are likely to be power limited (∿100-200TW) and their propagation to a target remains a very important unanswered question. If low power targets cannot be designed to ignite or propagation is impossible then REBs must be ruled out as ICF drivers. However, laser propagation to a target through a reactor environment background gas has not been tested either. This could be done using existing experimental facilities.

Those lasers under serious consideration as ICF drivers all include an electron beam system to excite the lasing medium. In this sense the REB system is simply a subsystem of the laser driver. In addition there is laser gas handling and reprocessing and the optics system. Because laser systems are far more complex than REB systems it is likely that REB systems will be more easily operated in a repetitive mode.

The electrical efficiency of laser systems is typically estimated to be 1-10% while the efficiency of REB systems is >20%. This high efficiency of REB systems gives them a better chance to be economical in lower power level reactors (∿100 MW_e) than lasers.

Electron beam reactors are likely to be more easily shielded than laser reactors because they do not contain large aperture penetrations such as the laser beam ducts.

In conclusion, the REB driver has more unanswered fundamental questions regarding its ability to obtain adequate target performance in a reactor environment than does the laser driver. However, if adequate target performance and beam propagation can be obtained in a reactor environment, then the REB driver offers some significant engineering advantages over the laser.

I. Introduction

The basic concept of inertial confinement fusion (ICF) is to compress and heat a small pellet of D-T fuel to thermonuclear conditions.[1-2] These conditions must then be maintained for a time sufficiently long to allow the energy from thermonuclear reactions to exceed the energy expended in compressing and heating the pellet.[3] To compress and heat the pellet and maintain these conditions by inertial confinement it is estimated that a modest amount of energy (~megajoules) must be absorbed by the pellet in a short time (~nsec). This results in the rapid ionization and ablation of the pellet surface and this in turn acts like a spherical rocket thrust to compress and heat the inner portion of the pellet. A critical element of this concept is a source that can deliver the necessary energy to the target at a high power. Two such energy sources (or drivers) are under active development in the United States at this time. These are lasers and relativistic electron beams (REB). This report addresses the relative merits of lasers and relativistic electron beams as drivers for commercial ICF power applications.

A laser is a device that produces a coherent beam of light and is capable of generating large energies at high power. In order to create a laser, a medium must be excited in a manner such that a population inversion is formed; that is, there are more atoms or molecules in the upper level of a particular optical transition than in its lower level. A photon encountering the excited species can stimulate the species to emit a photon with the same phase and direction as the incident photon providing that the incident photon energy is the same as the transition energy. Since there are more excited than unexcited species the medium will exhibit gain and a light beam passing through the medium will be coherently amplified. To establish the inversion, energy must be supplied to the laser medium. This energy can be in the form of electrical (discharge or e-beam), or optical energy depending on the variety of laser. The laser medium is generally (but not always) an energy pulse compressing medium so that high powers can be readily generated. Unfortunately, this pulse compression is usually inefficient so that laser electrical efficiencies are rather low (<10%). The light energy can be delivered to the target by focusing the beam onto the target with mirrors.

Electron-beam accelerators are pulsed power devices that generate energy in the form of electron bursts across a diode. To form the electron beam, a high voltage, high energy pulse of electro-magnetic energy is first produced, usually by a Marx generator. This pulse is then compressed in time by transfer to pulse forming lines (and possibly intermediate storage capacitors). The EM pulse travels down a vacuum transmission line and finally appears across the diode; the high voltage rips electrons from the cathode and the electrons are accelerated toward the anode, forming the e-beam. The e-beam undergoes one less energy conversion step than do lasers so that the efficiency could be higher (~25 to 30%). However, this also eliminates the final pulse compression step that occurs in the laser amplifier so that the pulse width of the e-beam will be longer (~20 nsec). Finally, unlike the laser, a proven method for transporting the beam to the target is not known although potential methods are being investigated. Currently the target is mounted onto the anode. It should also be noted that by "reversing" the diode a light-ion beam can be produced with this technology and this has possible advantages over e-beams for ICF applications.

For the development of lasers and electron beams to reach the stage of reactor applications a variety of technical and economic questions must be answered. The questions include:

(1) Can lasers and/or electron beams deliver enough energy to the target at the required power levels to produce a significant energy gain?

(2) Can lasers and/or electron beams deliver this energy to targets repetitively?

(3) Are lasers and/or electron beams efficient enough to result in an acceptably low recirculating power fraction?

(4) Can lasers and/or electron beams be transported to an unsupported target on a repetitive basis?

(5) Can the final element in the focusing system (mirror or diode) be adequately protected from the pellet explosion and thermonuclear neutrons?

(6) Can the reactor first wall be protected from the pellet blast?

(7) Can targets be manufactured at a sufficiently rapid rate to fuel the reactor?

(8) Can a reactor cavity, blanket, and shield be designed to meet economic engineering constraints?

In the following sections, each of these questions will be discussed and where it is appropriate comparisons will be made between lasers and electron beams.

II. Target Performance

The most fundamental requirement for any inertial confinement fusion reactor is acceptable target performance. Target performance can be defined as the energy gain of the target measured as a function of the input energy, the power at which this energy must be delivered, the wavelength or energy of the beam particles and the shape of the energy pulse. Complex targets, designed to accommodate the characteristics of a particular driver, as well as design of the driver to meet generic target requirements are required to obtain estimates of this performance. This process, and its discussion, is complicated by the fact that all drivers will not require the same target gain to meet the requirements of an economically attractive system. A lower target gain is acceptable for higher efficiency drivers such as electron beams because these drivers do not require the large amounts of recirculating power that low efficiency lasers might require. The details of this relationship between target gain and driver efficiency will be discussed in Section IV. For the purposes of this current discussion the well known rule that the product of driver efficiency and target gain equal to ten is necessary for a 25% recirculating power fraction will be used. Therefore, a 30% efficient electron beam reactor system requires a target gain of 33 while a 2% laser system requires a target gain of 500 to meet this criterion. To assess the probability of achieving this performance requires an investigation of the basic features of target design. To achieve a high gain (>100) requires the efficient isentropic compression of the DT fuel to high densities (>100 g/cm^3) and a carefully programmed convergent shock to ignite the center of the compressed fuel. Deviations from the isentropic compression reduce the gain because then more input energy is needed to reach the final compressed state. Deviations from the carefully programmed spherically convergent shock result in a failure to ignite the DT fuel. In this case there is a catastrophic failure of the target to produce any thermonuclear energy at all.

Three factors currently dominate the design of such high gain targets for lasers and electron beams. These three factors are:

(1) efficient coupling of the beam energy into the target,

(2) hydrodynamic stability of imploding spherically concentric shells, and

(3) preheating of the DT fuel, destroying the isentropic compression process.

Efficient coupling of the beam energy into the target is obviously essential to good performance. If one assumes that a given amount of absorbed energy is required to implode a reactor target then the target gain will be directly proportional to the absorption efficiency. Estimates of absorption efficiency for reactor studies usually range between 50-100%. This is a higher efficiency than most published experimental results. Experiments show efficiences of 20-50% depending on the exact details. However it is anticipated that the larger reactor targets will be characterized by a higher absorption efficiency.

Relativistic electrons deposit their energy in a high Z material that forms the outside shell of the target. The rather long range of these electrons results in a low specific absorbed power in the absorption region of the target. This in turn leads to low temperatures (<100 eV) and a low implosion velocity ($<10^7$ cm/sec). It is postulated that as the electron beam intensity is increased, the self-generated magnetic field from the beam will effectively reduce the mean free path of the electrons.(4) This should improve the specific power in the targets and increase the implosion velocity. It is thought that this enhanced absorption is likely to be necessary for electron beams to be truly successful fusion drivers.

It was orginally thought that shorter wavelength laser light would more effectively couple into the target. This was based on the fact that most of the absorption occurred near the critical density of the plasma and shorter wavelengths implied a greater critical density and hence deeper penetration of laser light into the target. Those experiments done at wavelengths of 1.06 μm and 10.6 μm indicate that these scaling laws are untrue due to modification of the plasma density profile near critical density by the pressure of the incident high intensity laser beams.(5) These arguments have been replaced by scaling laws that translate the laser intensity and wavelength into an energy or effective temperature of the electrons into which the laser beam transfers its energy. The temperature of these so-called hot electrons increases with increasing intensity and wavelength. Because most of the laser energy is not absorbed by the bulk pellet material but instead is transferred into a very few, very hot electrons, the hydrodynamic implosion process is degraded considerably. Furthermore the long mean free path of these electrons allows them to stream into the pellet, ahead of the ablation front and preheat the compressing DT fuel. This destroys the isentropic implosion. This preheat of the fuel and degradation of the implosion process must be remedied to obtain high pellet gains. Two design options are possible. The interior part of the pellet, the DT fuel and its surrounding tamper, can be shielded from the high energy electrons by interposing a layer of high Z material. Unfortunately this high Z layer must also be imploded and this additional mass reduces the implosion efficiency. However target gains in the range of 100-200 appear feasible for such designs. Such target designs are likely to be necessary if the laser wavelength is long (i.e. 10.6 μm). Another alternative is to develop a short wavelength laser (2000-5000 Å) of high energy (>3 MJ) so that rather large pellets can be used.[(6)] In this case the large surface area over which the light is absorbed reduces the intensity at the critical density. Combined with the shorter wavelength, this design produces hot electrons at a lower temperature. The mean free path of such electrons is much less, hence less preheat shielding is required and the target gain can be as high as 1000. Such high gains allow the use of lower efficiency lasers. It should also be noted that preheat of the DT fuel in electron beam targets can result from the hard X-rays generated by the relativistic electron energy deposition. Preheat shields must also be considered in REB target designs.

Target designs are also constrained by the fact that thin shells are expected to be unstable when imploded. The growth of these fluid instabilities limits the aspect ratio (R/ΔR) of the shells to less than 10 according to current analysis. This represents a serious constraint on target design because thin shells, if they were stable, can be imploded at higher velocities then thicker shells. This increases the chances of ignition. Thin shells would also allow longer driver input pulses so that the energy could be delivered at lower power. Low aspect ratio shells must rely on velocity multiplication from multiple shell collisions to reach the final collapse velocity necessary for ignition. Evidence of fluid instabilities has not yet been seen in experiments because all implosions to date have been non-isentropic.

From this brief review of the generic target design characteristics necessary for high gain targets and the major factors impacting target design today, several conclusions can be drawn.

(1) The potential high efficiency of the electron beam driver mitigates all of the generic problems associated with ICF target design because the target gain need not be as high as that required for low efficiency lasers.

(2) To be successful, high gain REB targets must rely on enhanced deposition of the electrons to provide a higher specific power, thus driving a higher implosion velocity. Such enhanced deposition is not firmly established.

(3) Beam-target coupling at high power (>100 TW) is a problem for REBs because of the power limitation per beam and electric and/or magnetic field effects in the beam overlap regions near the target. Lasers do not appear to be so severely limited in the maximum power that they can deliver to the target. Low beam power requires sophisticated target designs to increase the implosion velocity for ignition. If thin shells prove to be stable this could be a great help to REB target design.

(4) REB pulse widths are likely to be no shorter than 20-40 nsec, compared to <1 nsec for lasers. Hence the success of long pulse target designs is more important to the success of REBs than to the success of lasers. Thins shells are one type of target design that can utilize long pulses.

(5) In summary, the relative probability of success of REB targets as compared to laser targets depends upon target physics questions that have not been answered experimentally. Because the REB driver has a high efficiency, the minimum acceptable target gain is much less than for lasers. However, the potential inability of REBs to deliver very high power beams to the target leaves open the question of ignition. Failure to ignite the DT fuel to a bootstrap condition implies a very low target gain. Hence, lasers offer a more versatile and "higher confidence" driver than REBs. Depending on the success of lower power target designs this may or may not be an advantage.

III. Repetition Rate

Assuming that acceptable target performance can be demonstrated for a single shot, the next step must be to accomplish this on a repetitive basis. This repetition rate will be limited by (a) re-establishment of the driver system to firing conditions, (b) re-establishment of the reactor cavity to the proper conditions, including pellet injection, and (c) target manufacturing rate. It is anticipated that repetition rates of 1-30 Hz will be required for laser or REB reactor designs. Specific details of each design sets an upper limit on the rate.

Repetitive pulsing of the driver system is distinguished from single shot operation by the necessity to rapidly replace short lifetime components and the reprocessing of recyclable materials. There is also the question of the lifetime of long lifetime components. Many of these considerations are very specific to the type of laser driver. For instance, CO_2 lasers require no reprocessing of the laser gas while HF lasers require substantial gas reprocessing. Some components, such as capacitive power supplies and switches,are common to almost all of the proposed laser and REB driver systems.

To place laser and electron beam drivers in a comparative framework requires a substantial amount of generalization. Block diagrams of several lasers and an electron beam driver are shown in Fig. 1. The CO_2, HF, I, as well as KrF laser systems use power amplifiers that are pumped by electron beams.

ENERGY FLOW IN LASERS AND E - BEAMS

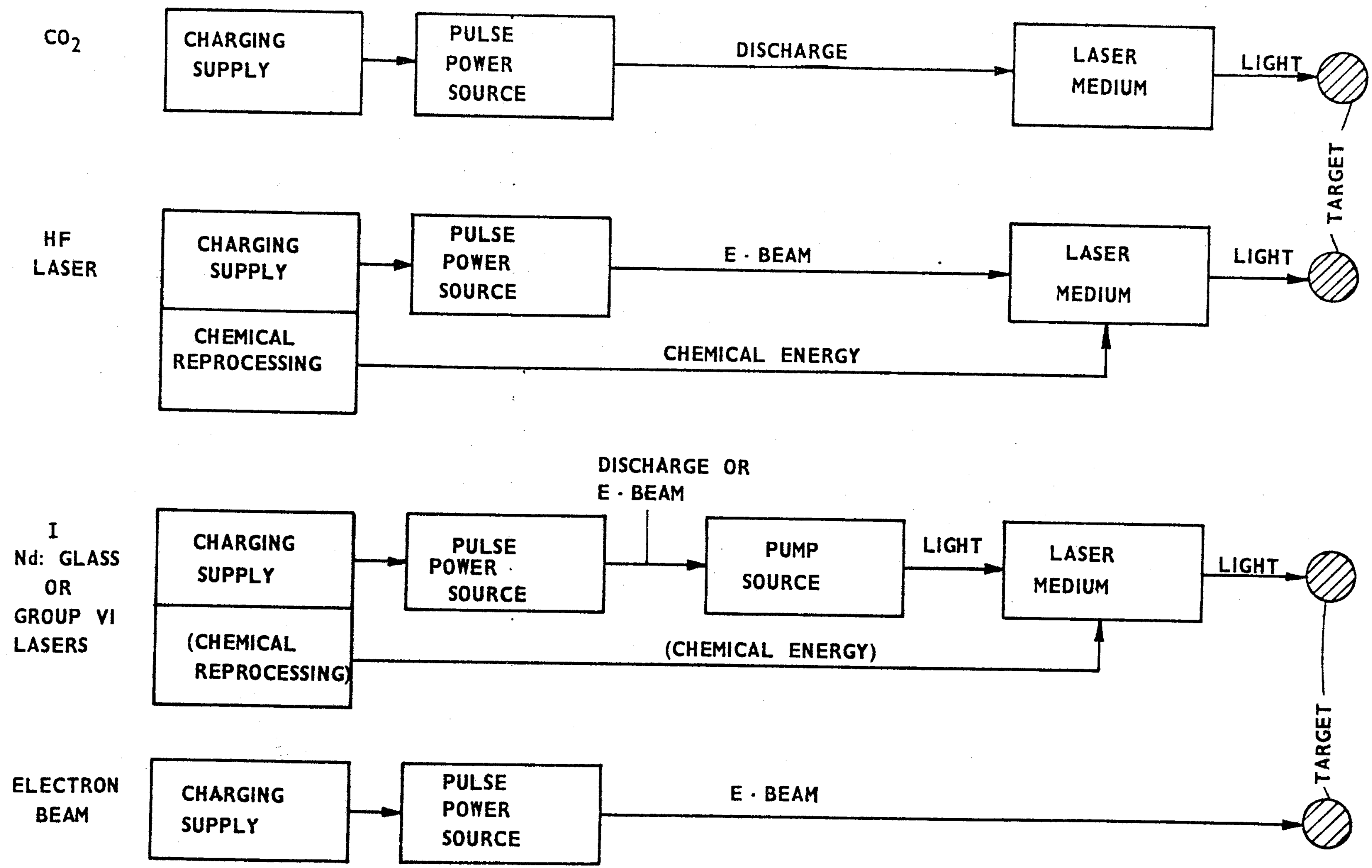


Figure 1

The front end of the laser system handles low power beams and a modest amount of pulsed energy transfer. For this reason it might be concluded that the front end of most proposed laser systems should not present unresolvable difficulties for repetitively pulsed operation. Because this part of the laser system represents such a small fraction of the recirculated power, problems can presumably be solved by redundancy and overdesign of individual components.

The laser power amplifiers require the greatest amount of recirculated power and thus their power supplies, switches, pulse forming, and electron beam hardware are too expensive to allow all problems to be solved by extensive overdesign and redundancy. These components must be economically designed to last for a long lifetime. It is important to note that this pulsed power technology is essentially the same as the electron beam driver with the exception of the diode design. Hence the development of these components is common to both lasers and REBs.

The power amplifiers also require pumping of the laser gas. This gas must be replaced after every shot for several differing reasons. In all of the lasers this gas is heated by the electron beam energy deposition and this heat must be removed. In the case of HF and KrF the gas must be reconstituted before it can be used again. In all of these designs the heat removal problem will be directly proportional to the repetition rate. Also the chemical reprocessing problem will be directly proportional to the repetition rate. These are problems that have no counterpart in the electron beam driver. Because the electron beam driver is more efficient than lasers, less power will be left behind as thermal energy,thus the overall heat removal problem will necessarily be less.

The laser optics that transport the beams from the final amplifiers to the last mirrors might be compared to the transmission lines in a REB machine. In the laser system, alignment of these optical components between pulses will likely be necessary. This will require sophisticated computer controlled feedback systems and possibly adaptive optics. Such computer controlled alignment systems have been developed for the single shot facilities and this may not present any problem for repetitively pulsed reactor systems.(7) However, this has not been demonstrated experimentally. Careful alignment of the transmission lines is not a problem. Both the transmission lines and optics systems may have their lifetimes limited by radiation damage. There is not a good estimate of this problem at this time.

The diode and last mirror can be compared for REB and laser systems. The last mirror in a laser system must be exposed to the 14 MeV neutrons from the target. It will be necessary to actively cool the last mirror but this does not appear to be an insurmountable problem. The last mirror can be placed quite far from the target, 10-100 meters, in proposed conceptual designs. Thermal distortion of the mirror due to transient heating by the laser pulse is a potential problem that must be resolved. These last mirror problems associated with repetitively pulsed operation appear to all have technical solutions by proper design. These solutions must of course be demonstrated experimentally. The lifetime of the diode in current REB experiments is one shot. The target is mounted on the diode and the diode is functionally destroyed by the electron pulse. Clearly, some form of replaceable diode or a newly designed diode with a long lifetime is essential to REB fusion reactors. Because this diode will likely be less than 10 meters from the pellet in a REB reactor, radiation damage and activation of it will be more severe than to the last mirror in a laser fusion reactor. However, the detrimental consequences of this radiation damage to each of these components is not well enough understood to make a comparison.

In summary, repetitively pulsed, pulsed power systems are likely to be a major component of both REB and laser drivers. These systems must have a long lifetime ($>10^9$ shots) for the total driver system to be economical. However, laser systems also include the power amplifiers, laser gas pumping/reprocessing systems, and optics and beam alignment systems. These must all perform in the context of a repetitively pulsed environment. Because these laser systems are far more complex than the REB driver, it can be argued that in general they will be more difficult to reliably operate in a repetitively pulsed mode. Furthermore, because the REB driver is more efficient, there is less hardware per unit of recirculating power. This might imply that the REB driver components have a greater chance to be economically over-designed and redundant than the laser components. This would improve chances of economically reliable operation. However, a fundamental component of the REB driver is the final diode. Current diode designs have a lifetime of only one shot. Therefore, a new diode concept must be developed for the total REB driver to operate with the required repetition rate.

IV. System Efficiency and Related Economics

Both laser and REB fusion systems can be viewed as the conversion of steady state electrical energy into pulsed thermonuclear energy which is converted back again into steady state electrical energy. This conversion system must be efficient enough to provide a substantial excess of electrical energy for the reactor system to be economical. Each conversion from steady state electricity to pulsed thermonuclear energy results in a compression of the associated energy pulse. Each of these pulse compression stages has an efficiency associated with it. For pellet gains much greater than one, the recirculating power fraction, a measure of the system efficiency, can be expressed as

$$f_R = [\eta_{PS}\ \eta_{PFL}\ \eta_D\ \eta_{LA}\ \eta_{BT}\ \eta_A\ \eta_H\ G_C\ M\ \eta_{th}]^{-1}$$

where

η_{PS} - efficiency of the power supply

η_{PFL} - efficiency of the pulse forming lines

η_D - efficiency of the diode

η_{LA} - efficiency of the laser amplifier

η_{BT} - efficiency of the beam transport system

η_A - pellet absorption efficiency

η_H - pellet hydrodynamic implosion efficiency

G_C - ratio of pellet yield to energy in the DT fuel at ignition

M - blanket energy multiplication

η_{th} - blanket thermal conversion efficiency.

Clearly, η_{PS}, η_{PFL}, η_D, η_{LA}, η_{BT}, η_A, η_H, and η_{th} are less than one, and G_C and M are greater than one. In the case of electron beams, there is no η_{LA}. Table 1 has a list of the estimated efficiences for lasers and electron beams. The conversion efficiency of electron beam energy into light in the laser amplifier is the weakest link in the laser system. For most lasers of interest, this efficiency is quite low. However, it is very much dependent on the particular features of any individual laser system. For instance, the HF laser is chemically pumped, so that this electrical efficiency can actually be greater than 100%. In this case, the chemical reconstitution of the HF into H_2 and F_2 has a rather low efficiency, so the total laser efficiency remains quite low.

The absence of this conversion step in the REB driver is the major reason for its high efficiency. However, its absence also results in a longer, lower power, energy pulse. This long pulse length could make target design questionable, as discussed in Section II. If long pulse lengths are acceptable, they can be produced by lasers as well. For many lasers of interest, a longer pulse length will increase the efficiency, η_{LA}, and will thus be beneficial.

Beam transport to the target in a reactor is an important unanswered question for both REBs and lasers. In the case of REBs, the transport technique is yet to be experimentally proven. The 70% efficiency in Table 1 is only an estimate. Although we know that laser beams can be propagated to a target in vacuo, it has not yet been established that these conditions are consistent with reactor operation. This will be discussed in detail in Section V. In current laser experiments, much of the laser beam energy must be wasted to improve the beam quality. High spatial frequency intensity

Table 1

Efficiency of Pulse Compression and Energy Conversion Stages in Laser and Electron Beam Drivers

Component	Estimated Efficiency: Laser	Estimated Efficiency: Electron Beam
Power Supply (η_{PS})	0.95	0.95
Pulse Forming Lines (η_{PFL})	0.9	0.9
Diode (η_D)	0.5-0.7	0.5-0.7
Laser Amplifier (η_{LA})	<0.1	--
Beam Transport (η_{BT})	0.8	0.7
Pellet Absorption (η_A)	0.9	0.7
Hydrodynamic Implosion (η_H)	0.1	0.05
Gain on Core (G_c)	10^3-10^4	10^2-10^3
Blanket Multiplication (M)	1-50	1-50
Blanket Thermal Conversion (η_{th})	0.3-0.4	0.3-0.4

variations across the beam profile are removed with spatial filters in the laser/optics chain. Removal of these hot spots in the beam improves its focusability and eases the problem of target diagnosis. The degree to which the beams in a reactor system must be "cleaned up" will depend on the spot size that they must be focussed onto and the sensitivity of the target to high intensity spots, leading to high temperature hot electrons. Therefore, the propagation efficiencies that are customarily assumed for laser reactor studies have not been experimentally established.

There is a high probability that the efficiencies estimated for the power supplies and pulse forming lines can be achieved. The question in this case will be the reliability of the components. Regular but stochastic failure of switches, etc. may require that the driver fire ten times for every nine successful target shots, for instance. This reduces the effective efficiency of the power supply system. Such problems are likely to be common to both laser and REB systems.

The efficiencies and gain associated with the target were discussed in Section II. The total target gain,

$$G = \eta_A \eta_H G_C$$

must be large ($\geq$100) for laser systems to be economical. Gains of 10-100 are likely to be necessary for REB drivers.

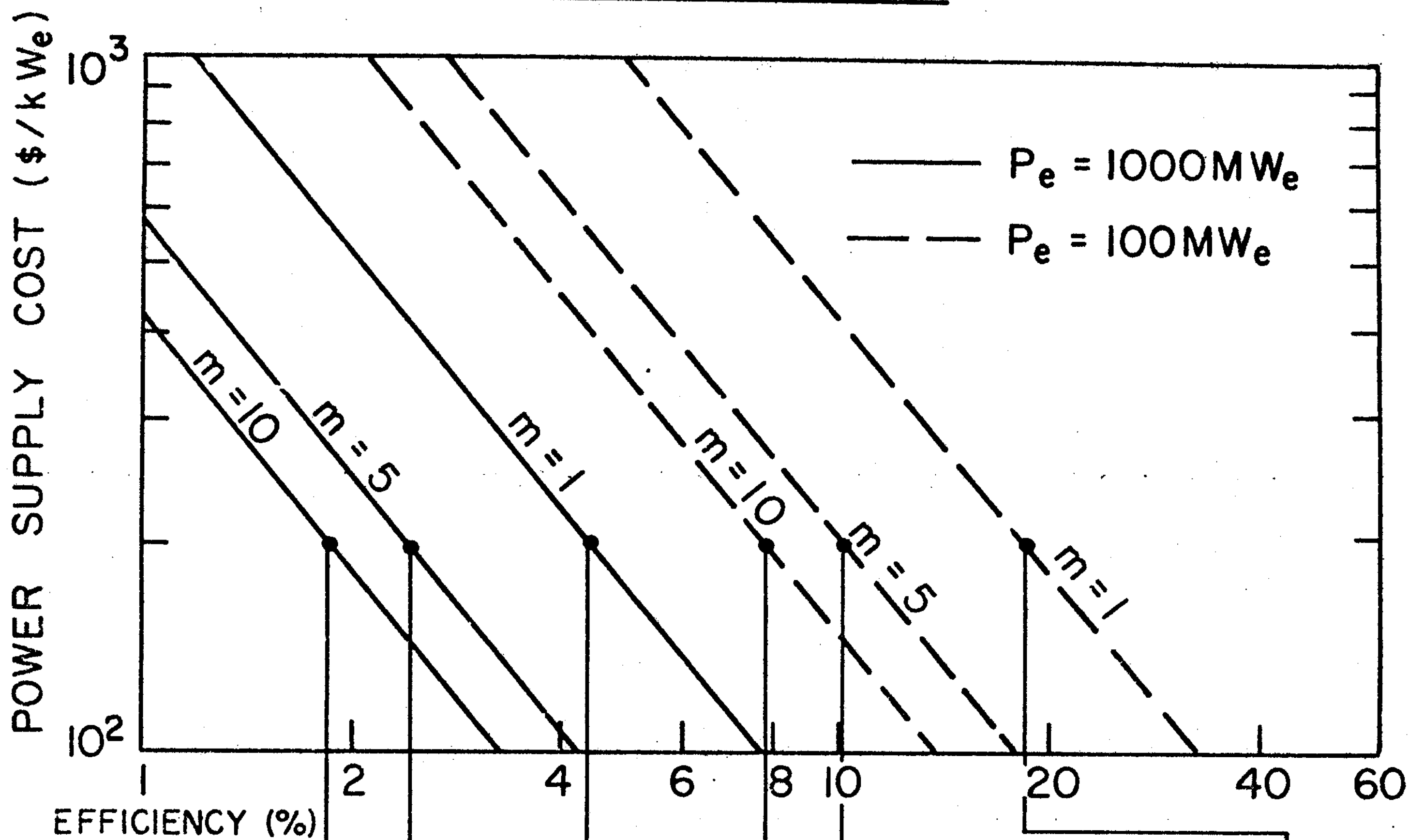
The thermal conversion efficiency of the blanket will be limited by the steam cycle and allowable blanket temperatures. High temperature blankets may have an efficiency as high as 40%. Gas turbine cycles or MHD conversion of the target debris can boost the "thermal" conversion efficiency to 60-70%. However, the choice of "advanced" conversion cycles will be determined by the same economic considerations that are used today.

Note that even these advanced cycles only improve this efficiency by 50%. This is small compared to the potential gains from improvement in the system's low efficiency components. Thermal conversion should be an efficiency that can be accurately predicted, once a real reactor system is designed. At the conceptual design phase, it is an efficiency that is computed with a reasonable degree of confidence, and there is little distinction between REB and laser fusion systems.

The blanket energy multiplication can vary from 1.1 for pure fusion systems to >50 for fusion/fission hybrid systems. This parameter, therefore, has the largest range of values. It is also a high confidence parameter, because the fission process is well understood. The relative suitability of laser and REB drivers for fusion/fission hybrid applications is a complex and important issue. Because it is so important, it will be discussed separately in a later report.

The power supplies and pulse compression stages of the driver will constitute a substantial fraction of the capital cost of the nuclear island. Therefore, plant economics will strongly depend upon the efficient use of this equipment for a long lifetime. Should adequate lifetimes be obtainable by using current capacitive power supply technology, there will be an economy of scale and cost that is related to the driver efficiency.(8) Such estimated relations are shown in Figure 2. Here, the cost of power supplies in $\$/kW_e$ is plotted as a function of driver efficiency for different blanket multiplications and gross power levels. Below the graph are tabulated the specific parameters associated for each case when the power supply cost is limited to $\$200/kW_e$. Note that the minimum driver efficiency for a 100 MW_e power plant with M = 1 is 19%. This is greater than the anticipated efficiencies of any of the proposed

LASER PARAMETERS WHEN LIMITED TO POWER SUPPLY COST OF $200/kW_e



P_e (MW_e)	1000	1000	1000	100	100	100
m	10	5	1	10	5	1
η_L	.019	.0245	.044	.081	.105	.19
G	52.6	81.6	227	12.3	19	52.6
E_L (MJ)	.685	.887	1.6	.292	.377	.685
y (MJ)	36	72	363	3.6	7.2	36
ω (s^{-1})	9.2	9.2	9.2	9.2	9.2	9.2

Figure 2

laser driver candidates. It is of the order of the REB driver efficiency. At 1000 MW_e, the minimum driver efficiency is 4.4%. This now falls within the range of most lasers. The general conclusion of this analysis is that economy of scale arguments show low efficiency lasers to be unsuitable for low power applications. Relativistic electron beams appear to have the required efficiency for these types of plants.

In summary, the following conclusions can be drawn from this discussion of ICF system efficiency and related economics.

(1) The power supplies and power conditioning equipment in the REB driver are also a subsystem of the laser driver. But in addition, the laser driver includes a conversion from electrons to light with an associated pulse compression and efficiency. It must therefore be concluded that REB drivers have a greater likelihood of high efficiency (>20%) operation.

(2) Beam transport efficiency has not been substantiated for either lasers or REBs in a reactor environment. However, high power beam transport to a target has not been demonstrated at all for REBs, but high power laser transport has been demonstrated in vacuum. The efficiency of laser beam transport must be improved to meet the estimates currently used for conceptual reactor studies.

(3) Economy of scale favors high efficiency REB drivers for low power applications. Low efficiency lasers appear to be uneconomical at power levels below about 1000 MW_e. This could lead to problems of commercialization of laser fusion.

V. Beam Transport to the Target

For ICF targets to be successfully imploded, it is estimated that 100-1000 TW of power in a 1-40 nsec pulse must be applied to them. This energy pulse must be transported from the driver, laser or REB, to the target on a repetitive basis in a fusion reactor environment. This has not been demonstrated for either lasers or REBs. Current laser experiments use a target chamber that is evacuated to $<10^{-6}$ torr. Laser beam propagation and focussing on the target is unaffected by this rarified chamber atmosphere. However, in a reactor environment, the cavity pressure will likely be 10^{-4} - 10^{0} torr. This atmosphere may include noble gases or Li vapor mixed with pellet debris impurities, according to current conceptual design studies. The effects of this background atmosphere on beam propagation and subsequent target performance is a very basic unanswered question about these proposed conceptual reactor designs. The presence of this atmosphere directly or indirectly results from a need to protect the first wall of the cavity and the last mirror from the exploding pellet debris and X-rays. Thus, it is essential to the design of the proposed laser fusion reactors. In most of the REB experiments to date, the target has been mounted on the anode, the so called in-diode configuration. This arrangement limits the power on the target to the maximum that can be transferred across a single diode. In future high power experiments, multiple electron beams will be propagated through ionized air channels to a mounted target. These channels will be established by applying a discharge across thin wires extending from the anodes to the target over the distance of approximately one meter. This channel formation has been experimentally demonstrated. Extrapolation of this beam propagation method to reactors is complicated by re-establishment on a repetitive basis and propagation to a free standing but electrically connected target. Each of these two problems might be solved by using laser beams to break down channels to the target from each diode and also other channels to establish an electrical circuit.[9] This has not been proven experimentally. The background gas in the chamber must be at a pressure of 50-1000 torr to support beam propagation, and this automatically serves as a first wall protection mechanism after the target explodes.

Beam propagation problems may also limit the maximum power that can be delivered to a target in a laser fusion reactor environment. Gas breakdown near the target may limit the maximum intensity, possibly the f/no. of the optics, or the number of overlapping laser beams. In a REB reactor, the limitations will come from the amount of power deliverable along one channel (currently presumed to be ~1 TW) and the electromagnetic fields generated near the target. High power per channel is necessary to limit the number of channels. The repetition rates in both types of reactors may be limited by the re-establishment of proper conditions for beam propagation.

The following conclusions can be drawn from this discussion:

(1) Beam propagation in laser and REB fusion reactor environments, as they are anticipated at this time, has not been experimentally demonstrated. Laser experiments are currently performed at very low background pressures compared to those predicted for conceptual reactor designs. The viability of these designs depends upon propagation through higher pressures. Current experimental facilities could be

utilized to substantially answer this question. REB experiments in the near future will use beam propagation along ionized channels. This closely parallels the scheme proposed in conceptual reactor design. However, channel generation on a repetitive basis will likely be significantly different than these one-shot experiments and the total power delivered per cm^2 of target area will be much more.

(2) The beam propagation scheme to be used in future REB experiments automatically serves as a first wall protection mechanism. Beam propagation in current laser experiments is in vacuum, hence the first wall would not be protected. If vacuum is required, then new reactor designs will be needed.

(3) The general conclusion must be that high power laser beams very likely can be propagated to a target, in vacuum. Hence, lasers are viable in the most pessimistic of all possible situations. Electron beams are likely to be power limited due to propagation problems. However, many important questions remain unanswered at this time. Until more is understood about the power required by ICF targets and the propagation of lasers and REBs through background atmospheres, no definitive conclusion can be drawn.

VI. Protection of the Final Element in the Beam Focussing System

In a laser fusion reactor, the last mirror will be in the direct line of sight of the target explosion. It will, therefore, experience a 14 MeV neutron flux. Radiation damage effects from these neutrons should be inversely proportional to the square of the distance to the target. It has been proposed that mirrors could be placed as far as 100 meters from the target explosion to minimize these radiation damage problems. Mirror placement will also be determined by the focusability of the laser beams onto the target due to wavelength and beam quality effects and the allowed alignment tolerances. Preliminary studies show that actively cooled bare metal mirrors should retain adequate optical quality when place approximately 10-20 meters from the target in a 1000 MW_e reactor. Active cooling to low temperatures reduces swelling effects from radiation damage. These studies also show that the mirror surface can be protected from pellet debris and X-rays by interposing a buffer gas between the mirror and the explosion. Dielectric-coated mirrors, needed for wavelengths less than 8000 Å, may experience color center formation as a result of neutron irradiation. This could lead to loss of reflectivity.

Radiation damage to the final diode in a REB driver has not yet been investigated to the same degree as last mirrors. It is anticipated that radiation damage of insulating material may be the most serious problem. Along with this, there is also the common problem of neutron activation. The final diode is likely to be closer to the target explosion than the last mirrors. The diode distance will be determined by the efficiency of REB propagation to the target. Propagation distances of <10 meters are expected to be required. Because REBs are charged particles, there is the possibility of slightly bending the beams to avoid direct line of sight from the target to the diode. Although this possibility exists, there is no seriously proposed scheme to accomplish it. The final diode must be vacuum isolated from the reactor cavity. Vacuums of $< 10^{-4}$ torr are likely to be necessary in the diode, while pressures of 50 -1000 torr are expected to be used in the cavity. Isolation using fast-acting shutters has been proposed, but there has been little development of the idea.(9)

In conclusion:

(1) Much more is currently known about the protection and radiation damage of the last mirror in laser fusion reactors than is known about the protection of the final diode in REB fusion reactors. Preliminary studies show that last mirrors and protection schemes can be designed for an economical lifetime in laser fusion reactors.

(2) The diode will likely be located much closer to the target explosion than the last mirror. However, the possibility exists of removing the diode from the line of sight of the target. It seems unlikely that the large aperture last mirrors can be removed from the line of sight of the target.

(3) Design basis radiation damage effects to the final diode have not been identified. However, the rather crude tolerance associated with REB vacuum transmission lines and diodes as compared to laser last mirrors would indicate that radiation damage might not be as critical to them as to last mirrors.

VII. First Wall Protection

Protection of the first wall in ICF conceptual reactor designs is such an important issue that all designs to data have been identified by their differing proposed schemes for wall protection: wetted wall,[10] magnetic protection,[11] lithium "waterfall",[12] gas protection.[13] The first wall must be protected from the high power pulse of short mean free path x-rays and ionic debris expanding from the target explosion. Lowering this energy flux on the wall to acceptable levels by moving the wall further away leads to uneconomical reactor sizes. The viability of any of these proposed protection schemes rests on many unanswered questions. Resolution of these questions is one of the major thrusts of the ICF reactor design effort and is continuously discussed and developed in the literature. A review of this material is beyond the scope of this comparison study, but there are reviews in the literature.[14]

The basic first wall protection scheme in REB reactors is gas protection. The gas is also fundamental to the beam propagation to the target. The high gas pressure in the cavity, 50-1000 torr, should easily stop the debris ions and x-rays before they reach the wall. A fireball will form and create a blast wave at the wall. The wall must be designed to accommodate this blast wave on a repetitive basis. Re-establishment of the cavity conditions after each shot may limit the repetition rate.

The conclusions of this brief discussion are as follows:

(1) There are at least four different proposed schemes for protecting the first wall of a laser fusion reactor. None of these schemes has been demonstrated to be viable in a reactor environment. Basic problems with each includes propagation of the laser beams to the target and re-establishmentof the necessary conditions between shots. If these problems can be solved for each scheme, then it is reasonably assured that they will, in fact, protect the first wall as the current computations indicate.

(2) Gas protection of REB reactor first walls comes automatically with the beam propagation method. In this sense, the beam propagation and first wall protection are combined into a closely coupled system. This can

be viewed as a positive result, because success of the beam propagation scheme implies the success of the wall protection. In the laser fusion case, the most ideal beam propagation medium is vacuum and each of the first wall protection schemes degrade this ideal medium to some degree.

VIII. Target Manufacture

Laser fusion target designs that are currently proposed for reactor applications are protected by national security classification guidelines. This is not true of many REB target designs. Today, all targets are built individually at a very high labor cost. For reactor applications, both laser fusion and REB targets must be built in an automated fashion at the rate of several per second. Because exact target designs cannot be compared, it is difficult to assess the relative difficulty of manufacturing laser fusion and REB targets.

(1) The basic conclusion at this time is that neither laser fusion nor REB fusion targets are clearly more advantageous from a manufacturing point of view. The development of the automated manufacturing processes will be common to both types of targets. These automated processes have not been demonstrated.

IX. Cavity, Blanket and Shield Design

The various proposed cavity concepts for laser fusion reactors and for REB fusion reactors have been either spherical or cylindrical in shape. The energy is of course obtained from a point source. Blanket designs vary from stainless steel structure and liquid lithium coolant to graphite structure and lithium oxide coolant. Inertial confinement systems allow a great deal of flexibility in blanket and shield design because of the absence of large magnets. Some hybrid blanket designs devote different parts of the blanket to specific functions such as fissile fuel breeding or tritium breeding. This flexibility is due in large part to the assumption that nonuniform target illumination is acceptable. This allows laser beams or electron beams to penetrate the blanket in a restricted fraction of the solid angle. Hence the remainder of the blanket can be easily disassembled for maintanence.

Possibly the most significant difference between laser and electron beam blanket and shield designs involves the shielding of penetrations, a very serious problem with all fusion reactor systems. Large aperture ducts to propagate the laser beams cover as much as 5% of the solid angle subtended at the target. Neutron streaming in these ducts to the laser building has been shown to be a very serious problem.[15] A possible solution to the problem is cross-over focusing in a evacuated cell contained in the primary containment building.[16] This requires low pressures in the beam ducts or windows on the cell. Each of these pose problems that are unresolved at this time. Electron beam reactor blankets do not contain large aperture penetrations. The vacuum transmission lines are 1 cm wide annuli that can be as much as 10 meters in length. These are connected to intermediate storage capacitors at the back end, hence insulation materials must be used there. Radiation damage to this insulating material may be the most serious problem associated with the REB delivery system. Neutronics calculations have not been done to determine the radiation dose at the back end of the vacuum transmission line. However, the simple solid angle fraction of vacuum in these systems is so low that neutron streaming is quite likely to be far less severe than in the laser reactor.

The conclusions of this short discussion are:

(1) Neutron streaming in the laser beam ducts is a very serious problem. Cross-over focusing might solve the problem but this is inconsistent with existing conceptual reactor designs.

(2) There is very little solid angle devoted to vacuum in a REB transmission line and diode. For this reason it is anticipated that the problems associated with neutron streaming will be far less severe in REB fusion reactors in terms of actual radiation dose that must be shielded. However these systems include insulators that are sensitive to radiation damage and a final conclusion cannot be made without the results of neutronics and radiation damage calculations.

X. Summary and Final Conclusions

There are many questions that remain to be answered before the viability of either laser or REB fusion reactors can be accurately determined. At this stage of development the U.S. program is devoting about 80% of its support to the laser fusion approach. Consequently its progress has been more rapid than the REB fusion approach and more is understood about its technical problems. With this fact kept in perspective, the final conclusions of this comparative analysis can be stated as follows:

(1) There are a greater number of "show-stopper" problems with REBs than with lasers. These are particularly in beam transport to the target and target performance. This makes lasers a relatively higher confidence and more versatile driver than REBs.

(2) REB reactors, as we now understand them, offer a number of significant engineering advantages over laser fusion reactor designs.

(3) REB reactors might be economical at low power levels (because the REB driver has a high efficiency) whereas laser fusion reactors are likely to suffer a severe economic penalty at low powers because the laser efficiency is so low.

(4) Because the advantages of REB systems over laser systems appear to be most strongly associated with the engineering and economic considerations, it is essential that further detailed analysis of the attractiveness of REBs in the context of fusion reactor systems be done. Only then can the relative advantages be weighed against the uncertainty of the REB target performance.

References

1. J. Nuckolls, et al., "Laser Compression of Matter to Super-High Densities: Thermonuclear Applications", Nature 239, 139 (1972).

2. K. Brueckner and S. Jorna, "Laser Driven Fusion", Rev. Mod. Phys. 46, 325 (1974).

3. G. Fraley, et al., "Thermonuclear Burn Characteristics of Compressed Deuterium-Tritium Microspheres", Phys. Fluids 17, 474 (1974).

4. W. Widner and J. Poukey, "Enhanced Relativistic Electron-Beam Deposition", Phys. Rev. Lett. 38, 10 (1977).

5. S. Gitomer and D. Henderson, "Re-examination of Strongly Flux-limited Thermal Conduction in Laser Produced Plasmas", Phys. Fluids 22, 364 (1979).

6. J. Lindl, "Low Aspect Ratio Double Shells for High Density and High Gain", Topical Meeting on Inertial Confinement Fusion, Feb. 1978, San Diego, CA, p. ThC7.

7. E. Bliss, et al., "Shiva Alignment Systems", Topical Meeting on Inertial Confinement Fusion", Feb. 1978, San Diego, CA, p. WE3.

8. G. Moses, et al., "Power Supply Costs for Inertial Confinement Fusion Reactors", Univ. of Wisconsin Fusion Design Memo, UWFDM-243, March 1978.

9. D. Cook and M. Sweeney, "Design of Compact Particle Beam Driven Inertial Confinement Fusion Reactors", Proc. of the ANS Third Topical Meeting on the Tech. of Controlled Nuclear Fusion, Santa Fe, NM, May 1978.

10. L. Booth, "Central Station Power Generation by Laser-Driven Fusion," Los Alamos Scientific Laboratory Report LA-4858-MS (1972).

11. T. Frank, et al., "A Laser Fusion Reactor Concept Utilizing Magnetic Fields for Cavity Wall Protection", Los Alamos Scientific Laboratory Report LA-UR-74-495 (1974).

12. J. Maniscalco and W. Meier, "Liquid Lithium Waterfall Inertial Confinement Fusion Reactor Concept", Trans. ANS 26, 62 (1977).

13. G. Moses, et al., "The SOLASE Conceptual Laser Fusion Reactor Study", Proc. of the ANS Third Topical Meeting on the Tech. of Controlled Nuclear Fusion, Santa Fe, NM, May 1978.

14. S. Abdel-Khalik, et al., "Engineering Problems of Laser-Driven Fusion Reactors", Accepted for publication in Nuclear Technology (April 1979).

15. M. Ragheb, et al., "Three Dimensional Neutronics Analysis of the Mirrors-Beam Duct-Shield System for a Laser Driven Power Reactor", Univ. of Wisconsin Fusion Design Memo, UWFDM-239, March 1978.

16. J. Howard, "Beam Port Reduction Schemes for Laser Fusion Reactors", Univ. of Wisconsin Fusion Design Memo, UWFDM-244, May 1978.