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OPTICAL DESIGN CONSIDERATIONS FOR LASER FUSION REACTORS*

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Abstract

The plan for the development of commercial inertial confinement fusion (ICF) power plants is discussed, emphasizing the utilization of the unique features of laser fusion to arrive at conceptual designs for reactors and optical systems which minimize the need for advanced materials and techniques requiring expensive test facilities. A conceptual design for a liquid lithium fall reactor is described which successfully deals with the hostile x-ray and neutron environment and promises to last the 30 year plant lifetime. Schemes for protecting the final focusing optics are described which are both compatible with this reactor system, and show promise of surviving a full year in order to minimize costly downtime. Damage mechanisms and protection techniques are discussed, and a recommendation is made for a high f-number metal mirror final focusing system.

Introduction

The Laser Fusion Program at Lawrence Livermore Laboratory is rapidly advancing toward a demonstration of scientific feasibility. This is being accomplished with a sequence of solid-state lasers, culminating in SHIVA NOVA, a 200-300 TW laser scheduled to operate at full power in 1983.[1,2] At this power level, it will be possible to initiate high gain microexplosions and demonstrate the scientific feasibility of inertial confinement fusion. Of course, neither the reaction chamber, the laser nor the target facility will have a high average power (pulse repetition) capability. This is certainly also true for the optical system. The laser fusion community has only begun to think about the long term survivability, optical performance and maintainability required of optical elements that must withstand 10^7-10^8 shots per year in a hostile nuclear environment.

The objectives of this paper are to define the expected environment of a future powerplant, and to discuss the options which are realistically available as cost-effective solutions to the protection problem for the final optics. Because we are only beginning to identify problem areas and suggest solutions, we feel it is of primary importance to share with the optical community our understanding of how laser fusion might develop and how optical systems will interface with the reactor system.

The Plan for Commercial ICF

Laser fusion is presently in the scientific stage of development. As such, the majority of the program's resources are being applied toward demonstrating high gain laser-driven implosions and developing suitable drivers (lasers, electron or ion beams) for commercial operation. As the program advances towards accomplishing its scientific goals, it becomes increasingly important to follow a well constructed long range plan for aggressively pursuing commercial fusion power. A scenario for the commercial development of laser fusion is shown in Figure 1.[2] This plan assumes that the program will progress through several phases: exploratory development, advanced development, engineering development, and commercial development. The demonstration of technical feasibility has been split between the advanced and engineering phases because of the prevailing assumption that two experimental-power-reactors will be needed before a demonstration power reactor can be built.

The criteria required to demonstrate the scientific feasibility of inertial confinement fusion will be met in the exploratory development phase. The major program elements in this phase are separated into three distinct segments: inertial confinement physics, source coupling physics, and source feasibility. Neodymium:glass lasers operating at 1.06 μm with low-average-power capabilities will be the primary tools in the inertial confinement physics program. Shiva Nova, the largest of the Nd:glass laser facilities, is projected to provide the on-target energies and powers required to drive targets suitable for commercial power plants on a single-shot basis.

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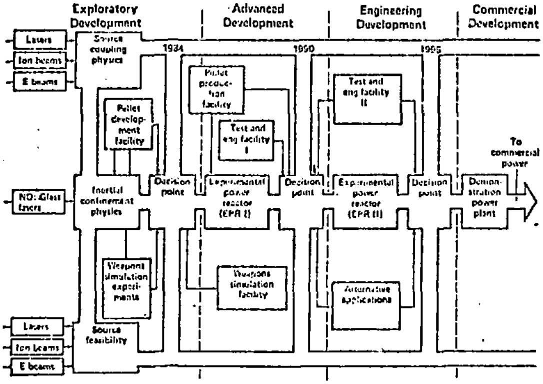

Fig. 1. Phases of Development in the Long Range Plan for Inertial Confinement Fusion.

The source-coupling physics program will be concerned primarily with quantifying and maximizing the efficiencies of coupling other forms of energy--different-wavelength lasers, ion beams, and electron beams--to the fusion target. In the source-feasibility program, several high-average-power sources (gas lasers, ion beams, and electron beams) will be developed and analyzed along with their beam transport system.

The first experimental power reactor based on the ICF concept, EPR I, will be undertaken in the advanced development phase. This reactor will be the first of a series of major experimental facilities required to verify the physics and engineering principles that are required to commercially develop ICF. The primary function of EPR I will be to provide information on the integrated engineering performance of a complete ICF system (source, target, and reactor). In addition, EPR I will be expected to demonstrate the capability to produce electric power. An experimental power reactor supporting these objectives will operate at $\sim 10^3$ pulses/day, generate $\sim$ 10 MW of thermonuclear power and have a limited plant availability $\sim$ 20%.

A second experimental power reactor may be built to demonstrate limited steady-state electrical generation in a smaller and less costly facility than a full scale powerplant, perhaps at the 10^5 pulses per day level. It would focus on the major technical problems associated with an ICF power plant. These include the development of:

- A high-average-power driver with the required efficiency (> 1%) and reliability (> 70%)
- A first-wall able to withstand the effects of x-rays, debris, and neutrons from the microexplosion.
- Structural materials that can withstand the cumulative damage effects of high-energy neutrons and cyclical stresses.
- Final-focusing elements that can be placed far enough away from the microexplosion that they can last a reasonable length of time.

The final phase of development will be associated with planning, constructing, and operating a demonstration power reactor. This facility will be required to demonstrate the potential for economically produced ICF electricity over alternative long-range sources of energy by operating in a safe, reliable, and environmentally acceptable manner. In short, the demonstration power reactor (DPR) will:

- Generate 500 to 1000 MW (several 100 MW_e) of thermonuclear power.
- Reach a plant availability ≈ 70%.
- Breed tritium.
- Be fully licensed as a power reactor.
- Consume less than 25% of generated power as recirculating power.
- Achieve a fusion-energy gain > 10.
- Cost less than 2 billion dollars.

The fusion energy gain, defined as the product of laser efficiency and target energy gain, is a measure of system efficiency. In order to have a recirculating power fraction of 25%, a fusion energy gain of 10 is required.[3]

The primary objective of our current conceptual design work is to develop reactor and optical configurations which will minimize the need for expensive test facilities and material development programs in conjunction with the EPRs. By evolving simple designs within or near the current state-of-the-art, we hope to shorten the time required to generate electricity by laser fusion.

The Lithium Waterfall Reactor

In developing a reactor concept, we were greatly influenced by the desire to exploit the advantages of inertial confinement fusion while confronting its problems. A successful laser-fusion reactor must deal with the effects of high energy neutrons and cyclical stresses on blanket structures, and the effects of x-rays and debris on the first wall. If these problems can be solved, laser fusion, as an alternative to magnetic confinement fusion, offers features which could significantly reduce the technical complexity and, thus, the amount of advanced technological development required to produce a successful fusion power plant.

These features include:

- Sizing flexibility (i.e., lower power units)
- Possibility of multiple chambers to provide higher availability
- Flexible geometry
- No magnetic fields (permits use of a liquid metal coolant)
- Reduced vacuum requirements (permits use of a first wall with a higher vapor pressure)
- Reduced radioactivity from neutron activation
- Reduced neutron damage to structural materials

While the first three points are generic advantages of laser fusion, the final four points are design dependent. We sought to develop a concept that would exploit these advantages; a simple concept that could be constructed with existing materials to circumvent the decade or so required for advanced material development and testing. The liquid lithium waterfall concept meets these criteria.[4,5]

The concept (Fig. 2) features a thick, continuously recyclable first wall of liquid lithium that protects the first structural wall from direct exposure to the microexplosion. The waterfall is disassembled by each shot and reestablished between shots. The lithium is continually pumped to the top of the vacuum chamber through a reservoir region which separates the first structural wall from the pressure vessel. A small fraction of the lithium flow circulates as the primary coolant to the heat exchanger. The return flow from the heat exchangers is injected through a vortex generator to provide protection to the top of the chamber.

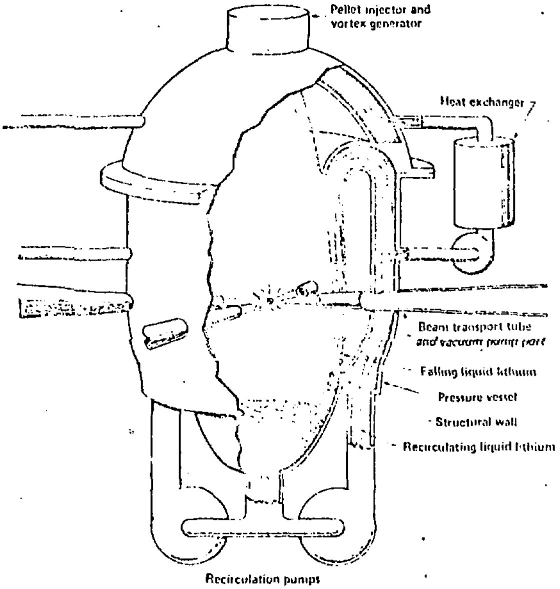

Fig. 2. Lithium Waterfall Laser Fusion Reactor Concept.

The principal purpose of the fall is to reduce the neutron radiation damage in blanket structural materials, allowing them to survive for the useful life of the plant. Besides moderating neutrons, the fall also absorbs the photons (x-rays and reflected laser light) and pellet debris (alpha particles, unburnt fuel, and other target material). By keeping the fall separated from the chamber wall, any shock wave produced in the fall will not be directly transmitted to the structural wall.

The falling liquid region contains enough lithium to significantly reduce neutron damage to the reactor structural materials. The primary neutron damage mechanisms are atomic displacements and gas production. The damage limits for 316-SS at an operating temperature of 500°C are estimated to be 150 displacements per atom (dpa) and 500 atom-parts-per-million (appm) of helium production.[6] For an unprotected stainless steel wall operating at a 14 MeV neutron wall loading of 1 MW/m^2, the damage limit for helium production would be reached in only 2.3 full-power-years. This would present a severe maintenance problem and result in the generation of large amounts of radioactive waste. One MW/m^2 is generally considered to be the lower flux limit for an economically attractive fusion reactor. At this wall loading, a fusion reactor would operate with power densities that are an order of magnitude lower than a light water fission reactor.

The product of neutron wall loading, in MW/m^2, and the wall lifetime, in years, is a figure of merit for any fusion reactor design. This product, the allowable first-wall fluence, increases exponentially with the protective thickness of the lithium fall as shown in Figure 3. We have evaluated the requirements of a system that maintains a minimum protective lithium thickness of 60 cm. Since helium production damage dominates, the allowable fluence is 50 $MW\text{-}Yr/m^2$. In other words, the system could be operated at an equivalent 14 MeV loading* of ~ 2.4 MW/m^2 for the 30-year plant life at a 70% capacity factor. Thus for a given power, the reactor can be made smaller with structures that never require replacement.

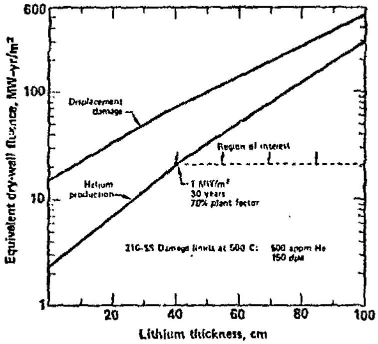

Fig. 3. Allowable first wall fluence increases exponentially with lithium thickness. Helium production is the dominant damage mechanism.

The liquid lithium waterfall concept has excellent energy conversion, energy removal, and tritium breeding characteristics. Nearly 99% of the total energy is deposited directly in the primary lithium coolant. This essentially eliminates cyclical thermal stresses in the structural walls. Thermal conversion efficiencies approaching 40% can be obtained by operating at corrosion limited temperatures of 500°C. Tritium is bred at a more than adequate rate. At a pulse repetition rate of 1-2 Hz, the fall has sufficient velocity to reestablish itself between microexplosions, while consuming less than 5% of the gross electric power production of the reactor.

Our results indicate that laser beam defocusing and attenuation losses in the fusion chamber can be reduced to acceptable levels with chamber pressures of 0.1 torr or less. This relatively high allowable pressure makes it possible to use liquid lithium in the vacuum chamber. Corrosion considerations require that, for use with stainless steel, lithium temperatures must be limited to less than 500°C. The vapor pressure of lithium at this temperature is less than 5×10^{-3} torr. Each microexplosion will vaporize a certain amount of lithium, which increases the chamber pressure above the required 0.1-torr vacuum condition. However, there is so much liquid lithium in the chamber at the time of the microexplosion that the lithium fall acts as a condensing vacuum pump for the chamber, returning it to the required 0.1 torr in less than 0.1 sec.

Our goal is to arrive at a configuration for the final optics which is both compatible with this reactor concept and offers equal promise for solving the critical optical lifetime problems.

The Final Focusing System

We envision that the laser system will be housed in a building separate from the reactor

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*Loading on the wall if the lithium fall were removed.

containment building to minimize building costs and construction time, and to increase access and maintainability of the laser. The laser light is transported to the reactor via evacuated pipes. The final focusing mirrors are located at the turning point of the beam tubes in a direct pathway to the thermonuclear microexplosion. As a result these mirrors would be exposed to the x-rays, debris, and neutrons from the fusion reaction. A sketch of the final focusing system is given in Fig. 4. The beam enters the containment vessel through a window and is focused through a small hole in a fast acting valve. The valve provides secondary containment protection in case of window failure. A fixed off-axis parabolic focusing mirror directs the beam onto a mirror flat which is exposed to the neutron flux. The mirror flat may be mounted on a carousel of several mirrors, if more than one are needed. Separate vacuum pumps are shown on each side of the fast-acting containment valve.

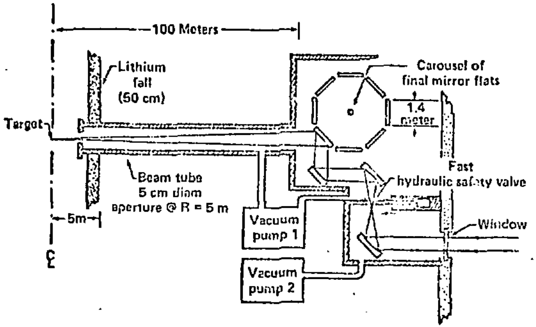


Fig. 4 Schematic of Final Focusing System

To assess the exposure levels of the final optics, we need to postulate laser fusion powerplant operating conditions. Our present estimates of these conditions are given in Table 1. They have been calculated using the LASNEX computer code, which takes advantage of the extensive experience at LLL in laser fusion target interactions and thermonuclear physics. In Table 1 we have also listed some parameters for a specific system, notable only in that it allows us to use a concrete example.

Table 1: Requirements for a laser fusion powerplant and an example chosen for present calculations.

	Laser System Requirements for Laser Fusion	An Example for this paper
Average Power (megawatts)	1 - 10	1
Pulse Energy (kilojoules	300 - 3000	500
Pulse Width (nanoseconds)	1 - 10	1
Pulse Power (terawatts)	>200	500
Pulse Rate (hertz)	1 - 10	2
Wavelength (micrometers)	0.25 - 2	1
Efficiency (percent)	>1	-

Inspection of these requirements reveals that higher target gains significantly relax the laser efficiency required to obtain an attractive recirculating power fraction.[7] In addition, these laser target interaction calculations lead to relaxed illumination requirements which will allow higher f-number optics. Perhaps many beams can be combined into several clusters for target illumination. This has an important impact on the design of final optics for survival, for we can increase the distance from the microexplosion to minimize the damaging fluence of neutrons.

The optical damage threshold for a laser is relatively fixed, say at 10 J/cm^2. For a 1 MJ laser energy pulse, we must therefore have at least 10 m^2 of mirror area "looking" at the microexplosion. Clearly it is an important advantage to place the mirrors as far as possible from the target to reduce the intercepted solid angle. For example, the solid angle subtended by mirrors located 100 meters away is 8×10^{-5}, an impressive reduction in exposure.

To better visualize the impact of high f-number optics on optical survivability, we have graphed in Fig. 5 the x-ray and neutron fluence as a function of distance for the example given in Table 1. Although the actual fractions of x-rays and neutrons are highly dependent on target design, we chose 70% neutrons, 5% x-rays and 25% debris for this illustration. Note that in moving 100 meters away, the x-ray fluence falls below the absorbed laser light, and the neutron fluence per shot is at the 0.2 Joules/cm^2 level. We shall examine the long term consequences of this neutron dose momentarily, after discussing some protection options other than using high f-number optics.

This is a dramatic departure from previous thought. In a 1974 paper on this subject, Teitel[8] considers the final optic to be 4-8 meters from the target; a truly challenging problem should it be necessary.

Protection of the Final Optics

One can identify several techniques for protecting the final optics against the various types of incident radiation. Some of these are listed in the protection matrix of Fig. 6. Only the solid angle reduction allowed by high f-number optics reduces fluences of neutrons, ions, x-rays and neutral particles and blast effects. Some techniques are specifically tailored to one effect, such as using a magnetic field to deflect ions. A continuously replaced transparent film, similar to a sandwich wrap might be used against x-rays and ions.

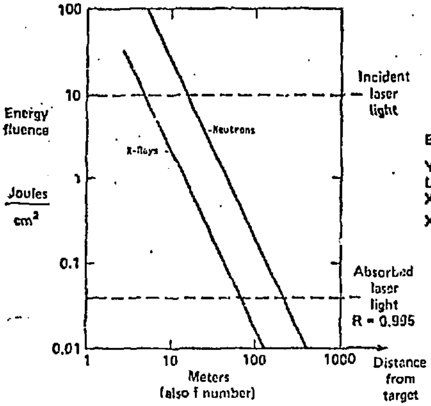


Fig. 5. High F-Number Optics Reduce Incident Energy Fluences.

Protection technique	Neutrons	Ions	X-rays	Neutral particles, shock waves
Solid angle reduction	X	X	X	X
Magnetic field		X		
Transparent film		X	X	
Gas streaming		X	X	X
Rotating shutter		X		X
Gas refractor	X	X	X	X
Liquid metal mirrors		X	X	X

Fig. 6. Protection Matrix listing the effectiveness of several protection techniques against sources of damage to optics.

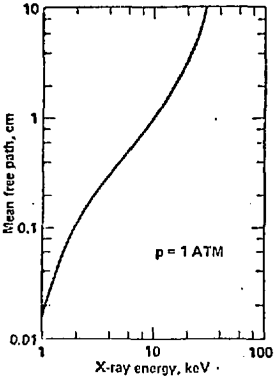
A rotating shutter might be an effective way to stop charged and neutral debris, accelerated drops of lithium, chunks of a misfired target, etc. If we imagine energetic deuterium ions for example, traveling at $v = 10^6$cm/sec, the time of flight from target to a shutter 15 meters away would be 1.5 ms. Assuming a six bladed shutter arranged so that each blade need rotate only $\Delta\phi = \pi/3$ radians to close the aperture, the required angular velocity is $\dot{\phi} = 700$ rad/sec = 6670 rpm. There would be no problem rotating 60 cm diameter blades at this rate.

The disadvantages to the rotating shutter concept are threefold, i.e. it will not stop the x-rays or neutrons, it will become highly activated, and the rotating blades must endure loads perpendicular to the spin direction, a very unfavorable situation for long lifetime rotating components. Although a shutter might be feasible, other non-mechanical options seem more attractive at the present time.

Liquid metal mirrors have been suggested, in the same spirit as the lithium waterfall, as components which could be self-healing after each shot. We have investigated the use of mercury, gallium and sodium, but they unfortunately all suffer from the same problem. The optical absorptivity (a) is so high in the visible to near-infrared ($0.1<a<.25$) that vaporization of surface materials occurs during a 1 nanosecond pulse. Thus, on the basis of their unacceptably low damage thresholds, we reject liquid metal mirrors.

The most effective technique for preventing the x-rays and debris from striking the final optic involves the use of a simple region of relatively high atomic number gas. This gas will stop the x-rays by the photoelectric effect and thermalize the debris through collisions. To some extent, this will already be done both in the target, e.g. if it has a thick pusher tamper region, and in the lithium vapor in the chamber. Therefore the density-length product of additional gas which might be required to stop the remaining x-rays is very design dependent; but we can estimate the requirement from mean free path arguments. We envision a region several meters long near the optical surface, in which gas flows toward the target. The gas is injected at the optical surface providing some face cooling and protection from particulates. It is pumped out of the tube at an intermediate station, filtered and reinjected. Too much gas should be avoided to prevent interaction with the laser beam. The gas must be replaced between shots.

Xenon is taken as an effective high-Z absorber, although almost any gas which is otherwise compatible could be used. In Figure 7, we have graphed the mean free path of x-rays as a function of their energy in one atmosphere of xenon gas, using data from the Livermore photon cross-section library.[9] We expect x-rays throughout the 100 eV - 20 keV region of the spectrum, but the softer x-rays have extremely short mean free paths both in the gas and in the mirror. Fortunately these soft x-rays are more readily absorbed in the lithium vapor. From Fig. 7, we see that 0.32 cm-atm of xenon will provide one attenuation mean free path for 3 keV x-rays. To obtain a factor of a hundred reduction x-ray intensity we need to provide 4.6 mean free paths of gas, equivalent to .147 cm-atm of xenon. Since we want to absorb the radiation over a long distance to prevent generation and effective transmission of shock waves, a 10 meter section of the beam tube containing 1 torr of xenon should be adequate. If any pressure disturbances are created in this low density gas they are unlikely to have sufficient amplitude to affect the mirror. An additional benefit that would accrue to this scheme is that the counter flowing gas isolates the cooled optical surface from the hot lithium vapor, which might otherwise tend to condense on the optical surface.



- Stopping of x-rays is by photoelectric effect
- Majority of x-rays in .1–20 keV range
- Example
  for E = 3 keV
  obtain 5 mean free paths
  $(e^{-5} = 0.0067)$
  for 1.05 cm–atm of $_{54}$Xe

Fig. 7. X-Ray Stopping Power of Xenon Gas.

<u>Transparent Optics, Insulating Substrates & Dielectric Coatings</u>

The optical damage limit and the energy per pulse required on target combine to dictate the area of the final mirror or lens. Since we anticipate ~10 m^2 of area, and relatively few final optical elements, each one might be 1.5-2 m in diameter. We visualize mirrors rather than lenses for these elements, for it currently appears to be substantially more cost effective to diamond-turn large mirror blanks on an interferometer-controlled lathe than to cast and polish glass blanks of similar size, for the same surface figure accuracy. This is less true for short wavelengths and may change in the future. Also, bulk neutron damage thresholds are in general lower in glasses than in metals. In all cases we are more worried about loss of optical performance due to physical or optical changes which are radiation-induced, than we are about changes in strength, embrittlement, etc.

If the mirror substrate is a glass such as ULE or fused silica, with either a dielectric coating or a metallic film coating, the thresholds are likely to be determined by nonuniform change of shape due to structural deformation of the lattice, which occurs before such catastrophic damage such as cracking. Disordered phases can also appear. The volumetric expansion in insulators is not likely to be from helium production, since the diffusivity of helium in such glasses as SiO_2 is high.[13] For example, density variations of ± 2% are characteristic of neutron doses of 2 x 10^{19} cm^{-2}, (crystalline quartz decreases by this amount, vitreous silica increases by about the same fraction).[12] This dose corresponds to a 2.6 year lifetime at a distance of 100 m in our example. The quartz continues to decrease in density, saturating at -15% for 2 x 10^{20} n/cm^2.

Dielectric coating performance in a 14 MeV neutron environments is a large unknown. Radiation damage to thin dielectric films is available exclusively for electron and UV irradiation, not for neutrons. The damage mechanisms we have identified are (1) decrease in damage threshold from increased absorptance of induced color centers, (2) delamination due to uneven stresses from swelling damage, (3) degraded optical performance due to layer thickness and/or index of refraction changes. Increased bulk absorption should not by itself be harmful since the layer is so thin and the marginal heat load small.

Color center formation in glasses such as BK-7 can be severe in the visible at quite moderate doses, but the impact on the performance is highly dependent on the laser wavelength. At 1.06 μm for example, color center absorption is far less than in the visible. We note that in recent experiments at Lawrence Livermore Laboratory[15] multicomponent glasses such as BK-7, when subjected to γ and neutron irradiation, discolored at 3 orders of magnitude less dosage than a high purity fused silica. Furthermore, at the highest dosage (3 x 10^9 rad) the BK-7 was falling apart while the fused silica had only slightly discolored. Significant annealing of color centers can occur at elevated temperatures, so perhaps coated mirrors could be allowed to run hot, as other factors allow. A large selection of available coating materials, and extremely high control of impurities, should enable us to minimize this effect.

Effective multilayer coatings for high reflectivity require strict limits on variation of index of refraction and layer thickness. Both are compromised by radiation damage, since index of refraction also changes as density changes. Because the reflectivity of a coating is a relatively easy parameter to measure and the neutron doses of interest are within current experimental reach (see later section), we are optimistic that coating performance in a neutron environment is an approachable and solvable problem. Of course, since the resistance to surface damage by x-rays and debris is small, these types of radiation must be avoided.

Metal Mirrors

The final optic could be a metal mirror, with or without coatings. If the metal acts only as a substrate for a dielectric coating, absorptivity is not relevant, but in both the coated or uncoated modes, dimensional stability is important to maintain surface figure. The mirror will be heated by an average power input of neutrons and absorbed laser radiation. The laser radiation heat load is readily calculated. Taking an optical absorptivity of one percent, an incident fluence per pulse of 10 J/cm^2, and a pulse repetition frequency of 2 Hz, we obtain a power input density of 0.2 watt/cm^2. This will be no problem, since conduction cooling can prevent distortion of the mirror figure at this heat load. The neutron heating contribution is comparable, perhaps slightly higher.

Two potential mechanisms have been identified that could lead to shortened lifetimes for metal mirrors.

1. Increase in optical absorption by reduction of electron conductivity in a damaged lattice. (Uncoated mirror).
2. Increase in optical distortion due to swelling from (n, α) helium production reactions. (Both uncoated and coated).

The first effect occurs throughout the metal but is only important within a few skin depths of the mirror surface. The dislocations and other lattice damage impede the freedom of the electrons compared to that in an undamaged solid. The restricted electron mean free path is effectively a loss mechanism; the electrons absorb more energy from the optical field and are poorer reradiators. M. Sparks[10] has estimated that the effect will saturate with an increase in absorptance of about a factor of 2 at a neutron dose of 10^{19}-10^{20} neutrons/cm^2.

If this increase in absorption occurs, there are two immediate possible consequences. First, the waste heat removal requirement is doubled: this should be no essential limitation. Second the damage threshold will decrease, if the threshold is of a thermal or surface melting nature. On the other hand, if the intrinsic damage threshold is electric field dependent (depending on the pulse length and wavelength) then there may be no effective consequences. Furthermore, one can always simply increase the mirror area to compensate.

Suppose this effect is critical however. A limit of 3×10^{19} neutrons/cm^2 translates to an accumulated fluence of 0.021 MW-years/m^2. Let us use the example laser parameters listed in Table 1. The mirror lifetime in full-power years, based on accumulating a neutron fluence of 0.021 MW-years/m^2 depends on the distance to the final mirror, as given in Table 2. At 100 meters, a lifetime of a few years seems possible.

Table 2: Mirror lifetime based on increased neutron induced absorption.

Mirror Distance - R, meters	Lifetime, years
50	0.9
100	3.8
200	15.1

The second possible important effect is surface distortion due to nonuniform swelling of the metal. The helium produced in (n,α) reactions migrates to form bubbles. These microscopic bubbles can cause a surface distortion on the order of a wavelength of light, thereby degrading optical performance. There are no experimental data to demonstrate this postulated optical effect, but we can predict its onset based on well known volumetric swelling rates of neutron irradiated materials. The University of Wisconsin has tabulated some swelling rates as a function of temperature for 316 stainless steel for two conditions, a nominal and a maximum possible swelling rate.[6] Higher temperature favors swelling, with an increase in temperature from 250°C to 350°C bringing more than an order of magnitude increase in volumetric swelling rate. For a first wall neutron flux of 7.65 MW/m^2, and a first wall temperature of 300°C, they calculate a swelling rate of 0.323%/year nominal, 1.04%/year maximum.

We would like to determine the time interval for volumetric swelling to cause a nonuniform $\lambda/8$ surface change at 1.06 μm in a 1cm thick mirror blank. Unfortunately we do not have swelling information at 14 MeV on copper or other substrate materials. We will use the stainless steel data to see if we need to worry about this effect. Again using our example system, having an equivalent 14 MeV drywall neutron flux at the 5 meter inner radius of the structural wall of 2.2 MW/m^2, we can calculate the mirror lifetime based on the time required to distort a distance of one-eigth wave. The results are given in Table 3.

In this example, we estimate the linear extension by $\Delta x/x = (\Delta V/V)/3$ where $(\Delta V/V)$ is the volumetric swelling, and scale proportionally with neutron flux.

Table 3: Mirror lifetime based on helium production in metal substrate material and subsequent surface distortion.

Mirror Distance Meters	Neutron Flux MW/m^2	Years to Distort $\lambda/8$	
		Nominal Swelling	Maximum Swelling
50	2.2×10^{-2}	4.3	1.3
100	5.5×10^{-3}	17.1	5.3
200	1.4×10^{-3}	68.5	21.3

Notice that for a mirror distance of 100 meters we show a lifetime of 5 to 16 years, a relatively favorable outcome. The use of a 300°C temperature is also probably a conservative assumption. Moreover, there are two circumstances which may alleviate this swelling problem and lead to mirrors which can last essentially the life of the plant. First, some metal alloys, such as nickel-rich inconel, will contract with radiation damage. Perhaps an alloy can be found which will be exceptionally dimensionally stable, particularly since strength or ductility is really not a dominant issue. Second, simple adaptive optical components for wave front correction may be able to largely remove the effect of moderate distortions introduced by the final optical element.

Since the two lifetime limitations we have considered lead to maximum lifetimes of several years at 100 meters, the technology risk of assuming a one year time between routine changeouts of the final metal mirror, at the time of the normal yearly plant shutdown for preventative maintenance, seems acceptable. If we have been too conservative, we would simply bring the mirrors in closer, perhaps to 75 or 50 meters, or consider lifetimes in the 10 year range. Since there is always the possibility of rather catastrophic unexpected optical damage, the inclusion of a remotely operated carousel of a few mirrors may be desirable insurance.

Testing Requirements

The solid angle reduction allowed by the use of high f-number optics is of fundamental importance in eliminating the need for new and expensive test facilities, since the neutron fluxes the mirrors will experience are a hundred times less than those on a reactor first wall, and are therefore accessible experimentally much earlier. For example, the Rotating Target Neutron Source (RTNS-II) at Lawrence Livermore Lab[11] will produce a continuous source of 13-15 MeV neutrons at the rate of 4×10^{13} neutrons/sec in Summer 1978. Although this source is not designed to gather laser fusion data, it is interesting to note that if it were used to irradiate a one inch diameter sample of our final optic, we could obtain a neutron flux of 0.18 MW/m^2, about the right level to obtain significant data in a few weeks. In the very near future it will be possible to obtain superb data on radiation damage to optics without waiting for fusion test reactors. Only the question of the pulsed vs continuous irradiation will remain.

The Gas Refraction Lens

We briefly mention the only known scheme to prevent all radiation from the fusion microexplosion from impinging on the mirror. This device is related to an aerodynamic window, in that it uses a supersonic stream of gas to set up a density distribution which acts exactly like a prism. It forms a wedge of higher index of refraction material which will bend light, but not neutrons or debris. X-rays will be practically unaffected. Shown in Fig. 8, the concept follows our philosophy of substituting a self-renewing medium for a supermaterial. Because there is a great deal of experience with this technology in the high energy laser field, we know it will both be feasible and have acceptably low optical distortion. The disadvantage to the concept is the high pumping power required for the supersonic wind tunnel. The power required is proportional to the angle of bending desired, and the laser beam area. Although more detailed calculations are being performed, we estimate that this gas prism would consume 20-30% of the gross electrical power, so we prefer to use passive techniques if possible.

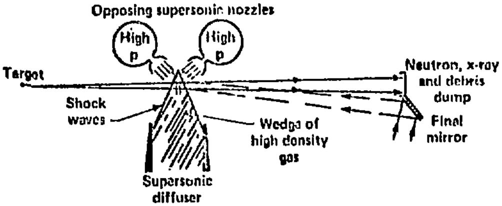
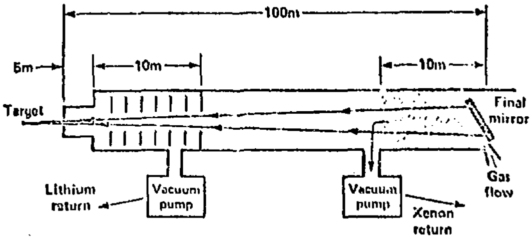


Fig. 8. Mirror Isolation Using a Region of Refracting Gas.

Conclusions

Laser fusion is advancing rapidly toward a demonstration of scientific feasibility at the Lawrence Livermore Laboratory. Concurrently, we are performing conceptual design studies for commercial power reactors which promise a 30 year lifetime and high availability through the use of innovative designs such as the liquid lithium fall reactor. In seeking optical system designs which are as successful in solving difficult problems with near-term technology, we have identified some promising approaches. The most interesting approach is the use of high f-number optics in long beam tubes, a concept which minimizes the solid angle subtended by the final optics and significantly reduce neutron fluences. The entire concept is sketched in Fig. 9. Blast effects and lithium vapor are removed in a baffled section near the opening of the beam tube to the reactor. This section acts both like a silencer and a condenser. At the mirror end, a region of heavy gas such as xenon flows from the mirror toward the chamber and is recirculated back to the mirror. This region effectively absorbs the debris and x-rays. Only the neutrons survive. At a distance of 100 meters only 8 x 10^{-5} of the neutrons created actually reach the mirror. Therefore, only neutron damage mechanisms need be considered.

Coated metal mirrors would be most desirable. The most significant limitations on mirror lifetime identified are (1) a swelling-induced increase in surface distortion, (2) changes in dimension, index of refraction, and state of stress in dielectric multilayer coatings, and (3) increase in absorption of the metal mirror if coatings are not used. It appears that mirror lifetimes greater than a year can be anticipated, with a good chance for ten year lifetimes. Most importantly, significant experimental research and development can be performed in the very near future without new and expensive dedicated test facilities. We can therefore be reasonably confident that the use of high f-number optics will lead to designs for final optical systems which will not adversely affect plant availability factors.



Features
- Lithium vapor and blast effects removed in baffled region
- X-rays, energetic debris attenuated in counter-streaming gas
- >1 year lifetime of mirror assured by using solid angle reduction allowed by large f-number optics

Fig. 9. Schematic of Laser Beam Tube and Final Mirror.

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