SOLASE - A Laser Fusion Reactor Study - Summary and Conclusions

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FUSION TECHNOLOGY INSTITUTE

UNIVERSITY OF WISCONSIN

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SOLASE -- A LASER FUSION REACTOR STUDY

SUMMARY AND MAJOR CONCLUSIONS

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and

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UWFDM-301

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SOLASE, as in "their solase in dorckaness, and splattering together joyously the plaps of their tappyhands as, with one cry of genuine distress, so prettly prattly pollylogue, they viewed him, the just one, their darling, away".

J. Joyce, _Finnegans Wake_, The Viking Press, New York (1939), p. 470.

PREFACE

Research on inertial confinement fusion has expanded dramatically over the past few years. The results on compression and neutron yield from laser illuminated targets and the possibility of thermonuclear neutron yields from particle beam driven targets are measures of advancement. It is still difficult to have a clear picture of how these results can be implemented in a practical reactor but given the level of effort in experimental research, it is appropriate to begin developing the basis for understanding and analyzing the technological problems of inertial confinement fusion reactors.

The University of Wisconsin fusion reactor study group has completed a study of laser fusion reactor problems incorporated into a self-consistent reactor design, SOLASE. The purpose of the SOLASE study is to identify and quantitatively analyze the major technological features posed by laser fusion reactors, to assess the relative advantages and prospective problems, and to guide further research. This report summarizes the major technological issues posed by laser fusion in general and the conclusions we have drawn from the SOLASE study. Specific conclusions relating to SOLASE and its different subsystems are given in the Appendix.

CONTENTS

I. GENERAL CONCLUSIONS

In the following, the major technological issues posed by laser fusion reactors in general and the conclusions we have drawn from the SOLASE study are summarized. Specific conclusions relating to SOLASE and its different subsystems are given in the Appendix.

1. TARGET PERFORMANCE REQUIREMENTS

In order to limit the recirculating power fraction to economically acceptable values (<25%), the product of the target gain G, defined as the ratio of thermonuclear energy produced to the incident driver energy on target, and the driver efficiency η_D should be greater than 10 (e.g. for a driver efficiency of 1% a target gain of 1000 is required).

An energy gain on target of 100 to 200 or higher is difficult to achieve with a 1 MJ laser and although high gain target designs have been reported they still must be verified experimentally. The basic question is whether the laser energy can be coupled into the target efficiently enough to make the target work.

Physics analysis performed as part of the SOLASE study shows that inertial confinement systems will have much better energy economics (higher pellet gain and yield) if larger laser (or other driver) input energy can be used. High gain targets (G > 1000) will require several megajoules of driver energy and will, therefore, have a very high yield. This will have significant impact on driver cost, cavity design, reactor size, and overall system economics.

Small deviations from the perfect pulse shape required to achieve isentropic compression can sharply reduce pellet performance. Less sensitive target designs will be required for reactor applications. The experiments planned in the next several years should bring us much closer to an answer on these matters. Clearly the next 1 to 5 years will be critical for physics development in the field.

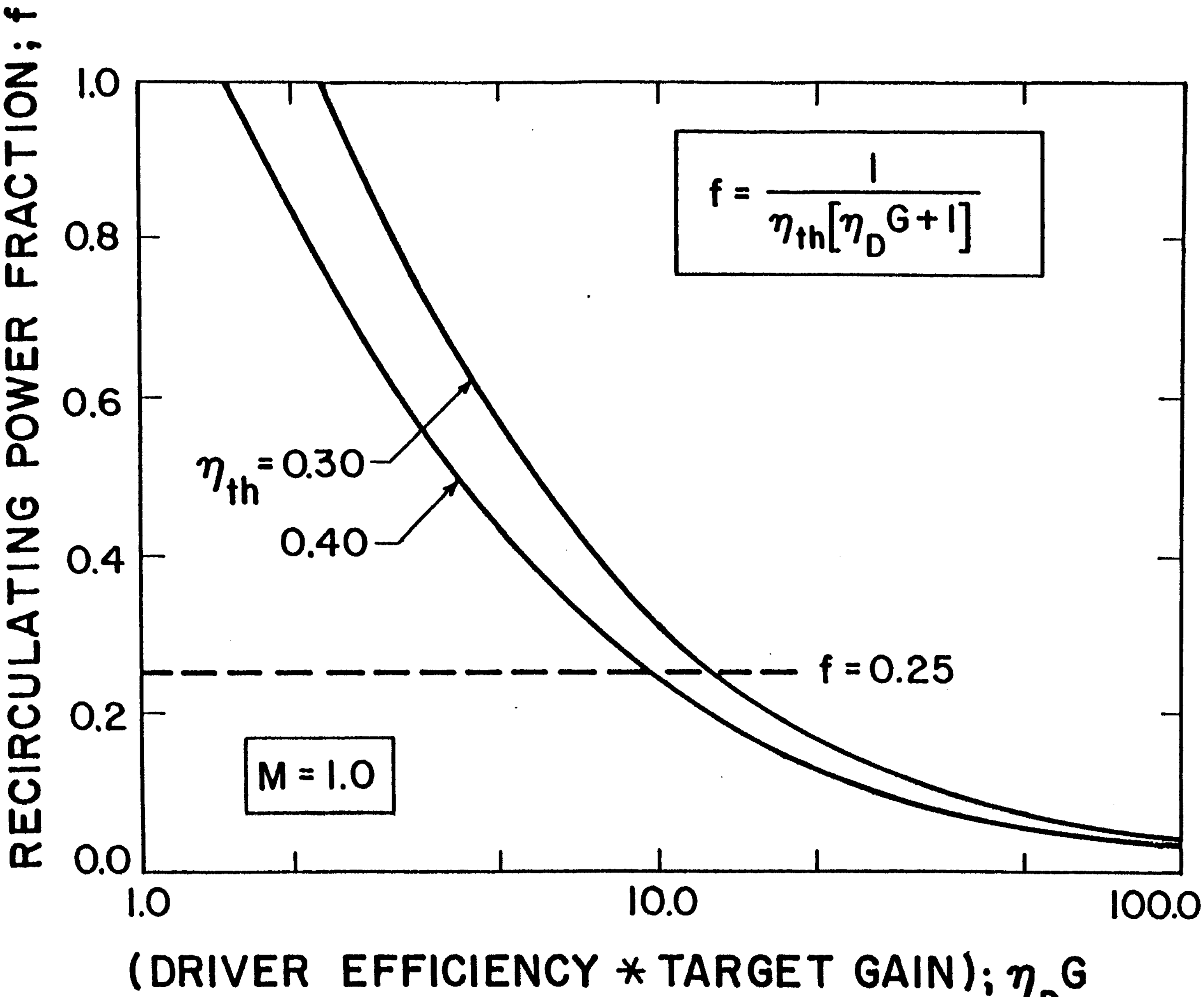


Figure 1 - Variation of recirculating power fraction with $\eta_D G$ (blanket multiplication = 1.0, waste heat from driver is used in the power cycle).

2. DRIVER EFFICIENCY REQUIREMENTS

The requirement that the product of target gain G and driver efficiency η_D should be greater than 10 implies that if high target gains can be achieved a low driver efficiency may be acceptable. This, however, is untrue because if the required driver energy remains at 1 MJ or more, the driver efficiency must be at least 5%, independent of target gain. The reason is that low laser efficiency, even when offset by high pellet gain, could prove uneconomical due to high power supply costs. For example, if η_D = 1%, G = 1000, and E_D = 4 MJ, the condition $\eta_D G \geq 10$ will be satisfied but a 400 MJ power supply will be required to drive the laser. Since all potentially acceptable lasers developed to date require short pluse power supplies which cost more than 2$/J, the driver cost in the above example will be at least $800M. This is unacceptably high except for very large electric power units. Higher driver efficiencies are required for smaller units (Fig. 2).

At present, there is no laser that clearly meets all the requirements for laser fusion but several lasers have potential efficiencies exceeding 1%. If the pulse width can be longer than 1 ns, then the design of a laser would become easier and in some cases the efficiency would improve. No conclusion can be drawn at this time on whether a laser can be developed to meet the efficiency, repetition frequency, wavelength, and pulse shaping requirements, particularly since the last two requirements remain ill-defined. The laser wavelength can be converted to more optimum ranges for pellet implosion but usually at a significant cost in net efficiency. Thus the broader the range of allowable wavelengths, the greater will be the probability of finding a suitable laser.

POWER SUPPLY COSTS (DIRECT + INDIRECT) vs. DRIVER EFFICIENCY FOR DIFFERENT POWER LEVELS

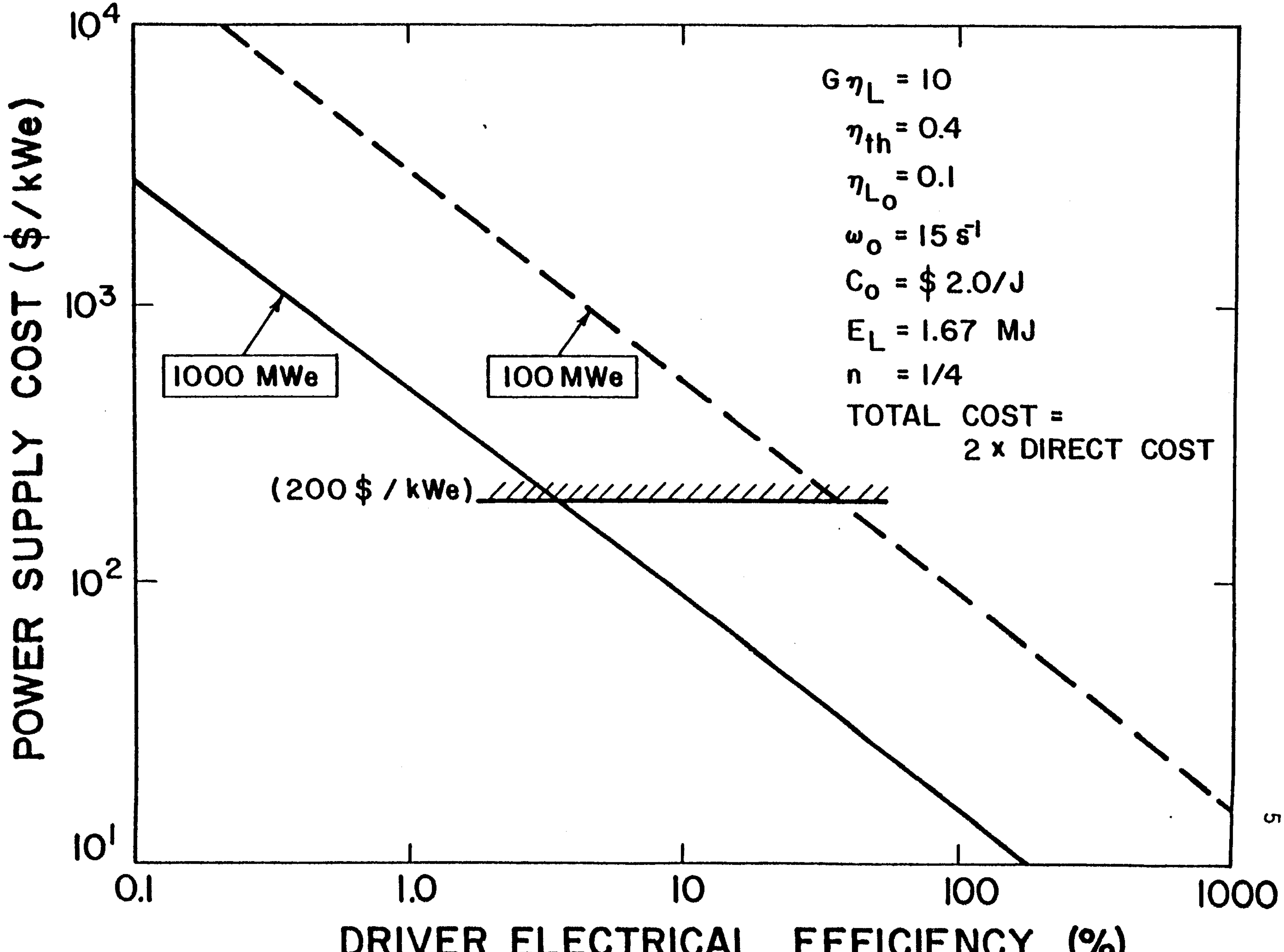


FIGURE 2

3. REPETITION RATE and PULSED POWER TECHNOLOGY

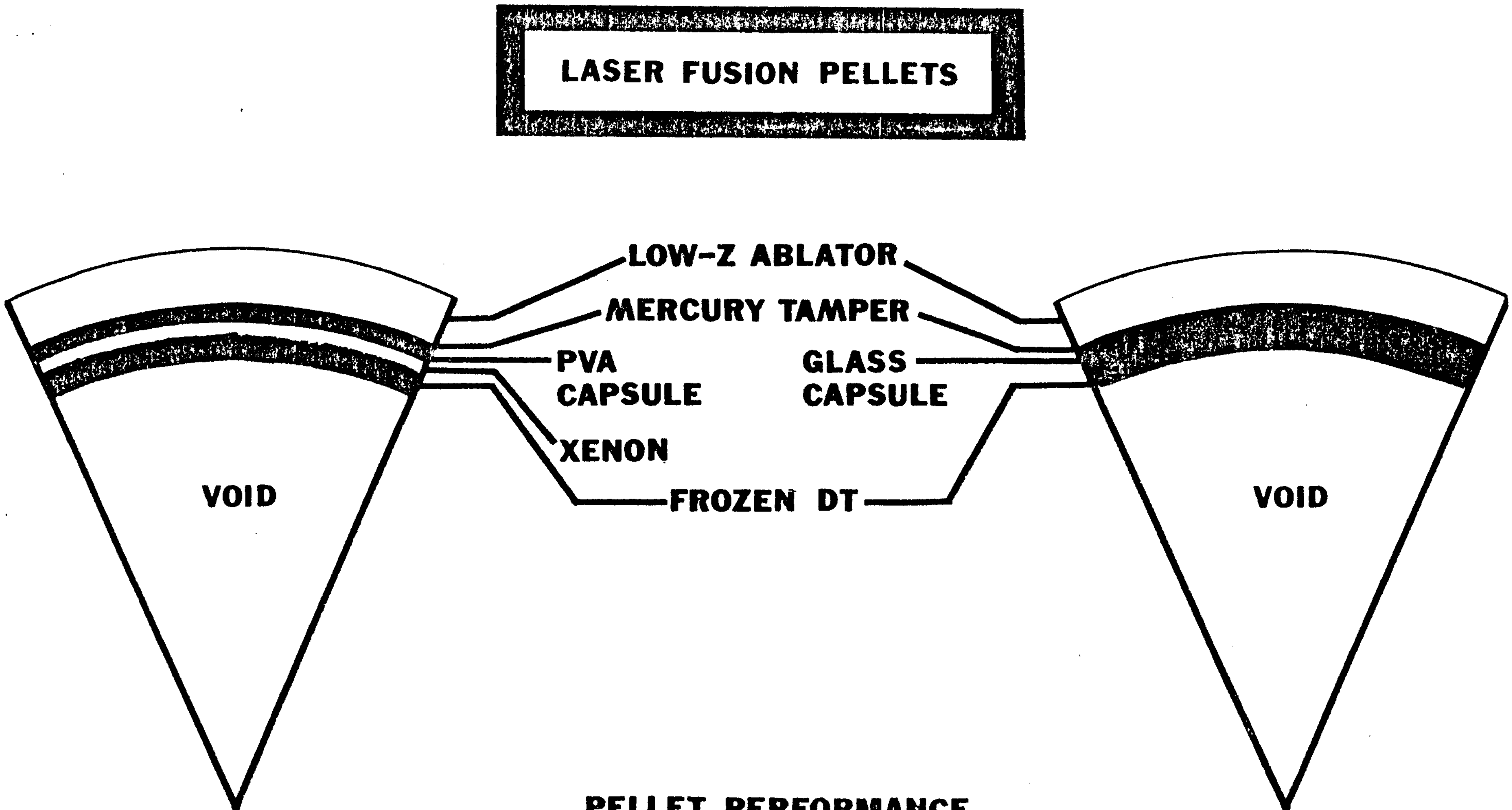
The development of short-pulse power supplies and switches of modest cost which can operate reliably for nearly 10^9 pulses is clearly critical. State-of-the-art lifetimes for power supply components are inadequate for laser fusion applications, being several orders of magnitude lower than those required for reactor systems. Current experiments do not require such long lifetimes since they are primarily single shot facilities. Hence, there has been no motivation for R&D so far.

Capacitor lifetimes can be increased by improving materials, reducing stresses and energy density, and using active cooling. Semiconductor switches appear to be most promising for laser fusion applications where they must operate in large parallel and series arrays. Adequate lifetimes have been demonstrated for slow risetime switches but must be verified for the short risetimes required for laser fusion systems. Spark gaps are also suitable for laser fusion applications.

4. MASS PRODUCTION and DELIVERY of TARGETS

A key issue is the development of a basic manufacturing procedure for the mass production of targets at an acceptable investment of capital. Pellet costs appear to be dominated by tooling costs which can be amortized over the life of the plant.

The delivery of targets into the reactor chamber appears feasible but trajectory correction in flight will be very difficult. A major issue for reactors (both near and long term) will be the maintenance of proper alignment in the laser optical train and the possible tracking of targets.



PELLET PERFORMANCE

PELLET GAIN =(YIELD/CORE ENERGY)X(CORE ENERGY/LASER ENERGY)
=(GAIN ON CORE)X(IMPLOSION EFFICIENCY)

UW

FIGURE 3

5. CAVITY DESIGN and FIRST WALL PROTECTION

Unprotected dry walls in laser fusion cavities will not survive the repetitive microexplosions at economically reasonable wall loadings (>1 MW/m^2) because of excessive evaporation and sputtering. The economic penalties involved in the increased cavity and blanket cost ($\propto R^2$), and containment building cost ($\propto R^3$) are significant especially for large-yield, low-repetition-rate systems (Fig. 4). Four different wall protection concepts have been proposed, viz., a gas-protected dry wall, a wetted wall, a liquid-lithium wall ("waterfall"), and a magnetically-protected wall. Of these, gas protection and the lithium fall concepts are the most promising, although numerous questions remain to be answered before the viability of these concepts can be established.

The wall protection schemes proposed so far appear suitable for limited regions of the target "parameter space". Gas protection is suitable for moderate yields (100-200 MJ) and repetition rates (10Hz) while the lithium fall concept is suitable for high yield (>1000 MJ) at low repetition rate (1 Hz) systems.

The gas protection scheme utilized in SOLASE with neon or xenon as the buffer gas protects not only the first wall but also the last optical elements from the charged particle debris and soft X-rays. At the laser intensity levels required on target (>10^{15} W/cm^2) gas breakdown will occur but for reactor size targets with spot size on the order of 2 mm, this may not be serious. The viability of this concept can be tested in both present and near term laser facilities. The lithium fall concept requires an extensive verification program before its viability can be established and a different protection scheme such as gas protection is required for the last optical elements.

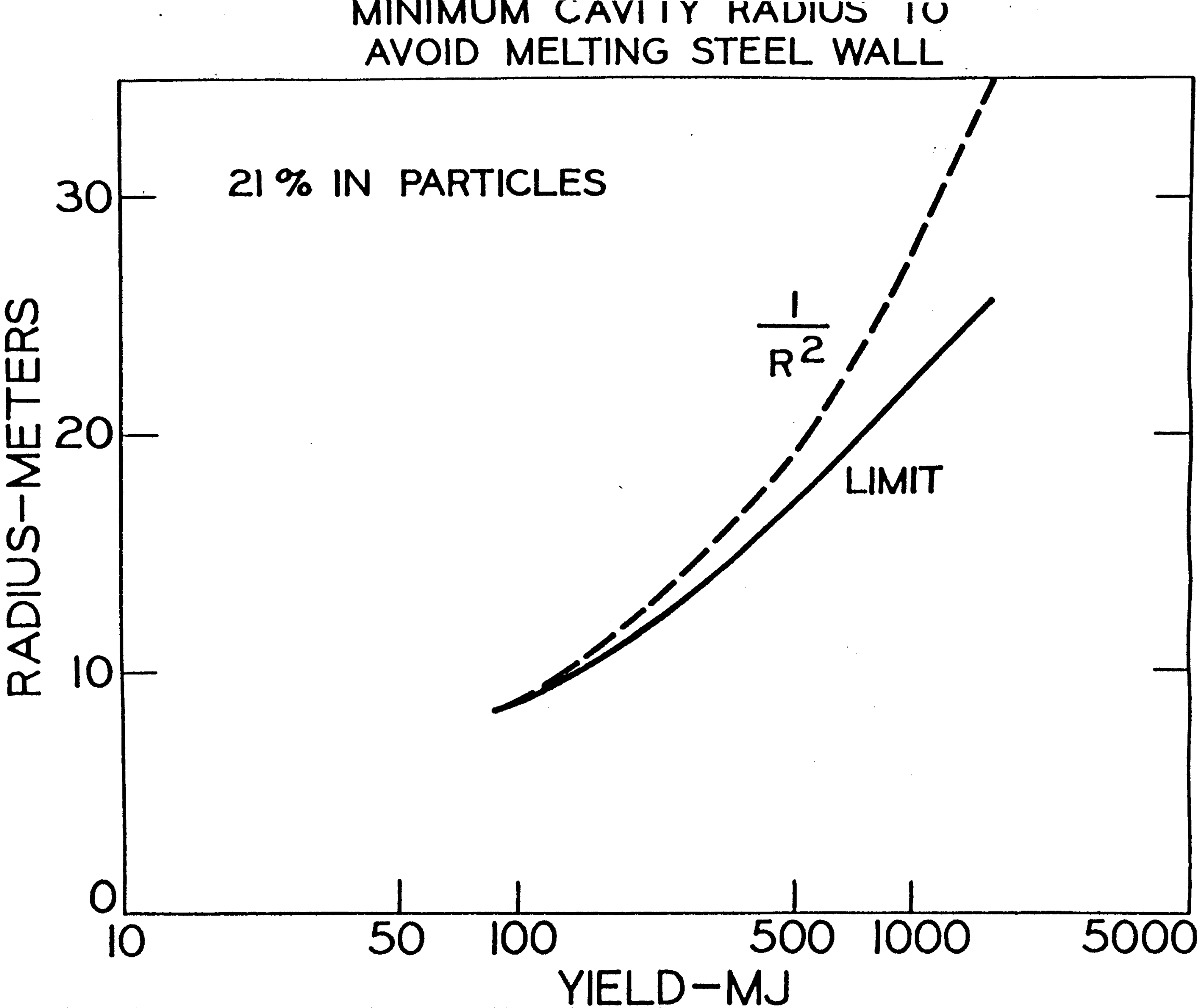


Figure 4 - Minimum cavity radius to avoid melting steel wall with pellet debris with typical spectra. (Sputtering will significantly increase the required minimum cavity radius above the values shown in this figure.)

6. LAST MIRROR DESIGN and PROTECTION

The design and protection of the last mirror poses no insuperable difficulties unless dielectric coatings are required. Such coatings are essential for lasers with wavelengths $\lesssim$8000 Å in order to obtain adequately high mirror reflectivity (>99%). Neutron damage to such coatings through the formation of color centers can occur at very low fluence levels. Unless overcome, this problem may prohibit the use of visible or UV lasers. Metal mirrors appear to be the best choice for the last optical elements. They are less susceptible to neutron and X-ray damage than glass lenses and for long wavelength laser light they may be diamond turned with no dielectric coatings necessary. Such mirrors can be constructed with present day technology.

Feasible methods exist to protect the last mirror from charged particle bombardment which is the major issue for uncoated-mirror protection. The gas protection scheme utilized in SOLASE (Fig. 5) allows the last mirrors to be placed only 15 meters away from the target. This is important since pointing errors grow increasingly larger as the mirrors are moved far from the target. Also, in the limit of very large distances (50 to 100 meters) the size of the primary containment building becomes an important issue if the last mirror must still reside within it.

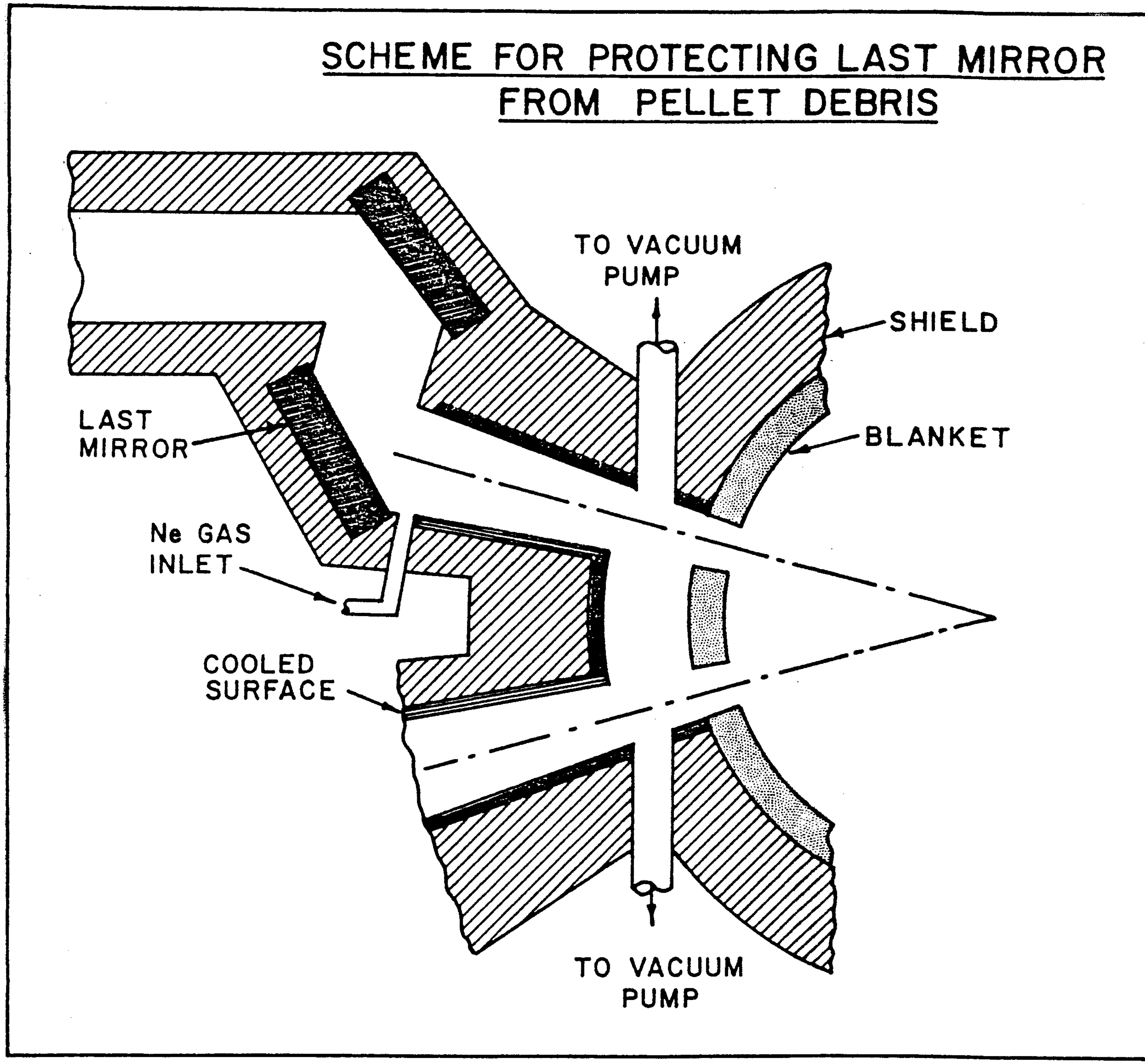

SCHEME FOR PROTECTING LAST MIRROR FROM PELLET DEBRIS
TO VACUUM PUMP
SHIELD
BLANKET
LAST MIRROR
Ne GAS INLET
COOLED SURFACE
TO VACUUM PUMP

FIGURE 5

7. RADIATION STREAMING and PRIMARY CONTAINMENT

Radiation streaming through the beam ports of a laser fusion reactor presents an extremely difficult engineering problem. This problem is the analog of neutral beam injectors, divertor slots and other penetration shielding in magnetic confinement systems. The basic problem is that these penetrations are generally large (~1 m in diameter) and are in direct line-of-sight of the exploding targets. Without significant attenuation (8-10 orders of magnitude) of the leakage flux, the radiation levels within the containment building will be unacceptably high. The addition of a few small angle bends (i.e. mirrors) along the beam path will not be sufficient and may have an adverse effect on the optical performance.

Several solutions have been proposed but have not been examined in sufficient detail to establish their feasibility. The possibility of using a point or line beam cross over through a fuzzy focus as a means of constricting the penetrations and reducing the leakage without deleterious effectson beam quality as a result of gas breakdown is critical and should be verified. This allows the last mirrors to be placed near the target and reduces the size of the containment building. The laser building may not be primary containment. The use of large f-number optics with the mirrors placed at very large distances (about 100 meters) from the target is an effective way to directly reduce the size of the penetrations. However, recourse to this approach should be a last resort since it significantly increases the size of the containment building and leads to problems regarding alignment and focusing of the beams.

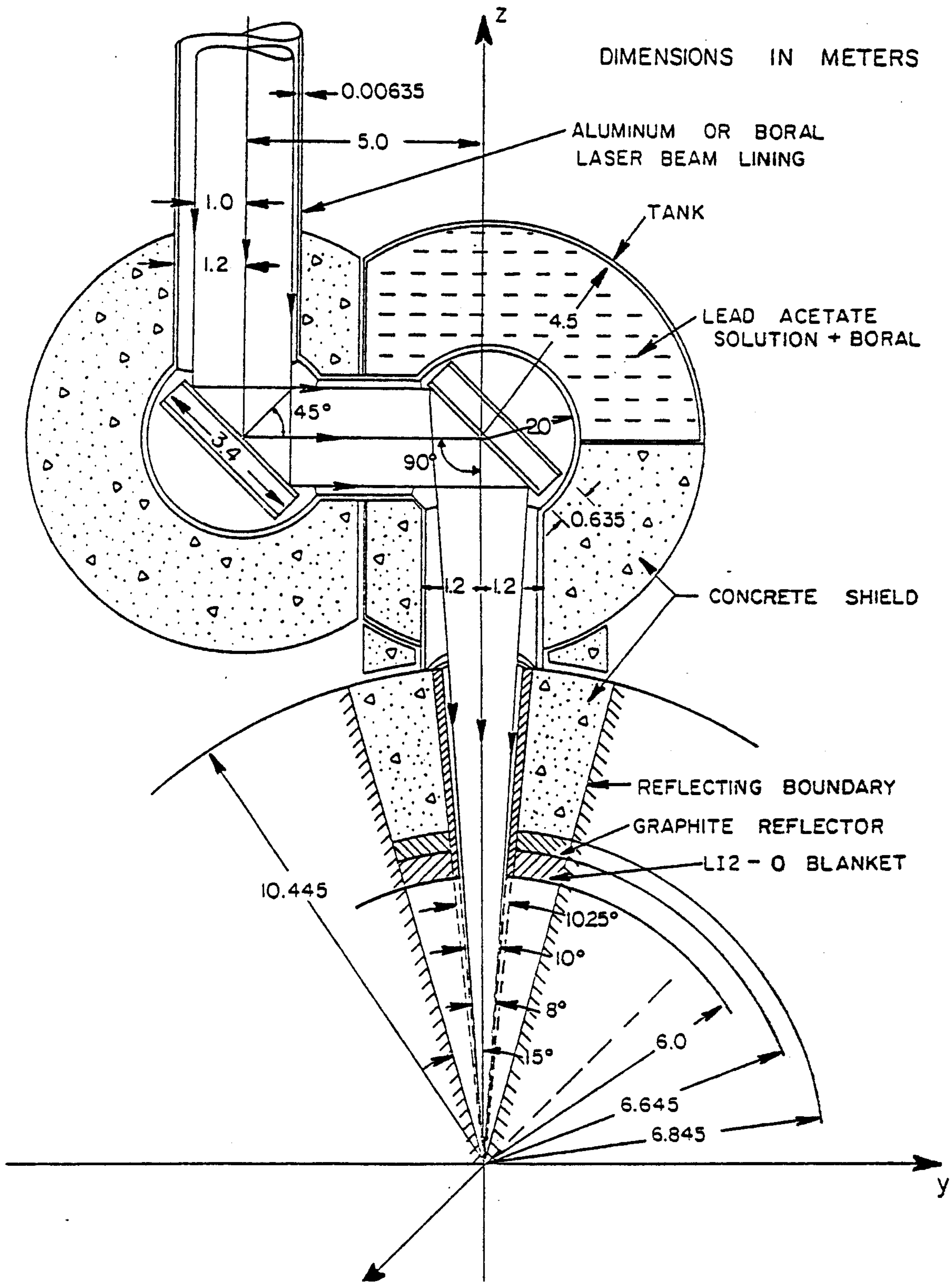


Figure 6 - Typical layout for beam penetration in a laser fusion reactor including last and next-to-last mirror and associated shielding.

8. TRITIUM INVENTORY and TARGET FABRICATION

The tritium inventory in laser fusion reactors will be dominated by the tritium associated with the filling and storage of targets. A one-week inventory of targets may be required to allow operation during a malfunction in any part of the tritium cycle external to the reactor. The inventory associated with other reactor subsystems such as the vacuum pumps and the tritium breeding and extraction system is small. When permeation filling is used, the tritium inventory will strongly depend on the target fill time. For example, since the diffusion reates of DT through glass are much lower than the rates through polyvinyl alcohol (PVA), the estimated total tritium inventory for SOLASE is approximately 11 kg with PVA encapsulation and 26 kg with glass capsules (Table 1). This is incidentally just one of many instances where pellet design has a significant impact on reactor analysis.

9. VACUUM SYSTEM REQUIREMENTS

The vacuum requirements of laser fusion reactors may be modest if pumping speed is set by wall erosion limits. However, the key issues relate to the nature of the pellet debris, to the influence of materials remaining in the gas on laser beam transport and gas breakdown, and to the energy content of the gas flowing from the chamber.

The design of the tritium reprocessing system for the pellet debris is strongly dependent on both pellet and cavity design. Chemical reactivity with the cavity wall as well as the potential variety of materials that might be used in the target complicate the problem. Special separation techniques are required to handle the radioactive chamber effluent, the unburnt tritium, and other materials that are recycled to the pellet factory. A definitive answer to vacuum requirements must await the availability of the final target design for reactor applications.

TABLE 1

TRITIUM INVENTORY in SOLASE

Location	Quantity (kg)	
	glass pellet	PVA pellet
Reactor, Scrubber		
Oxidizer, CO_2 absorber	2×10^{-5}	2×10^{-5}
H-isotope fractionator	0.03	0.03
Electrolysis equipment	0.1	0.1
Molecular sieves	0.67	0.67
Lithium oxide blanket loop	1.0	1.0
Pellet manufacturing and storage	24.0	9.4
TOTAL	26	11

10. LONG TERM RADIOACTIVITY -- GRAPHITE BLANKETS

The modest vacuum requirements in laser fusion systems allows the use of graphite to construct the blanket. This has significant environmental and economic impact inasmuch as these blankets have very low induced radioactivity levels (Fig. 7). The low activity levels allow the use of limited hands-on maintenance after only two weeks so that blanket replacement may be possible within scheduled shut down time for secondary system maintenance (one month per year. This can have a large impact on plant availability.

The performance of graphite composite blanket segments under reactor irradiation must be verified particularly at temperatures above 1200°C. The temperature decoupling of the grahite and Li_2O offers the possibility of operating the graphite at optimal temperatures but the reversal of thermal stresses on reactor shutdown could limit the blanket lifetime. The concept is extremely attractive from a utility standpoint and therefore deserves serious study in the future.

11. MULTIPLE REACTOR CAVITIES

The use of multiple cavities rather than a single cavity was briefly investigated. The primary motivation was to increase the potential availability time of the reactor. On the contrary, we have found that the most reliability-sensitive subsystem is the laser, rather than the reactor chamber. Multiple lasers and power supplies, while not economically attractive, would be preferable to multiple cavities. Further, the use of multiple cavities increases the complexity of the beam line system and reduces accessiblity. Multiple cavities may however be the only solution if methods to re-establish the required chamber environment take too long.

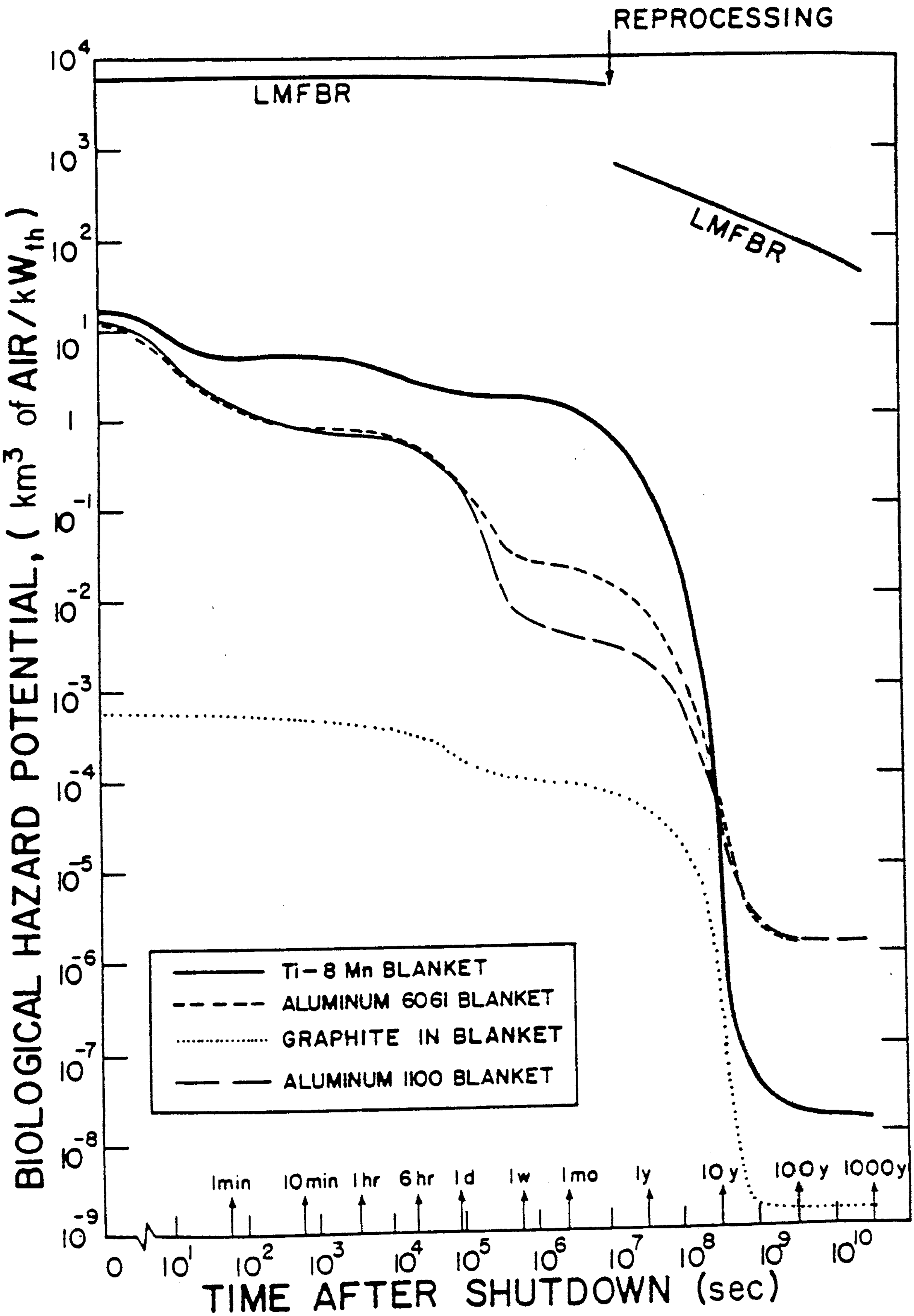


Figure 7 - Radioactivity in SOLASE blanket after one year of operation.

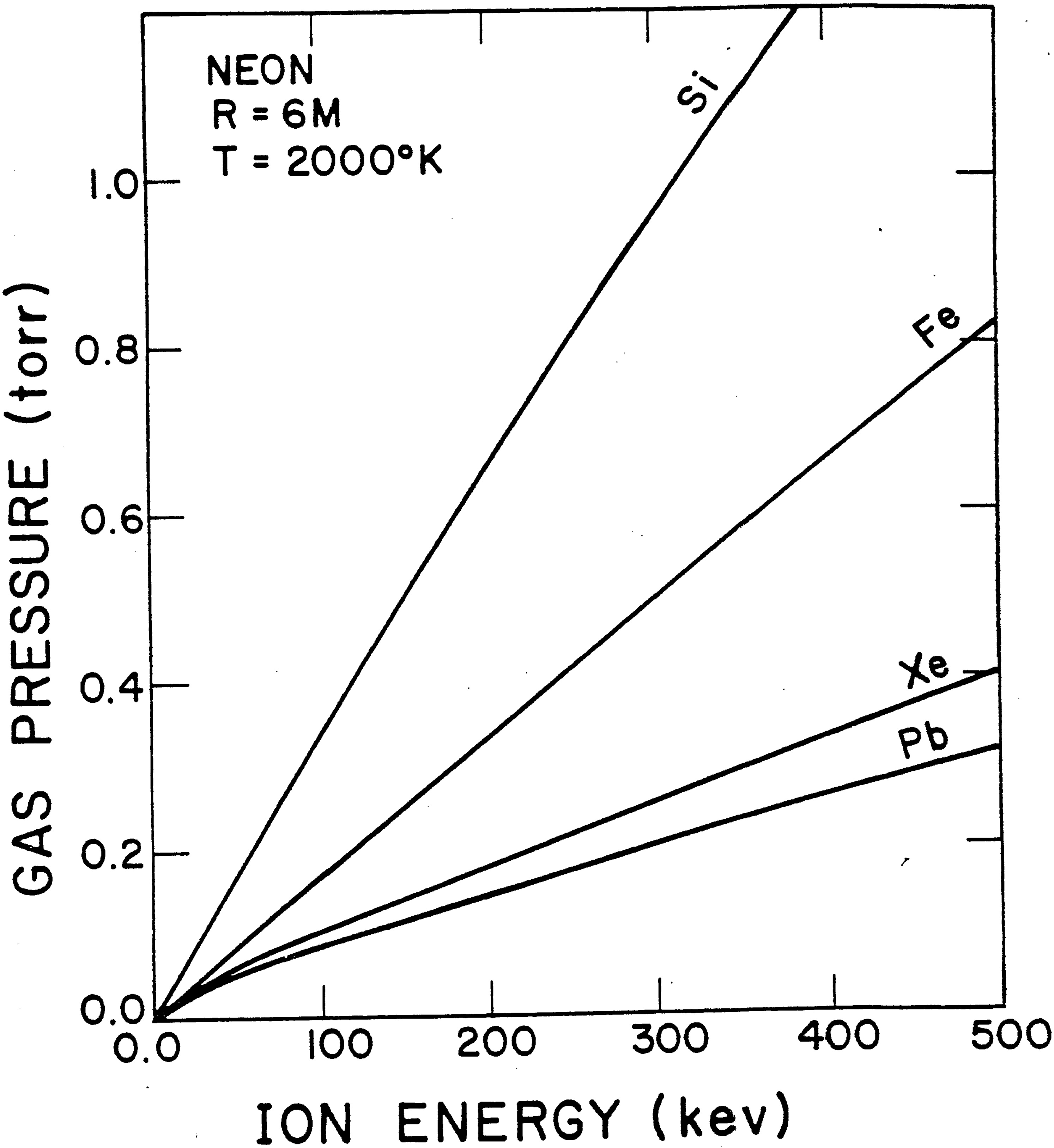
12. TARGET OUTPUT SPECTRA and FIRST WALL DESIGN

The success and choice of a cavity design will strongly depend on pellet materials and output characteristics. At this time little information is available on this subject. It is likely that a generic reactor design independent of the pellet spectra will not be optimum and may not make laser fusion appear as attractive as it ultimately might be.

Of the wall protection concepts proposed so far, the lithium fall concept appears insensitive to target output characteristics. On the other hand, gas protection may depend on the output spectra especially if low gas pressures are deemed necessary for beam propagation likewise magnetic protection will be sensitive to the fraction of yield carried away by the charged particles.

13. ACCESS and MAINTENANCE

A general advantage of laser fusion reactors is that the reactor cavity and blanket are not surrounded by complex magnet systems. This greatly improves accessibility. However, if uniform illumination of the target is required, this advantage tends to be offset by a complex beam delivery system with mirrors that must be closer to the target.


NEON
R = 6M
T = 2000°K
Si
Fe
Xe
Pb
GAS PRESSURE (torr)
0.0
0.2
0.4
0.6
0.8
1.0
0.0
100
200
300
400
500
ION ENERGY (kev)

14. COMMERCIALIZATION and CLASSIFICATION

An important issue specific to inertial confinement has to do with commercialization of this technology, nuclear proliferation, and security classification. There are many facets to this question because fusion produces more neutrons per unit of energy than fission and the fuel cycle involves tritium. However perhaps the most important issue is the relationship of ICF to technical ideas and information related to thermonuclear weapons. Such a connection, if any, could be protected by classification but this would surely impede the commercialization process. The problem of safeguards could thus be further complicated by the desire to protect ideas as well as materials. The introduction of commerical laser fusion would seem to require the declassification of relevant information to avoid social, institutional and political problems. The problems of accountability in the presence of an on-site inventory of $\sim 10^6$ target could mean that all such reactors would have to be government owned and operated. Licensing and public participation would be restricted and there would be a significant extra burden placed on local utilities. The program can proceed now without significant difficulty but further examination of this issue by an appropriate panel that includes government representatives is clearly desirable before a decision to move ahead with an Engineering Test Facility (ETF) is taken. Since the ETF is the first major step towardscommercialization, it would be best if such a facility is unclassified.

15. GENERAL COMMENTS

Experimental results on compression and neutron yield from laser and electron beam illuminated targets summarized in Table 2 are a measure of the progress being made in this field. The progress is such that several energy breakeven experiments as listed in Table 4 are planned for the not too distant future. The predicted performance for these experimental facilities, if realized, will mean that substantial advances will have been achieved in the physics of laser and e-beam pellet implosions. Predictions of target gains in the proposed NOVA facility have recently been quoted to be on the order of one to twenty. It is not clear that the physics basis for targets applicable to reactors will by demonstrated by such a facility. At the point when such a basis is established, the key technical issues will be many of those outlined in this report. Results from the next five years of physics experiments carried out with ever increasing driver energy and power on target, taken together with the results of reactor studies like SOLASE, should establish whether an ambitious engineering-oriented program aimed at reactor development is justified.

TABLE 2

NEUTRON PRODUCTION MILESTONES in ICF RESEARCH

Laboratory	Driver	Power (TW)	Neutron Yield	Date
KMS	Nd: Glass	0.2	~10^7 (DT Fuel)	1974
LLL	Nd: Glass (JANUS I)	0.2	10^6 (DT Fuel)	1974
LLL	Nd: Glass (JANUS II)	0.4	10^7 (DT Fuel)	1975
LLL	Nd: Glass (ARGUS)	4.6	10^9 (DT Fuel)	1976
KURCHATOV	e-Beam (TRITON)	0.06	10^6 (D_2 Fuel)	1976
LASL	CO_2	0.4	10^6 (DT Fuel)	1977
SLA	e-Beam (HYDRA)	0.1	10^6 (D_2 Fuel)	1977
LLL	Nd: Glass (SHIVA)	25	10^{11} (DT Fuel)	1978

TABLE 3

NEAR TERM EXPERIMENTAL DRIVERS for ICF EXPERIMENTS

Laboratory	Driver	Power (TW)	Completion Date	Predicted Experimental Results
SANDIA-A	e-Beam (PROTO-II)	7	1977	$10^7 - 10^9$ Neutrons
LLL	Nd: Glass Laser (SHIVA)	10-40	1977	10^{11} Neutrons
LASL	8-Beam CO_2 LASER	10-20	1978	$10^{10} - 10^{12}$ Neutrons
LLE-UR	Nd: Glass Laser (OMEGA-10)	3-30	1979-80	User Facility
SANDIA-A	e-Beam (EBFA)	30 (1 MJ, 40 ns)	1980	$10^{10} - 10^{13}$ Neutrons
KURCHATOV	e-Beam (ANGARA V)	80 (5 MJ, 85 ns)	1982	G ~ 100
LLL	Nd: Glass Laser (NOVA)	100-300	1983	$10^{16} - 10^{17}$ Neutrons G ~ 1 - 20
LASL	CO_2 Laser (ANTARES)	100-200	1983	10^{16} Neutrons G ~ 1
SANDIA-A	e-Beam (EBFA-II)	60-80	1983-85	$10^{15} - 10^{17}$ Neutrons G ~ 0.1 - 1

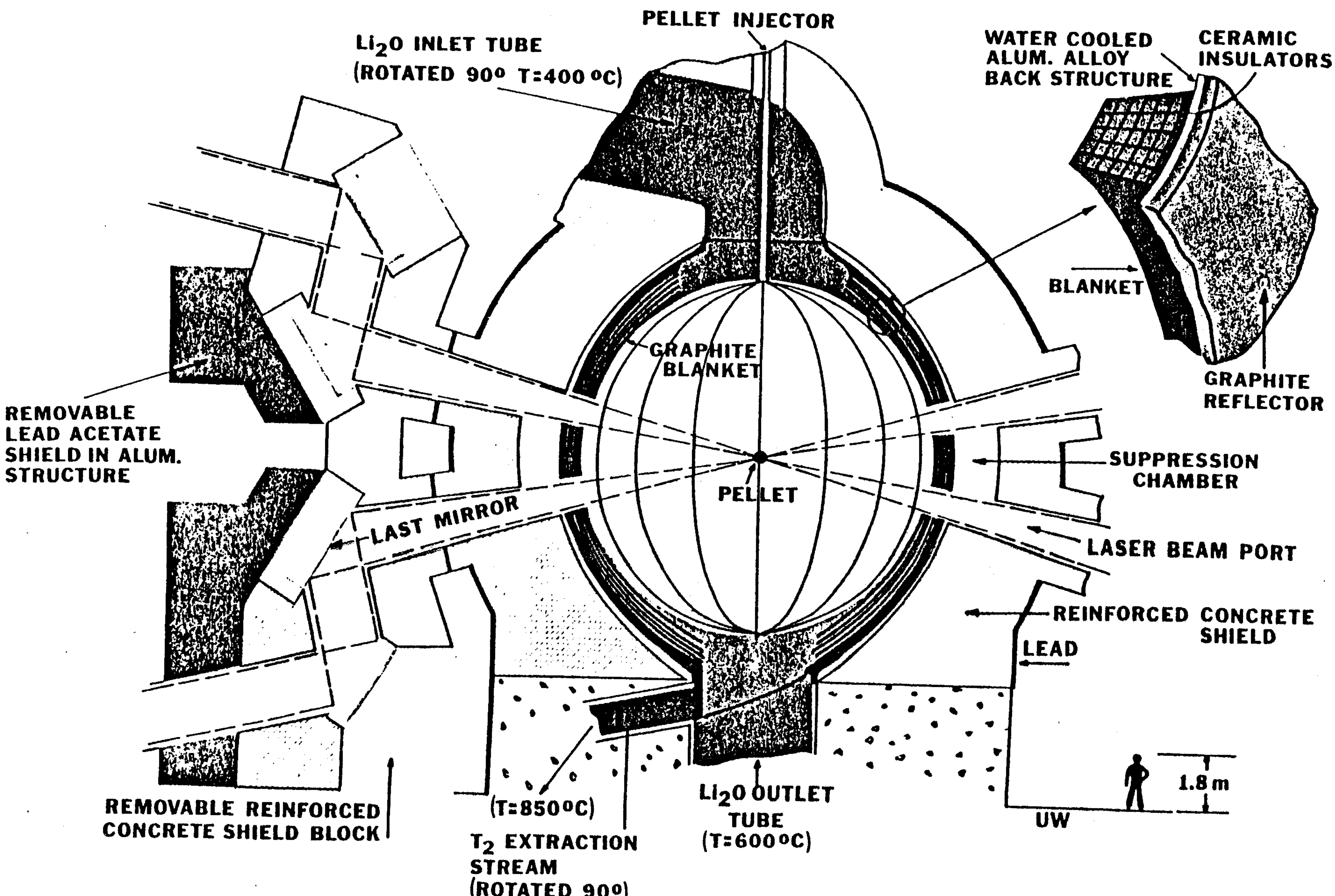
II. BRIEF DESCRIPTION OF SOLASE

SOLASE is a conceptual laser fusion reactor designed for the production of electric power. The main purpose of the SOLASE study is the self-consistent examination of problems, both in physics and technology, likely to be important to the future development and commercialization of this particular approach to fusion power. The major parameters characterizing SOLASE are listed in Table 4; an overall view of the cavity and blanket is shown in Fig. 9 and a plan view of the reactor system is shown in Fig. 10.

The SOLASE reactor is designed to produce 1000 MW_e at a net efficiency of 30% from laser ignited fusion pellets that have a gain of 150. The laser energy on target is 1 MJ and 20 targets are exploded per second. The net laser efficiency is about 7% including multipassing of the next-to-last and last laser amplifier. The laser is designed, generically where possible, as a gas phase laser modelled after the CO_2 system but no laser wavelength is specified. The optimistic laser efficiency still implies relatively large power supply needs and the recirculating power fraction is nearly 25%. These facts will have important consequences for reactor economics.

The reactor cavity (Fig. 9) is spherical with a 6 m radius. It is filled with neon or xenon gas at 0.5 to 1 torr pressure, sufficient to protect the first wall and last optical elements from the ions and soft x-rays produced by the exploding pellets. Thermonuclear burn dynamics calculations have been performed to determine pellet debris spectra for cavity design analyses. The analyses of various component operation have for the most part been carried out parametrically. This approach is necessary since pellet design is in its infancy and a wide range of pellet materials, and output characteristics is possible.

THE SOLASE LASER FUSION REACTOR SYSTEM



Multilayered cryogenic targets produced in a batch process are used in SOLASE. Target delivery is by pneumatic guns although trajectory diagnostic and correction techniques must be developed. The last mirrors are diamond turned copper on an aluminum structure located 15 m from the reactor cavity center with f/no. = 7.5. Heating of the mirror surface is minor so long as the debris ions are stopped in the buffer gas.

A novel blanket design is used in SOLASE. The blanket is constructed from graphite and is designed to guide the gravitational flow of lithium oxide particles (100-200 μm in diameter) serving as both the tritium breeding and heat transport medium. The use of graphite as a structural material is made possible by the modest vacuum requirements of laser fusion reactors. The neutron wall loading is 5 MW/m^2 so that SOLASE represents a reasonably compact system given the net power produced. The blanket back structure is made from an aluminum alloy and the shield can be either concrete or lead acetate solution. Thus, the overall levels of neutron induced activity decay very rapidly following shutdown. It appears that limited hands-on maintenance is possible after just one week.

This spherical system is highly accessible from the outside provided that two-sided target illumination (six beams on each side) is acceptable. A procedure has been developed for annual blanket replacement that is simple and fast. We expect down-time periods to replace graphite blanket segments to be on the order of two weeks. The philosophy is that blanket maintenance *per se* will be avoided; after draining the Li_2O, the graphite will be simply discarded. Such a simple procedure is critical if a high system availability is to be achieved.

TABLE 4
MAJOR PARAMETERS OF SOLASE

Cavity Shape	Spherical
Cavity Radius	6 m
14 MeV Neutron Wall Loading	5 MW/m^2
Thermal Power	3340 MW
Gross Electrical Power	1335 MW
Net Electrical Power	1000 MW
Net Plant Thermal Efficiency	30%
Recirculating Power Fraction	25%
Laser Type	Gas Phase
Laser Energy on Target	1 MJ
Laser Efficiency (with Multipassing)	7%
Number of Final Amplifiers	6
Number of Final Beams	12
Pulse Width	1 ns
Pulse Repetition Rate	20 Hz
Pellet Yield	150 MJ
Pellet Gain	150
Fractional Burnup of Fuel	45%
Initial Fuel Mass	1 mg
Generic Target Design	Multilayered-Cryogenic

Overall, the SOLASE laser fusion reactor concept is an interesting fusion system. It has a relatively simple and accessible reactor chamber design with a blanket system that has very low levels of long term induced radioactivity. The flowing lithium oxide system permits low pressure operation in the blanket while the modest chamber vacuum requirements make the use of graphite or graphite composites for the blanket structure more feasible. The recirculating power fraction of 25% will strongly influence economics but the replacement, rather than the maintenance, of reactor modules of low activity should permit short down times, improving overall system availability. Last mirror protection, initially considered a critically difficult problem, appears to be manageable by a simple design solution. The reactor is pulsed twenty times a second but is effectively steady state from a power production viewpoint such that a thermal energy store to smooth the power to the turbines is not required. The system is of moderate size for the power produced and the laser building, although quite large, may not be primary containment.

TABLE 4
(CONTD.)

Target Illumination	Two Sided
Number of Final Mirrors	12
F/No. of Final Mirror	7.5
Distance from Last Mirror to Pellet	15 m
Diameter of Last Mirror	3.5 m
Composition of Last Mirror	Cu on Al
Manufacturing Procedure	Diamond Turning
First Wall Protection Method	Ne or Xe Buffer Gas
Blanket Structure	Graphite Composite
Blanket Breeding and Heat Transport Medium	Lithium Oxide (Li_2O)
Tritium Breeding Ratio	1.3
Li_2O Inlet Temperature	400°C
Li_2O Outlet Temperature	600°C
Average Li_2O Flow Velocity	0.4 m/s
Tritium Inventory	
Glass Encapsulation of Target	25 kg
Polymer Encapsulation of Target	11 kg
Total Reactor Radioactivity Level 50 Years After Shutdown	3 Ci

TOP VIEW OF SOLASE

A CONCEPTUAL LASER FUSION REACTOR POWER PLANT

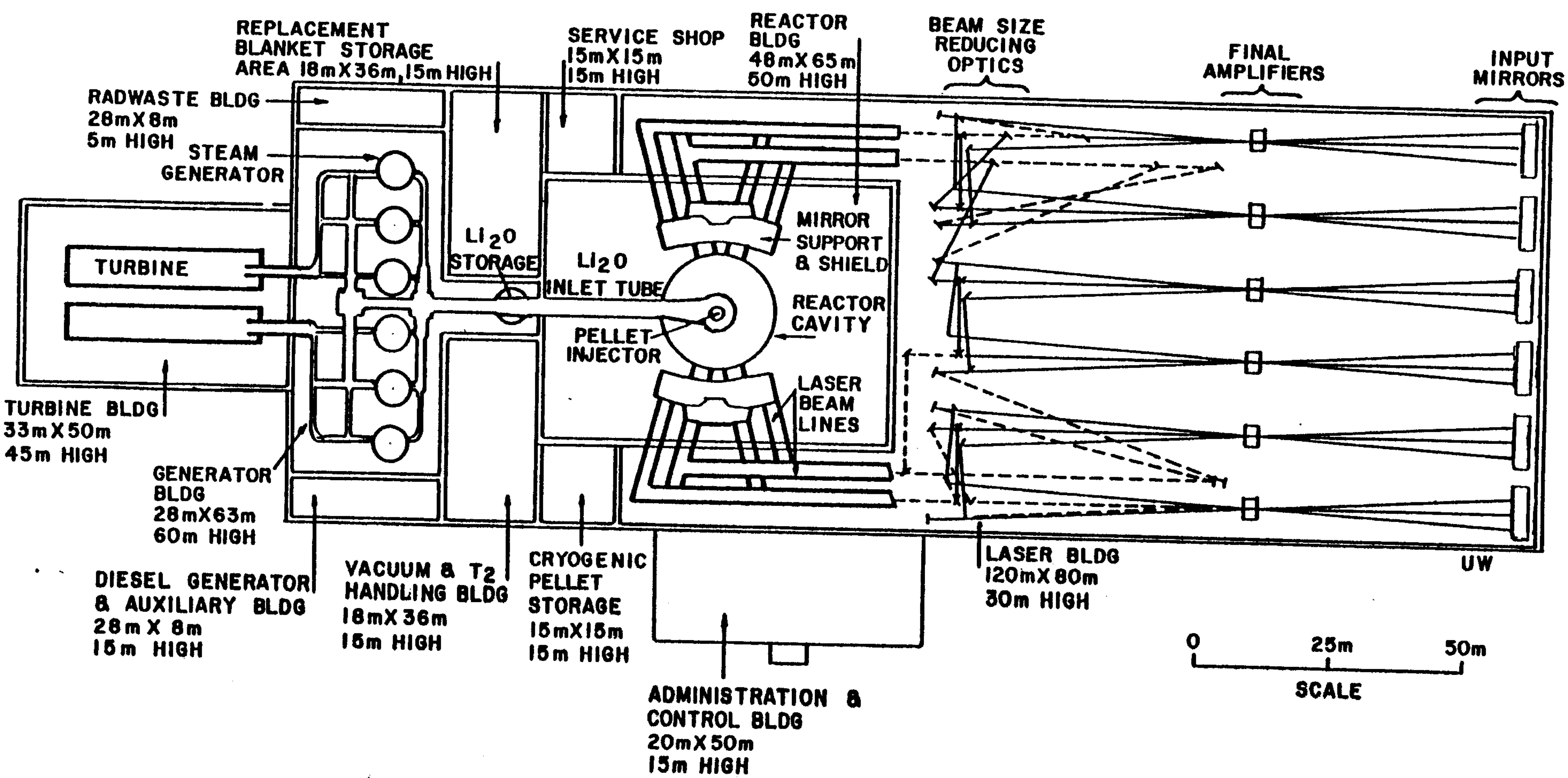


FIGURE 10