Reactor Aspects of Laser Fusion

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Abstract

A conceptual laser fusion reactor has been designed to ellucidate the technological problems posed by inertial confinement fusion reactors. Major issues include target energy gain, laser wavelength and efficiency, reliable and long-lived power supplies and switches, optics and beam train alignment, targeting and tracking, pellet fabrication and costs, and reactor chamber protection and design. Near term experiments over the next five years will establish whether an ambitious engineering-oriented program pointed towards such a reactor is warranted.

Research on inertial confinement fusion has expanded dramatically in recent years and experimental results on compression and neutron yields from laser[1-4] and electron beam[5,6] illuminated targets summarized in Table 1 are measures of this rapid progress. The theory that suggested the possibility of achieving high gains by illuminating small spherical deuterium-tritium targets[7,8] has likewise grown rapidly. The progress is such that several energy breakeven experiments listed on Table 2 are planned for the not too distant future. Given both this progress and the level of research effort, it is worthwhile at this time to determine the requirements for inertial confinement fusion reactors and the technological problems such systems might pose.

Laser initiated thermonuclear fusion is presently the most widely investigated inertial confinement area. As such, we have carried out a study of a conceptual laser fusion reactor, SOLASE,[9] designed for the production of electric power. The purpose of the study is the self-consistent examination of problems, both in physics and technology, likely to be important to the future development of this particular approach to fusion power.

The main parameters characterizing the reactor are listed in Tables 3 and 4. A top view of the reactor is shown in Fig. 1 and a more detailed view of the reactor cavity is shown in Figs. 2 and 3. 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 6.7% including multipassing of the next-to-last and last laser amplifier. The laser is designed, generically where possible, as a gas phase laser modeled after the CO_2 system. No laser wavelength is specified. Thermonuclear burn dynamic calculations have been performed to determine pellet debris spectra for cavity design analysis. A buffer gas of neon at 0.5 torr pressure is used to stop the ions and hard X-rays are benign. Multilayered cryogenic targets produced in a batch process appear to have low cost (less than 0.1 mill/kw-hr) because tooling costs can be amortized over the lifetime of the plant and materials costs are negligible. One can invest $100,000,000 in capital equipment to construct a pellet fabrication plant and add only about 1.5 mill/kW-hr to the cost of electricity in a 1000 MW_e plant. Target delivery is by pneumatic guns although trajectory correction techniques must be developed. The last mirrors are diamond turned copper on an aluminum structure. They are 15 m from the reactor cavity center and have an f/no. of 7.5. Heating and distortion of the mirror surface is minor so long as the debris ions are stopped in the buffer gas. We do not find the last mirror a fatally difficult problem.

The reactor cavity itself is spherical and has a radius of 6 m. It is constructed from graphite composite material designed to guide the gravitational flow of lithium oxide (Li_2O) which serves as both the tritium breeding and heat transport medium. The breeding ratio is 1.33 and the maximum Li_2O flow velocity is only about 1 m/s. 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. The biological hazard potential (BHP), defined as the radioactivity in Ci/kW_t divided by the maximum permissible concentration in air (MPC_a), is given on Fig. 4. It appears that limited hands on maintenance is possible after just one week. The LMFBR curve on Fig. 4 is from Häfele et al.[10]

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

Overall, the SOLASE laser fusion reactor concept is an attractive 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 approach permits low pressure operation in the blanket while the modest chamber vacuum requirements makes the use of graphite or graphite composites for the blanket structure more feasible. The low pellet costs can mean that laser fusion has a very low "effective" fuel cost and the replacement, rather than the maintenance, of reactor modules of low activity should permit short down times and improve overall system reliability. Last mirror protection, initially considered a critically difficult problem, appears to be manageable by 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, need not be primary containment.

From this study, a number of major issues have emerged. Some are related to the general laser and pellet performance assumptions while others have to do with certain specific design approaches taken in SOLASE itself. The more important of these will now be summarized.

First, the energy gain on target of 100-200 or higher is difficult to achieve with a 1 MJ laser. Although high gain designs have been reported,[11] they still must be verified by experiment. The basic question is whether the laser energy can be coupled into the target efficiently enough to make the target work. The experiments listed in Table 2 should bring us much closer to an answer on this matter. Clearly the next 1 to 5 years will be critical for physics developments in the field.

The assumption that a laser design with multipassing of the last two amplifiers can have an efficiency of about 7% must be verified. In particular, a laser with this efficiency and with the appropriate wavelength and pulse shaping characteristics is required. (If very large gains are possible, e.g., $G > 500$, then low efficiency lasers become acceptable. However, if the incident laser energy remains at about 1 MJ, the implied large pellet yield will pose unique cavity design problems.)

The development of power supplies and very short pulsed switches (1 μs or so) that can operate reliably for 10^8-10^9 shots are needed.

The gas protection method analyzed for SOLASE using either neon or xenon at 0.1-1 torr pressure to prevent charged particle debris (and X-rays in the case of xenon) from reaching the first wall and last mirror requires verification. At the laser intensity level required ($>10^{15}$ W/cm^2) on target, gas breakdown will occur but for reactor size targets with radii on the order of 2 mm; this may not be serious. The applicability of this concept can be tested in both present and near term laser experimental facilities.

A key issue is the development of a basic manufacturing procedure for the mass production of targets. 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 tracking of targets on a shot by shot basis.

The tritium inventory in such reactors may be dominated by the tritium associated with the filling and storage of targets. For SOLASE, we considered a one week inventory to allow operation during a malfunction in any part of the tritium cycle external to the reactor. There is also an inventory associated with pellets being fabricated and with other reactor subsystems such as the vacuum pumps and reactor blanket. However, the inventory is dominated by the pellet inventory, and particularly by the time to fill a target with DT fuel.

A generic cryogenic target can consist of multiple layers. Working out from the center of a sphere, these layers include a central void, the DT fuel, a capsule, a high Z tamper layer, and a low Z, low density ablative layer. The capsule layer may be glass or a polymer such as poly vinyl alcohol (PVA). The diffusion rates of DT through glass are much lower than the rates through PVA so that the estimated total plant tritium inventory is approximately 10 kg with PVA encapsulation and 25 kg with glass capsules. There is therefore a strong incentive to use polymer encapsulation. This is, incidentally, just one of many examples where pellet design has a significant impact on reactor analysis.

The performance of graphite or the graphite composite blanket segments under reactor irradiation must be verified. The temperature decoupling of the graphite 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 other viewpoints (e.g., very low induced radioactivity) and therefore deserves serious study in the future.

The experimental facilities outlined on Table 2 may lead to substantial successes in the physics of laser pellet implosions over the next several years. If a gain on target of 100 is achieved, as is suggessted for the NOVA facility, then the physics basis for targets applicable to reactors will have been demonstrated. At that point, the key technical issues will be the development of reliable, efficient, high repetition rate driver systems including the power supplies and switches, the development of targeting methods to allow tracking of targets on a shot by shot basis, the development of a basic manufacturing procedure for the mass production of the targets, and the development of an acceptable reactor chamber design. There is no apparent reason why these issues cannot be pursued on a rapid basis to allow the employment of laser fusion reactors beginning in the early part of the next century. The next five years of physics experiments carried out with ever increasing laser energy and power on target should establish whether an ambitious engineering-oriented program aimed at reactor development is justified.

Physics success will also bring to the forefront the important issue of security classification which is specific to inertial confinement. The development of laser fusion may be possible without declassification but the commercialization process will be severely impeded. Furthermore, these problems are complicated by the desire to protect ideas as well as materials, which can add considerably to the general problem of safeguards. At the present time, it is possible for groups such as utilities to make unclassified assessments but judgments should be made only with caution and qualifications.

The introduction of commercial laser fusion reactors will surely require declassification of relevant information to avoid social, institutional, and political problems. Otherwise, licensing and public participation will be severely restricted and the burden on private industry and particularly utilities will be great. Individual sites like the non-commercial gaseous diffusion plant at Oak Ridge to produce enriched uranium have been operated but there is no historical precedent in peacetime for so widespread a potential commercial application involving classified material as would be the case for laser fusion. One would hope that progress on this issue will proceed in parallel with advances in the overall technical program.

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Table 1

NEUTRON PRODUCTION MILESTONES IN INERTIAL CONFINEMENT FUSION RESEARCH

LABORATORY	DRIVER	POWER (TW)	NEUTRON YIELD	DATE
KMS[1]	Nd: GLASS	0.2	$\sim 10^7$ (DT FUEL)	1974
LLL	Nd: GLASS (JANUS I)	0.2	10^6 (DT FUEL)	1974
LLL[2]	Nd: GLASS (JANUS II)	0.4	10^7 (DT FUEL)	1975
LLL[3]	Nd: GLASS (ARGUS)	4.6	10^9 (DT FUEL)	1976
KURCHATOV[5]	e-BEAM (TRITON)	0.06	10^6 (D_2 FUEL)	1976
LASL[4]	CO_2	0.4	10^6 (DT FUEL)	1977
SLA[6]	e-BEAM (HYDRA)	0.1	10^6 (D_2 FUEL)	1977

Table 2

NEAR TERM EXPERIMENTAL DRIVERS FOR INERTIAL CONFINEMENT FUSION EXPERIMENTS

LABORATORY	DRIVER	POWER, TW	COMPLETION DATE	ANTICIPATED EXPERIMENTAL RESULTS
SANDIA-A	e-BEAM (PROTO-II)	8	1977	$10^7 - 10^9$ NEUTRONS
LLL	Nd: GLASS LASER (SHIVA)	20-30	1977	$\sim 10^{13}$ NEUTRONS $G \sim 10^{-2}$
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-I)	40	1980	$10^{10} - 10^{13}$ NEUTRONS
LLL	Nd: GLASS LASER* (NOVA)	100-300	1981	$10^{16} - 10^{19}$ NEUTRONS $G \sim 1 - 100$
LASL	CO_2 LASER (ANTARES)	100-200	1982	$10^{16} - 10^{17}$ NEUTRONS $G \sim 1-8$
SANDIA-A	e-BEAM* (EBFA-II)	100	1985	$10^{15} - 10^{17}$ NEUTRONS $G \sim 0.1 - 10$

* Planned but not approved for construction.

Table 3

Parameters for the SOLASE Laser Fusion Reactor

CAVITY SHAPE	SPHERICAL
CAVITY RADIUS	6 m
14 MeV NEUTRON WALL LOADING	5 MW/m^2
THERMAL POWER	3340 MW
GROSS ELECTRICAL POWER	1334 MW
NET ELECTRICAL POWER	1000 MW
RECIRCULATING POWER FRACTION	25%
NET PLANT THERMAL EFFICIENCY	30%
LASER TYPE	GAS PHASE
LASER ENERGY ON TARGET	1 MJ
LASER EFFICIENCY (WITH MULTIPASSING)	6.7%
NUMBER OF FINAL AMPLIFIERS	6
NUMBER OF FINAL BEAMS	12
ENERGY OUTPUT/AMPLIFIER PASS	48.8 kJ
PULSE WIDTH	1 ns
PULSE REPETITION RATE	20 Hz
PELLET YIELD AND GAIN	150 MJ
FRACTIONAL BURNUP OF FUEL	45%
INITIAL FUEL MASS	1 mg
GENERIC TARGET DESIGN	MULTILAYERED-CRYOGENIC

Table 4

Parameters for the SOLASE Laser Fusion Reactor

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	1.33
TOTAL ENERGY PER FUSION EVENT	18.6 MeV
TOTAL Li_2O FLOW RATE	3.12×10^7 kg/hr
AVERAGE Li_2O FLOW VELOCITY	0.7 m/s
Li_2O INLET TEMPERATURE	400°C
Li_2O OUTLET TEMPERATURE	600°C
TRITIUM INVENTORY	
GLASS ENCAPSULATION OF TARGET	24.7 kg
POLYMER ENCAPSULATION OF TARGET	10.9 kg
TOTAL REACTOR RADIOACTIVITY LEVEL 50 YEARS AFTER SHUTDOWN	3 Ci

Figure Captions

FIG. 1 Top view of the SOLASE laser fusion reactor design. The laser building on the right has beam delay lines indicated as dashed lines.

FIG. 2 Cross section view of the reactor cavity. The chamber is filled to a density of about 10^{16} cm^{-3} with a buffer gas. Ne or Xe are the most likely candidates. The suppression chamber is for pumping and to weaken any propagating shocks. Gas flows in front of the mirror to the chamber stopping residual charged particles and X-rays. Details of the blanket are seen at the upper right.

FIG. 3 Detailed schematic of the cavity blanket designed for SOLASE. Lithium oxide (Li_2O) particles of mean radius 100 μ flow under graphite through the blanket frame made from composite graphite. The Li_2O flow velocity is tailored to produce a uniform exit temperature of 600°C. The graphite itself operates at a significantly different temperature from the Li_2O and is useful in controlling radiation damage to the structure. The chamber is composed of 16 such segments.

FIG. 4 The decay of the biological hazard potential as a function of time after shutdown for the SOLASE blanket with various backing materials (see Fig. 3). The BHP is the activity in Ci/kW_{th} divided by the maximum permissible concentration (MPC). The curve for the LMFBR from Häfele et al.(10) includes reprocessing the fuel after one year.

TOP VIEW OF SOLASE

A CONCEPTUAL LASER FUSION REACTOR POWER PLANT

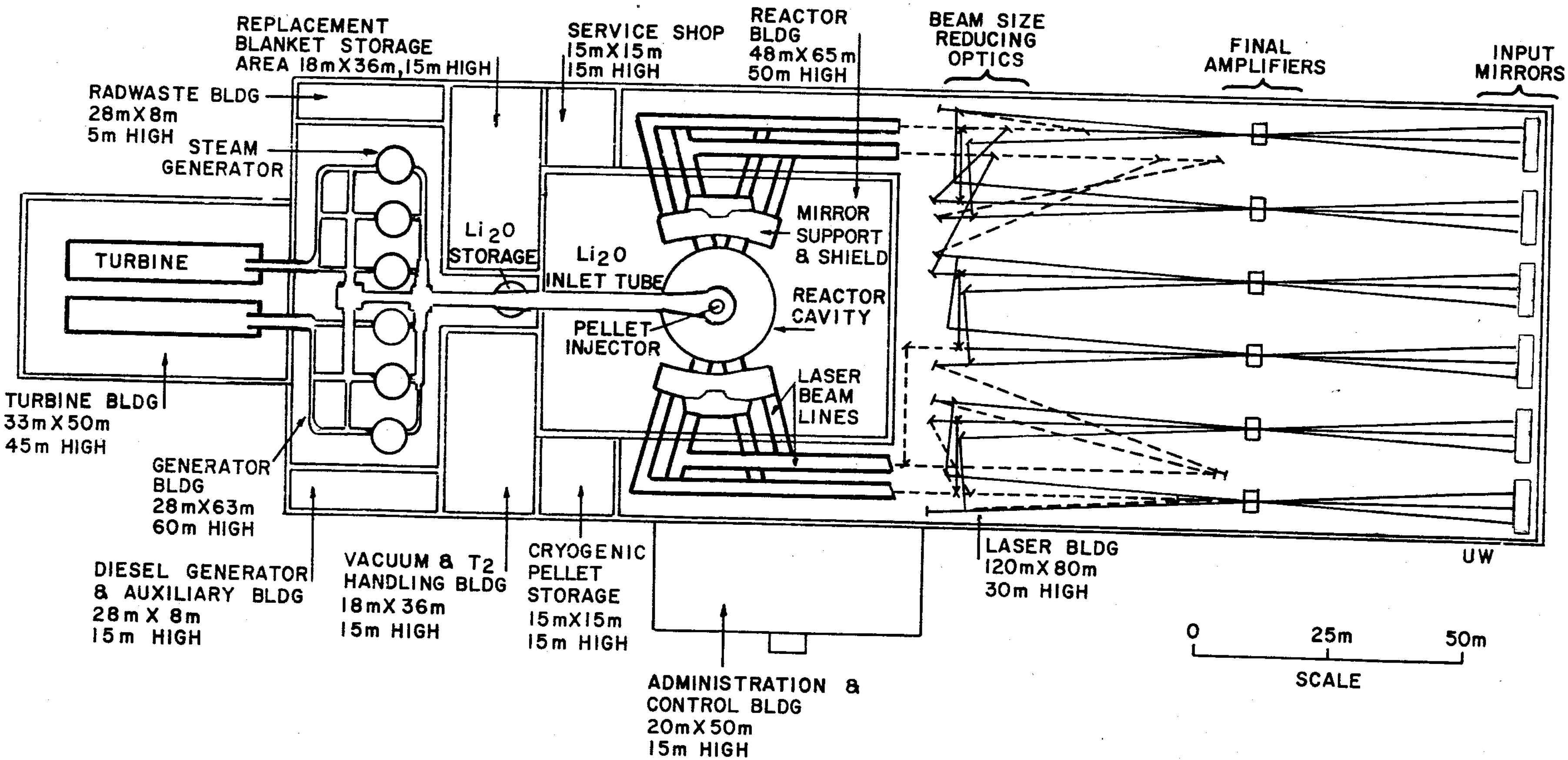

FIGURE 1

[redacted]

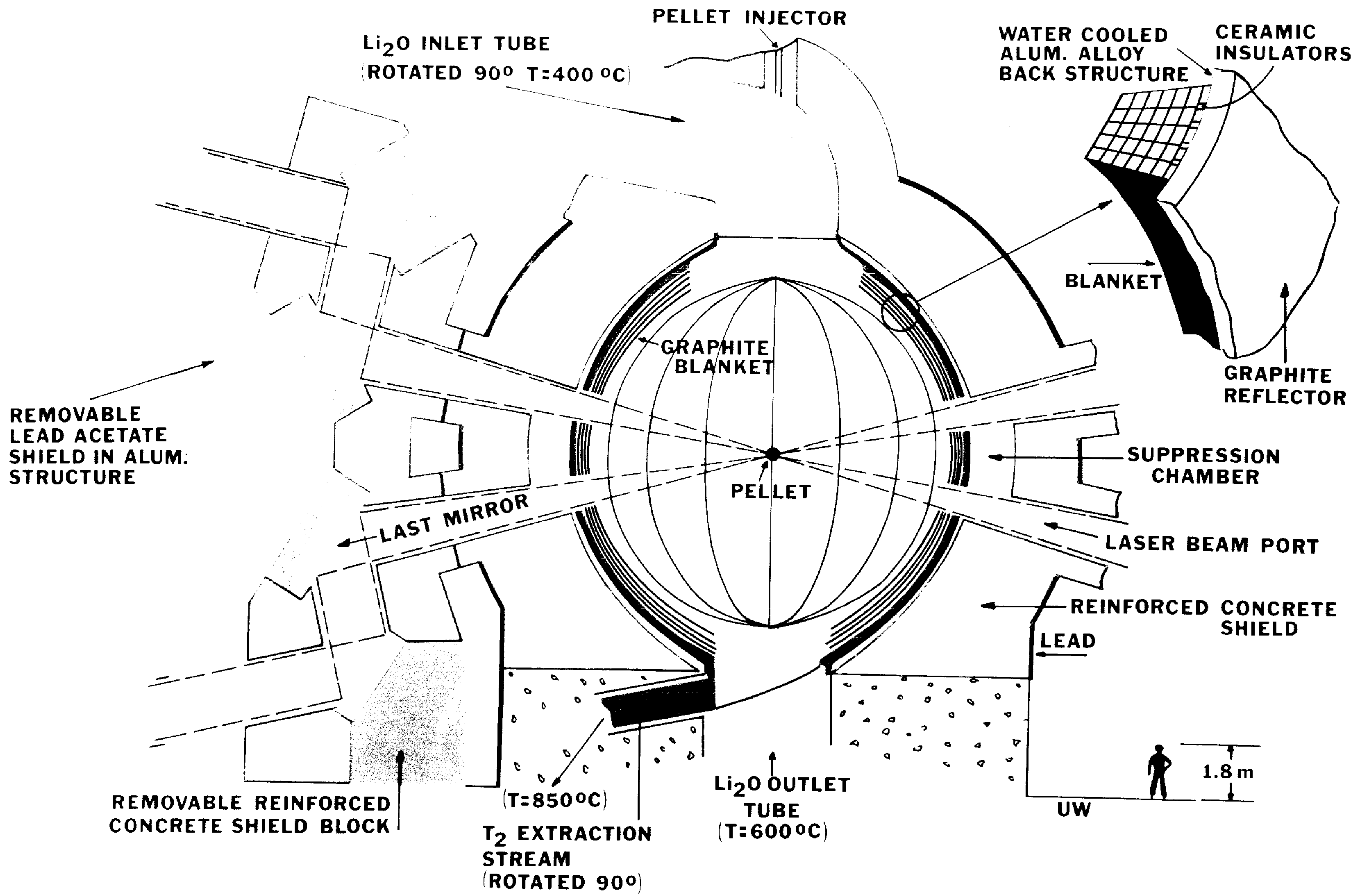

FIGURE 2

SCHEMATIC OF GRAPHITE BLANKET SEGMENT FOR SOLASE

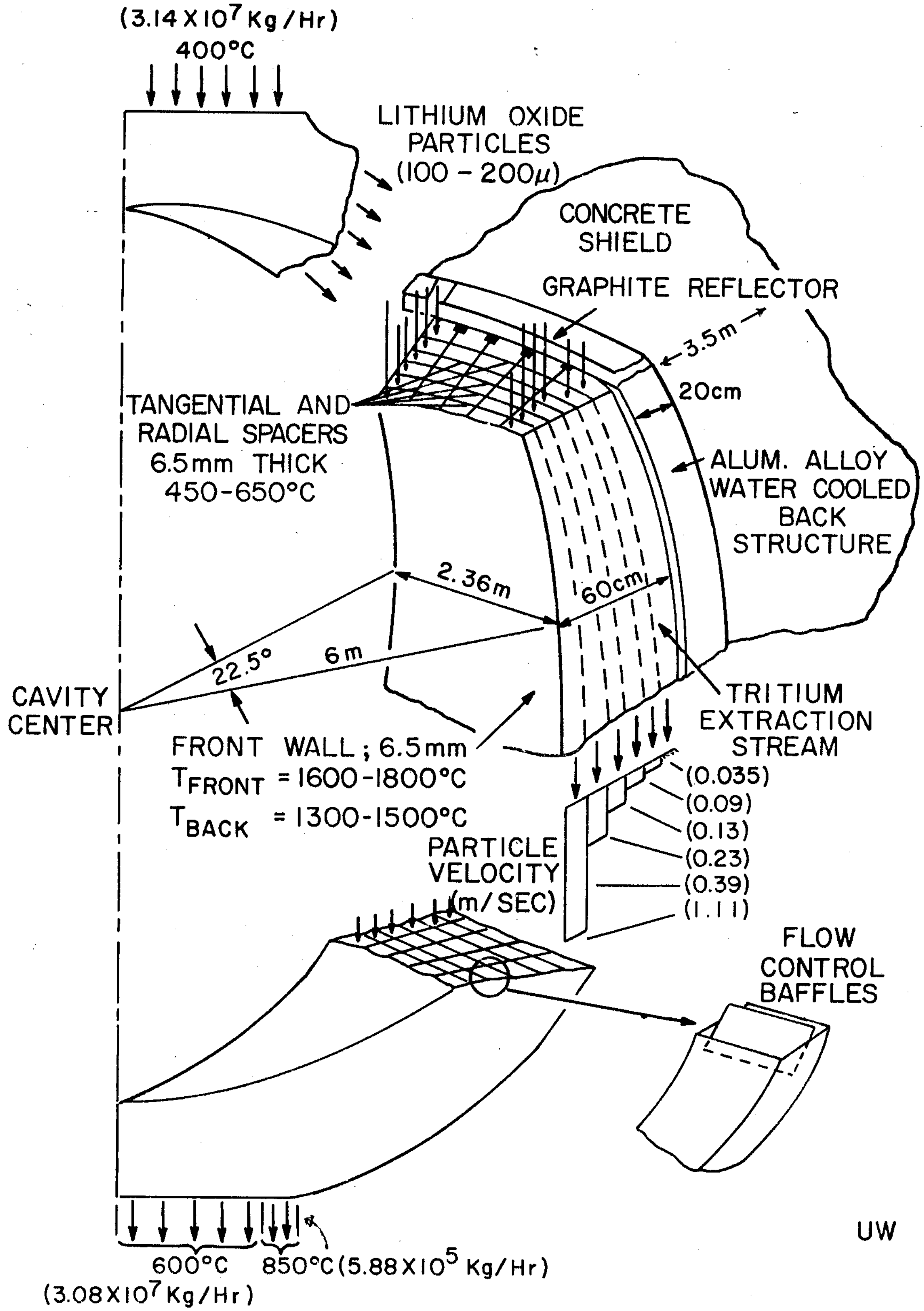

FIGURE 3

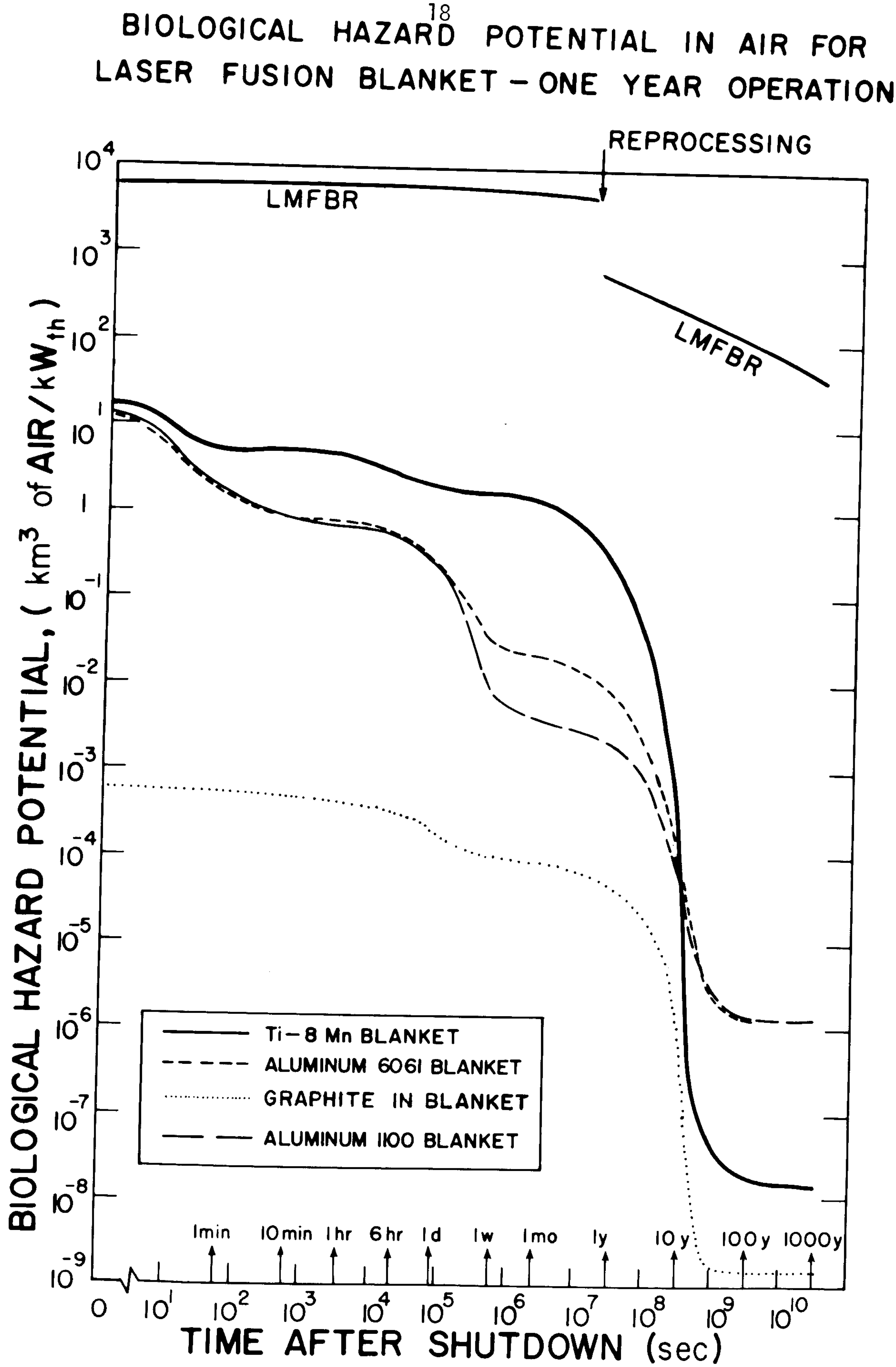
BIOLOGICAL HAZARD POTENTIAL IN AIR FOR LASER FUSION BLANKET - ONE YEAR OPERATION
REPROCESSING
LMFBR
LMFBR
BIOLOGICAL HAZARD POTENTIAL, (km3 of AIR / kWth)
10^4
10^3
10^2
10^1
1
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
Ti-8 Mn BLANKET
ALUMINUM 6061 BLANKET
GRAPHITE IN BLANKET
ALUMINUM 1100 BLANKET
1min
10min
1hr
6hr
1d
1w
1mo
1y
10y
100y
1000y
0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^10
TIME AFTER SHUTDOWN (sec)

Figure 4