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APPENDIX

DETAILED SUMMARIES AND CONCLUSIONS FOR DIFFERENT SUBSYSTEMS IN SOLASE

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Appendix

Detailed Summaries and Conclusions for Different Subsystems in SOLASE

A. Laser Pellet Physics and Pellet Design

The task of pellet design for SOLASE has been performed in a parametric fashion and no specific total pellet design is proposed. However, generic relationships that should guide the pellet design are developed. To study pellet physics, a plasma hydrodynamics-thermonuclear burn-radiative transfer computer code (PHD-IV) has been developed. This code represents the most sophisticated pellet modelling code available to the general scientific community. With this tool, thermonuclear burn propagation in bare compressed DT pellet cores has been studied by ignoring the compression phase of the process and beginning with the compressed core as an initial condition. The burn dynamics of compressed DT cores tamped with a compressed high Z material has also been examined. Charged particle and X-ray spectra resulting from the burn and explosion of these cores have been computed.

In addition to these results, the development of this code provided the opportunity to gain first hand experience in the detailed problems of laser fusion pellet modelling and we have used it to model the implosion of DT shells to thermonuclear conditions. The results were used to "normalize" a simple analytic description of the "energy economics" of pellet implosion and burn to determine the feasibility of laser fusion for reactor applications. The conditions necessary to burn advanced fuels has also been examined.

The main conclusions from these studies are as follows:

1. The pellet performance required for SOLASE (i.e., $G = E_{TN}/E_L = 150$ with input energy of 1 MJ) is possible but difficult to achieve. Laser light absorption (50%) and hydrodynamic implosion (5%) efficiencies are too low for gains of 100-200. Recently reported pellet designs[1] offer the possibility of achieving gains of 150 (or even much more) if they prove to be successful. These pellets are really two single shell pellets, one inside the other. The DT fuel is located in two different parts of the pellet. The massive outer shell is imploded at a velocity less than that necessary for ignition and compresses the low density gas between the inner and outer pellet. This compressed gas acts as a spring and subsequently implodes the inner pellet at a higher velocity. The inner pellet implodes, ignites, and burns with a gain of about 50. The exploding inner pellet delivers 10 MJ of X-ray and ion debris onto the inner surface of the outer pellet, thereby igniting it. Burn then propagates through the more massive outer shell providing a total gain of possibly 500. Hence the inner pellet gain of 50 can be multiplied by 10 by "propagating" the burn into the outer

pellet where ρR is achieved by more DT mass rather than high compression. This is in fact an implementation of the ideas for high gain pellets given in Section III-G and first reported in the preliminary SOLASE design.[2]

Should such pellet design concepts be only marginally successful they may offer the possibility of achieving gains of at least 150, (i.e., that which is needed for the SOLASE concept). Should they be highly successful, their high gain would reduce the laser demands considerably, both in pulse repetition rate and efficiency.

2. The maximum gain-on-core is achieved for a fuel ρR value of 3 g/cm^2 and a hot central microcore with $\rho R = 0.4\ g/cm^2$. For 1 mg of DT fuel, the gain on core is 4800.

3. The fractional burn-up of the fuel at 3 g/cm^2 is 31%, implying a specific yield of 100 MJ per milligram of DT compressed to 3 g/cm^2.

4. The maximum gain-on-core scales as $(M_{DT})^{1/3}$ for DT masses greater than 1 mg.

5. Conclusions (2), (3), and (4) imply that inertial confinement systems will offer much better energy economics if a larger laser (or other) driver) input energy and pellet yields can be used. For instance, an input energy of 10 MJ, rather than 1 MJ, will greatly increase the likelihood of achieving a gain of 150. Conversely, if a gain of 150 is achievable with 1 MJ of input energy, then the equivalently optimistic gain at 10 MJ is 279. This gain reduces the recirculating energy fraction for a 6.7% laser from 25 to 13%.

6. The burn dynamics of bare and tamped pellet cores is significantly different. In the case of a bare core the DT becomes transparent and the radiation escapes. For tamped cores, radiation is trapped, thereby raising the temperature and pressure inside the core until it explodes.

7. Both tamped and untamped cores explode with a high fluid velocity ($> 10^8$ cm/sec) that corresponds to hundred's of keV per ion.

8. The X-ray spectra for tamped cores varies as a function of the ratio of tamper to fuel mass. For ratios between 1 and 10 the spectrum actually becomes harder because the fuel is burning at a higher temperature. For higher ratios the spectrum becomes softer due to down conversion in the high Z material. A large fraction of the X-ray energy is in photons with energies greater than 1 keV even for tamper to fuel mass ratios of 100.

9. The fraction of total energy in X-rays is between 1 and 10% and peaks for mass ratios of about 10. The bare DT core has 1% of its yield in X-rays. For mass ratios greater than 10 the fraction again decreases.

10. The charged particle and X-ray energy fractions and spectra depend upon the fuel and tamper density profiles at ignition. Since implosion calculations of tamped fuel were not done, this situation is studied parametrically.

11. Implosion calculations of DT shells using the perfect pulse shape to achieve isentropic compression indicate that small deviations from the perfect pulse have catastrophic consequences. The most sensitive parameter is the initial intensity of the energy input because this determines the adiabat along which the implosion will take place. Differences in initial plasma temperature as little as 1 eV produce pellet yields differing by 2 to 3.

12. Burning D-D in inertial confinement systems appears to be very difficult because of the high values of ρR needed to support burn propagation. Input energies of 100 MJ appear to be necessary. However, recycling of unburned tritium (a DD reaction product) into the pellets could reduce these requirements considerably. Burning p-^{11}B requires even greater values of ρR (500 g/cm^2) and a very high ignition temperature (300 keV). To achieve such ρR values requires unrealistic compressions or fuel masses that imply unrealistically large input energies and yields. Hydrodynamic implosions cannot generate the necessary ignition temperature. Some other method must be developed.

13. The success of laser driven implosions depends sensitively on many non-linear coupled processes. To achieve isentropic compressions requires that each process (laser absorption, thermal conduction, fluid dynamics) is accurately modelled to within a few percent. This is complicated by the existence of non-thermal particles (electrons and photons) with long

characteristic mean free paths. These must also be modelled properly. The current understanding of these processes is inadequate to formulate such models. Recent experiments have generated considerable information but the degree of detail in even the best pellet modelling codes is inadequate. This inadequacy is due in large part to the extremely large computing times needed to simulate such processes in sufficient detail. (This is true for even the fastest computers available today). Future pellet designs must exhibit a reduced sensitivity to the detailed laser absorption, thermal conduction, hot electron generation and transport and fluid instabilities to have a reasonable success probability for fusion reactor applications.

B. Lasers for Laser Fusion and for SOLASE

The current estimates of the laser requirements for laser fusion were given in chapter I. We have performed a survey of three "proven" lasers, I, HF, and CO_2 giving characteristics, advantages, disadvantages and possible improvements for each. A survey of potential laser candidates is also given including various excimers, group VI lasers, and mercury-mono-halides. On the basis of this work, a decision was made to use the parameters of the CO_2 laser as the basis for a generic design of a laser for SOLASE. From our general analysis, the conclusions are:

1. No laser presently known will obviously meet the requirements for laser fusion but several lasers can probably be scaled to meet minimum requirements for energy (1-4 MJ), power (100-1000 TW) and pulse width (1-10 ns).

2. There are few lasers that have the potential to achieve an efficiency greater than 1 or 2%. If a power plant can be designed to operate with a laser of this efficiency then the number of potential laser candidates increases substantially and the chance of finding a suitable laser should also improve. Lasers with 1-2% efficiency demand pellet gain in the 500-1000 range in order that the plant have acceptable thermal efficiency and large power supplies.

3. If the pulse width can be longer than 1 nsec, the design of a laser would become easier and in some cases efficiency would improve.

4. 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.

The laser for SOLASE is designed as a generic gas phase laser wherever possible and is modeled after the CO_2 system when a more specific design is required. The SOLASE design requirements are that the laser be 6.7% efficient, fire at the rate of $20s^{-1}$, have an output energy of 1.1 MJ (1 MJ on target) with an optical beam energy density of 5 J/cm^2 maximum. The final amplifiers, the master oscillator, the gas handling system, and the power supplies have been studied in detail. In addition, questions of component lifetime and reliability have been considered including topics such as redundancy, modularization, on-line repairs, and rapid fault detection. The conclusions from the specific study of a laser for SOLASE include:

1. The laser design for SOLASE is generally representative of a "typical" laser for laser fusion applications.

2. Areas that will present difficulties in scaling up include optical isolation, beam quality, and pulse shaping.

3. Solutions to above problems tend to be specific to a given laser so that no absolute statements can be made about the ability to develop a laser fusion laser. However, ignoring power supply and beam transport problems, there appear to be lasers such as CO_2 and I that can be scaled to meet energy (1 MJ), power (1000 TW) and pulse width (1 nsec) requirements. On the other hand, no conclusion is possible on whether a laser

can be developed to meet the wavelength, efficiency, and pulse shaping requirements, particularly because the wavelength and pulse shape requirements remain ill-defined.

4. The state-of-the-art lifetimes for power supply components such as capacitors and switches are presently inadequate for laser fusion applications.

5. Capacitor failure generally results from breakdown of materials due to electrical and thermal stresses. It appears that the lifetime can be improved by improving materials and reducing stresses by redesigning foil placement and foil-terminal connections, by decreasing the energy density and using active cooling.

6. Switches must stand-off high voltages, carry large currents, have low inductance and resistance, close on command, and operate repetitively. Currently only spark gaps and semiconductor switches approach these requirements.

7. Spark gaps fail because of electrode erosion, degradation of the dielectric, cracking of the housing, and failure to stand-off voltages. These areas can be improved by developing better materials, decreasing the erosion rate, reducing the power loading, flowing the dielectric, using active cooling and cleaning.

8. Semiconductor switches have relatively low current and voltage capabilities and must be laser triggered for rapid enough risetimes. They fail because of damage to materials caused, for example, by carrying too high a current density. For laser fusion applications, they must operate in large parallel and series arrays. Adequate lifetimes have been demonstrated for slow risetime switches. This must be verified when the risetime is short, as required for laser fusion applications. These switches appear to be the most promising.

9. A sophisticated fault detection system will be required for the laser.

10. The exact lifetime requirements for all laser and power supply components must be about 10^9 shots. This is several orders of magnitude beyond the present state of the art but the question of lifetime has rarely been important in experiments and substantial improvements should be possible given the R and D effort.

C. Illumination and Optics Design

A study of the requirements to provide greater than 90% uniform illumination has been done. The methodology for the study is to vary the number of beams, N, the focal shift or beam overlap angle, the f/no. of the last mirror, and the laser beam profile. Given N, the f/no. is determined by the total solid angle allotted to optics, typically taken as 10%. Minimum aperture area is determined by damage threshold to last mirrors and 5 J/cm^2 is used. The focal distance is determined by the chamber size.

1. The results show that 20 beams are only slightly better than 12 beams in uniformly illuminating the target but that 8 beams will not work. More generically, we find that the requirements for uniform illumination are not consistent with the reactor requirements for accessibility, small solid angle devoted to beams, reasonable last mirror size (mirror diameter less than 3.5 m), and mirror protection from pellet debris. It appears that pellets requiring uniform illumination will not be feasible for reactor applications.

The final design for SOLASE is based on 12 beam, two sided illumination. The final mirrors are to have the shape of off-axis paraboloids. These can presently be rapidly and inexpensively produced with the diamond-turning method. However, the literature on paraboloids is sparse. The classical theory of aberrations does not apply to far off-axis rays and most packaged ray-tracing codes provide no insight. Using geometric optics, we have calculated analytically the image shape of a circular beam, the target intensity, and the effective f/no. Tilt error criteria for roll, pitch and yaw rotations are developed and the perturbed target intensity under a pitch tilt (in medium plane) is calculated based on a new expression for the caustic curve.

2. Results of the study are that the image is very nearly circular for moderate f/no. and that the optical axis is shifted from the centroid of the reflected beam. The effective f/no. is nearly independent of turning angle while tilt errors depend only weakly on this parameter. The perturbed intensity is less severe for smaller turning angles.

3. The last mirror can be diamond turned Cu on an Al substrate. Such mirrors can be constructed with present day technology. An analysis of the mechanical design shows the important characteristic to be a high ratio of flexural stiffness to weight in order to minimize transverse deflections and slope changes. Solid mirrors would be prohibitively massive and a rib-stiffened design could have unacceptable local deflections. The best configuration, as used in SOLASE, is to use a sandwich construction where essentially two face plates are separated by a light core such as an aluminum honeycomb.

4. The last mirror at 15 m from a target yielding 150 MJ per shot and ignited 20 times per second will not be affected by neutron bombardment or hard X-rays. The largest temperature change on the mirror face, using the

pellet spectra from PHD-IV, is about 20°C. The major issue is protection of the last mirror from the charged particle debris.

5. Feasible methods exist to protect the last mirror from charged particle bombardment. A specific design is used in SOLASE. Thus, it appears that a solid last mirror is feasible for use in laser fusion reactors. A major unresolved issue is maintaining proper alignment of the optical beam train in a way that is properly coupled to the target injection system.

6. The formation of color centers in dielectric coatings under relatively low neutron fluences may increase the absorption on mirrors to such a degree that they become unusable in short times. Such coatings are required if the laser wavelength is less than 0.8-1.0 μm and may therefore have a serious limiting influence on the acceptability of lasers in the 3000-6000 Å for use in a reactor environment.

D. Pellets for Laser Fusion Reactor Applications

As noted previously, a specific pellet design for SOLASE has not been developed but a generic target as described in Chapters I and IX has been studied. This target consists of frozen DT encapsulated by a glass or polyvinyl alcohol (PVA) shell. This shell is then surrounded by a high Z layer and there is a final low Z, low density ablative zone. We have reviewed the present status of laser fusion target fabrication and discussed the reactor aspects of pellet manufacture, storage, and delivery. The conclusions are:

1. Pellet costs appear to be dominated by tooling costs which can be amortized over the life of the plant. These costs appear reasonable for the generic target studied in SOLASE but the conclusion can be strongly affected by target design.

2. High volume processing of generic targets requires only limited extensions and modifications of well-established techniques.

3. The lifetime of cryogenic targets during delivery is a generic problem for all ICTR's.

4. Compatibility of pellet materials with cavity walls is critical and pellet designers should avoid the use of reactive materials. Oxygen should be eliminated if possible and the hydrogen content should be held to a minimum.

5. Fabrication of targets involves three main processes: permeation filling, cryogenic processing, and deposition techniques; all these techniques are used today.

6. The use of PVA capsules requires a protective layer between the frozen DT and the shell to prevent degradation due to radiation damage from β-particles. Xenon is particularly attractive for this purpose.

7. The total plant tritium inventory is highly sensitive to the DT filling time of the capsules. This in turn depends on the capsule material and PVA is much more advantageous than glass in this respect.

8. Storage of pellets is required because the manufacturing process is a batch process and because a store is needed to allow plant operation in the event of a failure. The storage is likely to be at cryogenic temperatures to minimize the out diffusion of the fuel. In addition, active cooling will be required to remove the β-decay heat.

9. Target injection and flight determination as well as coordination with the firing of the laser is sensitively dependent on conditions in the chamber. A complete analysis remains to be done.

E. Cavity Design and First Wall Protection

1. The cavity design for SOLASE is based on the use of neon or xenon as a buffer gas to prevent the charged particle debris from striking the first wall unimpeded. The neon pressure required is between 0.5 and 1 torr at 300°K. The momentum transferred to the wall is less than half the value one would calculate from simple strong shock theory, i.e., assuming all the energy becomes kinetic energy. The maximum overpressure at the first wall in SOLASE is thus only 90 torr. The energy deposited in the gas is transferred to the first wall by radiation and the characteristic time exceeds 1 ms. However, an exact time has not been evaluated because it requires a full radiation transport calculation. An experiment on this topic would be highly valuable.

The feasibility of the neon gas approach also depends on the pellet output X-ray spectrum. The K-edge in neon is at about 900 eV and there is a window in the absorption spectrum between about 100 eV and the K-edge.

The use of xenon removes this difficulty and acceptable X-ray absorption is found using 0.25 torr xenon regardless of the X-ray spectrum.

Laser induced gas breakdown is an important aspect in the feasibility of the buffer gas approach. Breakdown proceeds in the pressure range of interest by multiphoton absorption and data on this topic are sparse and conflicting. The result of our analysis is that breakdown will occur but that the consequences appear manageable for reactor size targets. Breakdown is sensitive to the type of gas, the laser wavelength, and the laser intensity. Targets that can operate with a peak intensity of 100 TW would produce no gas breakdown problems.

2. The use of multiple cavities, rather than a single cavity, was briefly investigated. The primary motivation is to increase the potential availability of the reactor. On the contrary, we have found the most reliability-sensitive subsystem is the laser rather than the reactor chamber. Multiple lasers and power supplies, while not economically attractive, would be preferrable to multiple cavities. The use of multiple cavities may however be necessary if the appropriate reactor chamber conditions for pellet injection take too long to re-establish.

3. 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 output spectra may not be optimum and will not make laser fusion appear as attractive as it might ultimately be.

4. The vacuum requirements of laser fusion reactors are modest and can be met with existing technology.

5. Unprotected dry walls will not survive the microexplosion at "economically reasonable" wall loadings ($\gtrsim 1\ MW/m^2$) for the following reasons:

(a) Excessive Thermal Ablation: Both graphite and metallic first walls (Mo, Ta, S.S.) will experience large surface temperature excursions since the ions and soft X-rays deposit their energy in a thin surface layer. Excessive ablation (> 1 cm/y) will take place.

(b) Sputtering: Sputtering will be significant (> 1 cm/y) since damage occurs at elevated temperatures. (Sputtering yields increase sharply as the surface approaches the melting temperature).

6. Spallation does not appear to be a problem since there will be no thermoelastic stress wave from ion energy deposition (because of the spread in arrival time). Also, if the X-ray spectrum is harder than ~ 1 keV only small amplitude transient stresses will be generated.

7. Hard X-rays produce a small surface temperature rise in the first wall. For example, with no residual gas, the SOLASE cavity can withstand about 7% of the energy yield in 1 keV black body radiation; the fraction increases to ~ 20% for 2 keV radiation.

8. The first wall temperature rise produced by the neutrons is insignificant (~ 2°C for SOLASE) because of the long neutron mean free path.

9. For short wavelength lasers with short pulses and high pellet reflectivity, the reflected laser light will cause excessive surface heating of the wall. For example, for a pulse width of 0.1 ns, the maximum tolerable pellet reflectivities for iodine ($\lambda = 1.3\ \mu$) and CO_2 ($\lambda = 10.6\ \mu$) lasers are ~ 7 and 18% respectively. These values increase to ~ 16 and 32% for a pulse width of 1 ns.

10. Ion bombardment of unprotected dry walls will cause excessive surface heating, evaporation, and sputtering. Without gas protection, the ions from a 150 MJ bare DT pellet would produce a surface temperature rise in the SOLASE front wall of ~ 2500°C; for a structured pellet with 10 mg Hg, the temperature rise is 2200°C.

F. Blanket Design

The blanket design in SOLASE is unique in many respects and attempts to take advantage of the unique aspects of laser fusion. It is not an adaptation of fission reactor design. The use of graphite is especially notable since the vacuum requirements are quite modest. Such an approach would be more difficult to apply to magnetic confinement reactors. Specifically, our conclusions are:

1. A flowing lithium oxide/graphite composite blanket allows the Li_2O temperature to be decoupled from that of the graphite. This permits the choice of an optimum operating temperature from the viewpoints of maximum lifetime, acceptable particle temperatures, and tritium recovery.

2. Tritium breeding is adequate in Li_2O without the need for a neutron multiplier.

3. The blanket can operate at low pressures, low stress levels, and moderate lithium oxide flow velocity.

4. The lithium oxide acts as a heat transport medium (rather than as a coolant) and is efficient in this regard.

5. The induced radioactivity levels of the blanket are very low at long times after shutdown. A comparison of biological hazard potential between the SOLASE blanket and decaying spent fuel from an LMFBR show the levels in SOLASE to be 10^{-8} of the radioactivity levels from LMFBR spent

fuel at 50 years after shutdown. This includes reprocessing of the LMFBR fuel after one year.

6. The stress levels in graphite produced by differential swelling are adequately relieved by irradiation creep. The blanket lifetime appears to be about 1 year at 5 MW/m^2 wall loading but blanket replacement does not appear difficult in the open geometry of a laser fusion system. The most severe stresses in the blanket structure arise during reactor shutdown and are due to the reversal of thermal stresses.

7. The general attractiveness of the blanket design approach developed here suggests that further experimental investigation of the concept be explored. In particular, one must examine the fabrication of sufficiently pure Li_2O microspheres, the temperature decoupling concept, and the flow characteristics of a circulating Li_2O system.

G. Radiation Effects to Materials

G.a. The Blanket

For the purpose of structural analysis of the blanket and its lifetime determination, models have been developed for the radiation-induced dimensional changes of graphite, for the change in the elastic properties, and for the change in the tensile strength. It is found that the porosity P of graphite can be described by the equation

$$P - P_o = \frac{AF^3}{P_o/C+F^2} - P_o \, [1 - \exp(-CF)]$$

where P_o is the original porosity, F the displacement damage, and A and C are temperature-dependent functions. The graphite strength can be related to the elastic modulus and the change in this modulus can be computed from the porosity P.

A self-consistent inelastic analysis has been performed on the blanket structure which follows the distribution of the stresses (during on and off power) and the distribution of the tensile strength as a function of time. The lifetime criterion is that the stresses should not exceed 50% of the tensile strength at any time.

The major results of the inelastic analysis on a graphite structure in SOLASE can be summarized as follows:

1. The structure must not be rigidly restrained at its boundaries in order to avoid excessive thermal and swelling stresses.
2. Stresses generated internally by differential shrinkage and growth are sufficiently relieved during operation.
3. However, stresses on shutdown, mainly due to the reversal of thermal stresses, are life limiting.
4. The safe limit of the tensile strength reduces with increasing growth of the graphite porosity. This represents the other life-limiting factor.
5. Low-density graphite develops tensile stresses due to excessive shrinkage which when added to the reversed thermal stresses exceed the allowable tensile strength very early in life.

From these results we can draw a number of important conclusions. The graphite structure must either be manufactured from a high-density material (~ 5% initial porosity) or, possibly, a tailored density distribution must be achieved so that the dense graphite is in the high-flux and medium temperature region (~ 1000°C). The mechanical connections between the blanket structure and its surrounding support structure must be flexible. These two basic requirements are well within the range of present-day technology. Nevertheless, the behavior of graphite under irradiation was based on models which need further experimental verification in particular with regard to irradiations at high temperatures (> 1200°C) and high fluences (> 10 dpa). Since the extrapolation of graphite behavior under irradiation is rather modest in this study, the results indicate that graphite is a suitable structural material for the blanket of fusion reactors and lifetimes of about one year or more are realistic.

G.b. The Lithium Oxide

For the assessment of this problem, the same model was used that describes successfully the densification of uranium oxide fuel in LWRs. Our analysis shows that radiation-enhanced densification in Li_2O will not occur because the stopping power of the recoiling atoms is too small to result in localized melting.

G.c. Radiation Effects to Dielectric Coatings on Mirrors

A preliminary survey has shown that dielectric materials are much more susceptible to radiation damage than metals. Color centers of many kinds and with different absorption bands are readily produced by the neutrons, by transmutation products, and even by X-rays. The presence of color centers drastically reduces the transparency of dielectric coatings.

Irradiation also leads to substantial density changes. This will result in the generation of stresses in the coatings and in a change in their refractive indices. The latter may again induce enhanced absorption by laser light.

The collision cascades produced by 14 MeV neutrons have dimensions similar to the coating thickness. Localized absorption of light may lead to further damage and the process may then spread continuously with every laser pulse.

In sumary, it appears that radiation damage to the dielectric coatings may pose a severe problem when short wavelength lasers (λ_L < 8000 Å) are used in inertially confined fusion reactors.

H. Tritium

1. The tritium inventory in laser fusion reactors strongly depends on target design. For the generic targets with glass or polymer encapsulation we have discussed, the inventory is determined by the fill time of the targets. In this respect, when permeation filling is used, the use of glass encapsulation can more than double the plant tritium inventory. A more definitive analysis of this problem must await clarification of the target design.

2. The blanket tritium inventory in SOLASE can be on the order of 1 kg. The exact method of tritium recovery will depend on the purity of the Li_2O, the value of the tritium diffusivity, and the porosity of the Li_2O microspheres.

3. Tritium release rates from the plant through the steam generators and reheaters appears to be acceptably low. This rate is 4-6 Ci/day or 40-60 nCi/l of water. Thus it appears the Li_2O blanket concept is compatible with a power cycle that does not have an intermediate loop.

4. 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. While we have analyzed the issue for several pellet designs in SOLASE, more information on pellet composition will be required before a firm assessment of the difficulties here can be made.

I. Mechanical Design and Blanket Replacement

1. A general advantage of laser fusion reactors is that the reactor cavity and blanket are not surrounded by complex magnet systems greatly improving access. 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.

2. A procedure is proposed for blanket replacement which is within present day technology because of the ready access to the chamber, the simplicity of the blanket design and the fact that entire blanket segments of graphite are simply replaced rather than maintained. In addition, the low levels of radioactivity after shutdown can allow limited hands-on work about one week after shutdown.

3. The down time to replace blanket sections can be short and the graphite itself is inexpensive. The method proposed to fabricate the graphite composite blanket segments must be verified.

J. Neutronics

1. The time dependence of the radiation damage can be important in determining materials behavior. The normal procedure for calculating this

information leads to negative angular and scalar fluxes when the source is highly anisotropic. Procedures have been developed to correct this problem and a correct computation predicts a peak atom displacement rate in graphite that is 6 m from a 150 MJ microexplosion of 1.65 dpa/s.

2. Steady state neutron transport calculations, adequate to predict integral parameters, shows that breeding is no problem in a graphite/Li_2O system. For SOLASE, the total energy per fusion event is 18.83 MeV.

K. Radiation Leakage Reduction

The radiation levels at the containment building exit are considered here as unacceptable. The radiation could not be tolerated in the laser building and cannot be attenuated by material zones, since optically transparent media will be damaged (in optical performance) by the radiation.

To increase the attenuation, the path must be made either longer, more constricted with additional bends, or some combination of these. However, each approach adds costs and has an adverse effect on the optical performance.

The following ideas have been suggested as specific approaches to the streaming problem.

1. A major cause of the observed leakage problem is simply that the ducts are too large. The penetration is 240 cm in diameter, offering long paths for the leaking particles. It has been reported that the neutron flux is approximately proportional to d^4, where d is the characteristic dimension of the penetration cross section. Thus, one can suggest:

a. Increasing the number of beams. This will lead to a smaller characteristic dimension of the penetration and to a better uniformity in pellet illumination. If a circular beam is divided into n equivalent beams so that the beam cross sectional area is preserved, the surface area of the penetration is also increased by a factor of $\sqrt{n}$, leading to more absorption of the leaking radiation in the walls. This approach may have an adverse effect on access and maintenance.

b. Controlling the cross sectional shape of the laser beam. Elongated rectangles and annular beams will have a smaller characteristic dimension d, and subsequently decreased leakage.

c. Beam cross-over. Use of cylindrical-parabolic mirrors allows a line cross-over, and use of spherical and paraboloid mirrors allows a point cross-over of the beam. Around the cross-over region, shielding can be provided with a minimal characteristic dimension for the penetration. The use of this approach may be limited by the particular design adopted. For example, the SOLASE design called for first-wall protection in the cavity against X-rays, charged particles, and pellet debris by use of a xenon or neon fill gas. A sharp focus would result in breakdown in the gas. The possibility of using a fuzzy focus as a means of pratically achieving the constriction of the penetration has been examined. This may work, although data for gas breakdown in the presence of radiation is not adequate for definitive conclusions. There is also the possibility that a plasma in the focal region can be tolerated. Other wall protection schemes such as magnetic protection may be better in this respect.

2. Use of flux traps. This is a standard shielding technique, where the surface area of the penetration seen by both the detector and source is minimized. Tapering of the penetration wall can be used. The particles in the flux traps scatter several times, lose their energy, and get absorbed in the penetration liner, rather than directly leaking through the duct.
3. Use of extra mirror reflections. This leads to extra segments in the duct, decreasing leakage.
4. Use of multiple reflection catotropic optics,after the flat mirror, is expected to appreciably reduce leakage.
5. Use of smaller turning angles. This leads to smaller size mirrors and subsequently smaller subtended solid angles by the last optical element.
6. Iris type rotating choppers can be used to mechanically close the duct at times when the laser beam pulse is not travelling through it. This is only possible at low microexplosion repetition rates.
7. Locating the last mirror further from the cavity center (large f-number optics) as adopted by the Lawrence Livermore Laboratory Group is the most effective direct way of reducing the solid angle of the duct. Recourse to this approach has limits and must be a last resort, since it increases the size of primary containment and cost, and leads to problems regarding alignment and focusing of the beams in a plant vibration environment.

8. Use of gas refraction lenses which use supersonic gas streams to set up a density distribution, forming a prism of higher index of refraction material, will bend light, but not neutrons or debris.

Our analysis and modelling of a laser reactor penetration identifies the radiation leakage problem as a major area of concern.

L. The Power Cycle

1. The high Li_2O blanket exit temperature (600°C) allows the use of a high temperature reheat steam cycle with an overall thermal efficiency of 42.9%. Operation at this high temperature should be possible in view of the high melting temperature for Li_2O. The presence of low melting impurities in the Li_2O may necessitate lower-temperature operation to avoid particle agglomeration and flow maldistribution.

2. The energy deposited by the hot gas leaving the chamber into the suppression chamber coolant is utilized in a low pressure saturated steam cycle with a thermal efficiency of 21.1% which reduces the overall plant thermal efficiency to 41.8%.

3. Steam generator design is within present technology but experimental verification of heat transfer data from gravitational flow of particles is needed.

4. The use of Archimedes pumps to transport the Li_2O particles offers many advantages including low particle attrition, low power requirements, compatibility with blanket pressure, and simplicity. Design of these pumps is within present technology but again experimental verification is required to allow scale up.

5. The use of lithium oxide as a primary coolant may eliminate the need for an intermediate heat exchanger. Tritium leakage from the Li_2O to the steam side is well below release limits. The use of double-walled steam generator tubes with continuous monitoring of a He gap allows detection of tube failures or leaks to prevent Li_2O/water reactions.

6. The relatively large recirculating power fraction (28% in SOLASE) is characteristic of inertial confinement fusion systems where the driver is inefficient and the produce of driver efficiency and target gain is about 10. Of course, inefficient lasers can be countered with very high gain targets ($G > 500$) but if the laser energy required to permit such targets to work is 1 MJ or greater, the very large target yield will pose unique cavity design problems and the low laser efficiency will imply large power supply requirements and thus high laser costs.