5.4 Key Issues Description

This section provides more detail on the key issues previously identified in Section 5.2, Table 5.2-1. The same designation noted in Table 5.2-1 will be used in this section. Each issue will be described in depth, followed with more detail regarding each of the table entries. The same abbreviations and notations explained in Section 5.1 and used in Table 5.2-1 are used in this section. Some of the issues have substantiating analyses.

Issue A. Target

A.a Target Physics

Issue A.a.1 Direct Drive Target Coupling

Description - Absorption of driver radiation by direct drive laser targets is a complex process involving inverse bremsstrahlung, resonance absorption and various light scattering instabilities such as stimulated Brillouin scattering (SBS), stimulated Raman scattering (SRS), laser light filamentation and two plasmon decay (TPD). These processes occur both at the critical surface and in the volume space about the target. All of these processes can play a potentially critical role in affecting the uniformity of direct drive illumination and target coupling efficiency.

It is now believed that illumination nonuniformities in IFE reactors must be kept below 1% to avoid the excitation of hydrodynamic instabilities. This is a difficult technical requirement in view of the fact that on the order of half a million targets per day must all be accurately illuminated by approximately 60 laser beams. These targets will not be mounted on stalks and accurately positioned before each shot as has been done in previous laser fusion experiments. Rather, they will be injected into the reaction chamber with the aid of pneumatic, electromagnetic, centrifugal, or other accelerating devices. Inaccuracies will inevitably occur in this complex process in the form of slight variations in injection velocity, beam pointing errors, etc. It is necessary to consider all these factors in judging the technical feasibility of a reactor design.

Reactor Concept - Laser and Heavy Ion

Potential Impact - (DW, UL, RP) The design window may be closed if a beam arrangement cannot meet illumination symmetry requirements under realistic conditions. Unavoidable beam pointing and target injection errors may result in unacceptable reliability even if a beam arrangement would work under ideal conditions. Failure to meet symmetry requirements would reduce system performance by forcing the reactor to operate on a less favorable gain curve.

Design Specificity - (Generic)

Overall Level of Concern - (Critical) Unpredicted target coupling deficiencies are not expected to lead to a gradual drop off in target gain. Instead, because of the physics of implosion, hot spot generation and propagating burn presently envisioned for all reactor types, failure would be sudden and catastrophic.

Operating Environment - (H, L, TWI, G, N) Tritium inventory will be affected by the efficiency of target burn. Laser type and wavelength will influence coupling efficiency more than choice of heavy ion driver design parameters. Poor target coupling can lead to incomplete vaporization and the generation of solid target debris. Beam geometry will affect coupling efficiency. The severity of the technical problem is increased by the need for cyclic operation.

Degree of Relevance to MFE - None

Analysis - A code has been written to analyze the problem of target coupling efficiency. Results obtained to date will be reported at an upcoming IEEE conference.

Issue A.a.2 Indirect Drive Laser Target Coupling

Description - The indirect-drive IFE laser target design consists of a cryogenic DT fuel capsule located inside a radiation-enclosing cavity (or hohlraum) designed to accomplish the following three goals:

(1) Convert the incident laser energy efficiently into soft X-rays,
(2) Using the particular shape of the hohlraum enclosure, these soft X-rays are focused into a uniform irradiation of the cryogenic DT fuel capsule,
(3) Uniform irradiation (and consequent absorption) of the soft X-rays by the DT fuel capsule leads to ablation and the resulting rocket reaction produces a uniform DT target compression permitting the interior of the DT Target to reach values of ρr (product of density [ρ] and compressed target diameter [r]) with 3/2kT ~ 25 KeV adequate to achieve rapid fusion of the fuel via the reaction:

$$_1D^2 + _1T^3 = _2He^4 + _0n^1 \text{ (14 MeV)}$$

A number of problems have been identified with achieving these three indirect-drive laser driven (IDLD) IFE target goals.

Attainment of Goal #1 - Goal #1, the efficient conversion of incident laser energy into soft X-rays is hampered by the physical structure of current ID LD targets. Access of the incoming laser beams to the hohlraum wall is attained by transmitting the high power laser beams through two small apertures (in the case of 2-sided laser illumination scenarios) in the radiation-opaque ID LD target casing. Great care must be taken to avoid allowing high intensity portions of the incident laser beams to irradiate the opaque ID LD target casing.

Previous research has demonstrated that the interaction of the high power laser light with the edges of the entrance apertures to the hohlraum produces sufficient densities of plasma above the critical density to reduce the transmission of laser light significantly into the ID LD target capsule. This plasma closure process is time dependent.

Attainment of Goal #2 - Uniform irradiation of the DT target with the soft X-rays generated by the target represents a difficult technical problem requiring the simultaneous achievement of homogeneous X-ray conversion together with isotropic illumination by the quasi-ellipsoidal optical figure of the radiation enclosure itself. Physical optical analyses of such homogeneous irradiation have indicated that a high degree of DT target irradiation uniformity is very difficult to achieve in certain design configurations.

Attainment of Goal #3 - DT target implosion, avoiding any significant Rayleigh-Taylor instabilities, is a complex magnetohydrodynamic process requiring stringent initial conditions on the irradiation uniformity, spectral distribution of the incident X-rays, avoidance of target preheating by hot electrons or hard X-rays, etc. The achievement of this goal is crucial to the success of both indirect-drive and direct-drive laser IFE targets.

Reactor Concept - Laser

Potential Impact - (DW, RP, IC, RS) The design window may be closed if the majority of the laser light cannot propagate into the hohlraum for efficient soft X-ray conversion. This would necessitate increased laser irradiation energies, shortening of the laser pulse duration, etc. If the optical figure of the hohlraum radiation enclosure is unable to provide uniform irradiation of the DT fuel capsule, high yield will not be obtained from the target implosion. This would force the IFE reactor to operate at a lower efficiency.

Design Specificity - (Generic)

Overall Level of Concern - (Critical) Low conversion efficiency of incident laser light by the target may result in the laser light interacting strongly with the plasma cloud generated around the IFE target. These laser/plasma interactions may result in the generation of hot electrons and hard X-rays which may cause catastrophic target preheat, leading to enormous fluctuations in IFE reactor output power.

Operating Environment - (L, TWI, G, Q, N, I, S, F, T, q, s, t) Operating power for the laser driver will be strongly affected by the target coupling efficiency and target yields. The tritium inventory will be affected by the target yields. Poor target coupling for indirect drive targets can lead to additional debris problems. Enlargement of the hohlraum may lead to increase in contaminants if materials other than Pb are used.

Degree of Relevance to MFE - None

Analysis - Several codes are available to analyze the problems of indirect-drive laser IFE target physics. These analyses must be anchored to realistic laser IFE experiments before the issues can be resolved.

Issue A.a.3 Survivability of Targets in Chamber Environment

Description - The chamber environment is hostile to the cryogenic integrity of the target and could even potentially cause significant ablation of the target surface. The precise physical conditions which will exist in an IFE reactor chamber is still a very open question. The evaporation/recondensation issue requires realistic experimental investigation for its resolution, and the radiation background will likely be non-LTE for much if not all of the cycle. However, parameter studies can be undertaken to find when chamber conditions become a serious threat to target survival.

Reactor Concept - Laser and Heavy Ion

Potential Impact - (DW, RP) If the present projections of chamber temperature, pressure, and radiation background prove overly optimistic, the cryogenic survival of the target in the chamber may be threatened.which would have a deleterious effect on system performance.

Design Specificity - (Generic)

Overall Level of Concern - (High) Target designs should protect the cryogenic fuel. It appears that significant departures from presently projected chamber conditions would be necessary for significant deterioration of target performance to occur.

Operating Environment - (S, T, A, G, Q, t, q, P, v) All factor which affect conditions in the chamber have an impact on target integrity. Background radiation and pressure are key factors.

Degree of Relevance to MFE - (Low) There is some similarity between this issue and the issue of ablation from the cryogenic pellets which may be used to refuel MFE reactors.

Analysis - Analysis of the question is presently being conducted by the team with the aid of a 3D hydrodynamics computer code. A parameter search is planned which will show at what levels various chamber conditions begin to pose a threat to the target. At the same time, the study will determine the ability of background gases in the chamber to affect the trajectory of the target. This work is not yet finished.

Issue A.b Beam/Target Interaction

Issue A.b.1 Demonstration of Injection and Tracking of Targets Coupled with Beam Steering

Description - According to the Target Working Group, illumination nonuniformity must be kept below 1% rms. This means that injection and tracking must be sufficiently accurate to keep target mispositioning at less than 0.1 of the capsule radius during illumination. Assuming the target is exactly where is should be, beam mispointing errors must also be kept below about 0.075 of the target radius to assure adequate illumination uniformity. To meet these stringent requirements, some sort of a real time tracking system along with electronic beam steering is necessary.

Reactor Concept - Laser and Heavy Ion

Potential Impact - (UL) Symmetric implosions are critical to the success of inertial fusion. Excessive departures from adequate illumination symmetry will not lead to a gradual fall-off in target gain. rather, gain will show a steep drop to near zero levels if generation of hydrodynamic instabilities disrupts the implosion process.

Design Specificity - (Generic)

Overall Level of Concern - (Critical) Unless adequate illumination symmetry can be guaranteed, IFE is technically out of the question.

Operating Environment - (A, TWI, P) Cavity dimensions will have an affect on the impact of small deviations in injection velocity. Target failure due to beam mispointing and injection velocity errors will lead to the generation of solid target debris. Fluctuations in background pressure could potentially affect target velocity.

Degree of Relevance to MFE - (Low) Injection systems must also be used in MFE solid cryogenic pellet refueling schemes. However, although accurate pellet trajectories are important, they are not as critical as in IFE.

Analysis - A code has been written to study the effects of various combinations of injection velocity errors and beam mispointing on IFE reactor performance. Results obtained with the code will be provided as they become available.

A.c Fabrication

Issue A.c.1 Manufacturability of High Quality, Low Cost DD and ID Targets

Description - Previous target production for ICF has been in very small batches, often with each target custom made. Inspection for flaws in surface finish, concentricity and thickness could be made almost at leisure. Fusion energy generation will require the production of hundreds of thousands of targets of uniformly high quality ever day. These targets must be produced with a low turn around time to avoid high tritium inventories. Efficient fill techniques must be demonstrated for reactor size targets. The ability to create uniform fuel layers using the beta heating process or some other procedure must be demonstrated. The feasibility of using artificial intelligence and mechanization for accurate mass inspection must be proved. For an indirect drive target, a case must be mated to the capsule, probably under cryogenic conditions, which assures symmetric burn while at the same time providing a sufficiently robust overall configuration to survive acceleration and transit through the target chamber.

Reactor Concept - Laser and Heavy Ion

Potential Impact - (UL, RP, IC, RS) To avoid high tritium inventories it is advisable to produce targets on a "just in time" basis. Therefore, if any of the major steps in the production process proves unreliable, reactor shutdown would result. Failure of inspection and quality assurance procedures to assure uniformly high quality targets would result in lower gain and poor system performance. Targets must be manufactured cheaply or the large consumption of targets will lead to excessive costs. Target manufacture will require the presence of large tritium inventories in the factories. Rapid fill rates and efficient beta heating must be demonstrated to assure that these inventories do not become excessive.

Design Specificity - (Generic)

Overall Level of Concern - (High) Resolution of this issue will mainly affect the issue of cost. Inability to produce targets efficiently will not preclude the generation of fusion power. It will simply make it economically unattractive.

Operating Environment - (H, TWI, N) Reactor tritium inventories will be strongly affected by the efficiency of the target fill and beta heating processes. Poor target quality will lead to incomplete burn and the resultant generation of target debris. The continuous operation of the reactor assumes no interruption of the target supply.

Degree of Relevance to MFE - Similar problems will be faced in MFE if solid fuel pellets must be produced and injected into the reactor on a cyclic basis. This presently seems a likely MFE refueling method.

Analysis - A technical note is available from KMS on required factory tritium inventories. Theoretical and experimental work on the beta heating process presently indicates that the process will generate uniform fuel layers efficiently and quickly under ideal conditions. It remains to be shown that such conditions can be provided for millions of targets at once in a factory environment. Diffusion filling of a reactor size CH (plastic) target has not been demonstrated to date. However, diffusion rates for CH are well known and this step in the production process is not expected to present any technical problems. However, diffusion filling will require large tritium inventories.

Issue B. Driver

B.a. Laser Driver

Issue B.a.1. DT Target Illumination Issues

Description - Current Target Working Group (TWG) Guidelines[1] call for tangential illumination of the direct-drive spherical DT target with at least 60 beams producing an overall ~1% intensity uniformity, no polarization specification, a pulse duration of 6 ns, an incident laser energy (at λ = 248 nm) of 5 MJ, together with a pre-pulse ramp of 60-80 ns with ~1% of the laser energy. The TWG stated the laser/target coupling efficiencies are implicitly included in the provided target gain curves. Elementary calculations for inverse Bremsstrahlung (IB) assuming an laser light/target coupling dependence of $(\cos \theta_0)^5$ derived from planar target experiments[2] indicate that DD coupling may be relatively inefficient. Furthermore, the prepulse is expected to generate a 6-cm diameter underdense plasma atmosphere around the DT target which in the presence of summed laser intensities as high as 10^{15} W/cm^2 could give rise to significant stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS) together with attendant production of suprathermal electrons unless very high laser bandwidths were available. Lastly, the influence of resonant absorption (RA) has been assumed to be negligible assuming that the laser driver operated in the 250 nm wavelength range. Since RA deposits energy in the plasma in a two-lobed pattern[2], the concern arose that if this mechanism were enhanced by the tangential illumination criterion of the TWG, it would not be possible to meet the ~1% target illumination uniformity requirement.

The worst case scenarios for the direct-drive illumination issues break down into two possibilities: (1) the DD illumination can be accomplished with inefficient coupling of laser light into the target, and (2) it may be necessary to go to an indirect drive target design.

There are additional key issues associated with indirect-drive laser-driven targets; i. e., plasma closure of the hohlraum entrance apertures preventing laser pulses from efficiently coupling to the target.

References

1. Ronald C. Davidson (MIT), et al., "Inertial Confinement Fusion Reactor Design Studies Recommended Guidelines," prepared for DOE Office of Fusion Energy, September 1990.
2. J. J. Thomson, C. E. Max, J. Erikkila, and J. E. Tull, "Absorption of Focused Light by Spherical Plasmas," Physical Review Letters, 37, pp. 1052-1056, (1976).

Issue B.a.2 Large Laser Bandwidth Issues

Description - By virtue of their quantum mechanical properties, excimer lasers are theoretically capable of generating efficient, high power, partially-coherent laser beams having relatively large bandwidths of up to 0.1%. Thus, for $\lambda = 250$ nm, the laser frequency would be $\nu = c/\lambda = 1.1\times10^{15}$ Hz, so that the maximum bandwidth would be $\Delta\nu \sim 10^{12}$ Hz or 1000 GHz. Hitherto excimer lasers operated with very wide bandwidths have exhibited temporally unstable oscillation characteristics in part because of the complex mixture of laser modes which broad-band resonators would permit to exist within the laser. A second problem arises if non-linear optical (NLO) processes (such as stimulated Raman scattering [SRS] and stimulated Brillouin scattering [SBS]) are required for beam combination and pulse compression. Both SRS and SBS become inefficient for laser bandwidths significantly greater than 10 GHz unless careful attention is paid to the NLO device design. Lastly, propagating intense, broad-bandwidth laser pulses through a significant number of dioptric elements can produce both temporal and angular dispersion, thereby endangering the target illumination uniformity budgets.

From a target illumination standpoint, laser beams having broad-bandwidths may solve some problems. Coherent beams incident at relatively small angles produce interference fringes on the surface of the target which "wash out" in a period of time, τ_c, of the order of $1/\Delta\nu$, which for $\Delta\nu = 10$ GHz, $\tau_c \sim 100$ ps. Secondly, intensity thresholds for SBS and SRS in the underdense plasma atmosphere around the target increase as the bandwidth of the illuminating laser is increased for $\Delta\nu_{laser} > \Delta\nu_{SBS}$ or $\Delta\nu_{laser} > \Delta\nu_{SRS}$.

Thus broad bandwidth illumination could reduce DT target preheat from suprathermal electrons.

Other key laser amplifier issues have to do with demonstrating a well-engineered laser amplifier design: This category of key issues includes:

(1) Developing a fail-safe design (i. e., if an excimer laser amplifier fails, no reactor shutdown will be required)
(2) Meeting a wall-plug efficiency of c. 12%
(3) Achieving a mean number of firings between failures of 10^9
(4) Producing a very high quality output beam quality. (This factor can be mitigated if a Raman accumulator is used to improve beam quality.)

Issue B.a.3 Final Optics Pointing System

Description - The final optics pointing system must meet a precise requirement for achieving target illumination uniformities using 60 laser beams defined in Section 3.1, above. This pointing requirement will be made for fusion targets moving at a high speed (possibly ~1 km/sec) through a residual atmosphere in a cylindrical target chamber. It is assumed that the nominal focal length of the focusing mirrors will be ~40 m, so that if the focusing mirrors were used also for pointing the laser, interbeam pointing accuracies of the order of $\Delta\theta \sim 1\times10^{-6}$ rad would be required, depending also upon the near-field apodizations of the 60 tangential illuminated laser beams. An additional uncertainty would be the degree to which all 60 beams would have to be deflected to compensate for a ballistic DT target that was off course by a distance, Δx. Small spatial misalignments, Δx, are not as serious for meeting the target illumination requirements (Issue B.a.1, above) since such a misplaced target would experience only second-order illumination uniformities since the interbeam alignment stringencies set the first order target illumination requirements.

Hitherto, IFE target alignment systems have had to deal with fixed targets so that the final optics pointing system would be significantly more complicated than previous systems. Methods and techniques exist to align the 60 beams relative to a precision surrogate target. Where needed, this methodology needs to be incorporated into the design of the mirror pointing and centering system.

Issue B.a.4 Grazing Incidence Mirror Damage

Description - A key issue for the excimer laser driver is the control of optical damage on mirrors and windows in the system. Excimer laser amplifiers put their amplifier windows at particular risk since these windows are simultaneously exposed to ionizing radiation, UV laser light, and the corrosive effects of F_2 gas. A key element in controlling optical damage is to design the laser elements to produce spatially smooth beams with little or no intensity ripples. Use of a Raman accumulator with excimer laser pump beams has hitherto proven to be the most effective method for controlling intensity spikes from excimer lasers.

The grazing incidence mirror for the Prometheus-L reactor is currently situated at distances of the order of 20 m from a source of X-rays, neutrons, charged particles, etc. having a total power of the order of 2.8 GW of which approximately 1/4% will be incident on the grazing incidence mirrors, assuming a pulse repetition rate of 5 Hz, a target gain of 124, and a laser energy of 4 MJ/pulse. In addition, assuming that the each of the 60 beam lines will have an energy/pulse of approximately 70 kJ delivered at an angle of incidence of 80°, these mirrors will be exposed to 6 ns pulses of ultraviolet laser radiation at an average fluence of $\Phi_{laser} \cos(80°) \sim 2$ J/cm^2. At the present time, a composite mirror structure of aluminum and silicon-carbide is proposed for the grazing incidence mirror, and with the leading edge of the mirror located at a distance of 20 m from the center of the chamber, swellings on the optical surfaces of the order of $\lambda/4$ are expected to occur during the first year of operation. Calculations by UCLA indicate that swelling in the aluminum layer will be sufficiently minor that piezoelectric-activated transducers for mirror figure control may not be necessary.

One of the serious hazards faced by grazing incidence mirrors is potential damage due to particles that may be deposited on the surface of the mirrors. These particles are illuminated not with fluences of 2 J/cm^2, but with much more dangerous fluences of 10 J/cm^2 since the cos (80°) does not apply in this case. Although many particles are expelled from mirrors under these circumstances, particles that stick to the mirror surface in the presence of laser fluences this high can produce catastrophic damage to optical surfaces.[1]

Reference

1. G. J. Linford, "Simulations of Intracavity Laser Heating of Particles," Proceedings of SPIE, 1415, pp. 196-210, (1991).

Issue B.a.5 SBS Pulse Compressor

Description - Although many experiments and theoretical analyses concerning the behavior of stimulated Brillouin scattering have been carried out, the use of large scale (E_{laser} > 1 kJ) SBS cells for performing 100:1 pulse compression with high efficiency has not yet been carried out in the United States. Calculations[1,2] have suggested that ~100:1 SBS pulse compression can be achieved, but it has been shown theoretically that it may be difficult to achieve 6 ns pulse durations with high conversion efficiencies. Mak,[3] et al., reported that in work performed in the Soviet Union, 100:1 compressions of long pulse KrF lasers had been achieved with 99% efficiencies at energy levels of the order of 1 kJ.

Additional experimental work needs to be performed to demonstrate that the Soviet approach using a "chirped" input Stokes, possibly in a ramped format, can achieve the requisite pulse shape with a high conversion efficiency. There does not seem to be a serious concern that the SBS pulse compressor can achieve the requisite pulse compression ratio and pulse shape—the primary problem appears to be that the conversion efficiency may lie between 50 and 70%. Use of large aperture Pockels cells and appropriate delay lines can permit the depleted SBS pump (representing the remaining 30% of the energy in the SBS cell) to be used as the 80 ns precursor for the main laser beam.

References

1. "New Techniques for KrF Laser Fusion Systems; Stimulated Brillouin Architectures," Spectra Technology interim report for Los Alamos National Laboratory, pp. 1-3 through 1-6, (1989?).

2. "Ramp Stokes Seeds for SBS Pulse Compressors," TRW IOC from Gary Linford to ICFRDS Team, K323-L-91-142, 18 July 1991.

3. Arthur A. Mak and Leonid N. Soms, "Optical Methods for Laser Beam Control," Proceedings of SPIE, 1415, pp. 110-120, (1991).

B.b Heavy Ion

Issue B.b.1 Timing of Heavy Ion Beams

Description - In order to meet the TWG's requirements for the heavy ion indirect drive target, it will be necessary to achieve better than a ~0.5-ns time difference among all 16 HI beams through the LINACs, channel formation, channel transport, stripping, and focusing into the hohlraum. This degree of precision is currently not within the state of the art and will need development to attain.

Issue B.b.2 Channel Formation

Description - A complete description of the individual beam properties including current, charge state, density, energy charge density profile, rise time, degree of symmetry, and beam radius will be required to characterize channel formation in the background gas. In addition, the physics of interaction with the beam in terms of the background gas properties must be made. These background gas properties are: composition (Pb, D_2, DT, He, plastics, etc.), density, ionization potentials, degree of ionization, etc. It is presumed that the heavy ions will have Z ~ 82, initial charge state +2, current tens of MA, and energies of approximately 5 GeV.

Issue B.b.3 Channel Transport

Description - There are key issues associated with the transport of space-charge limited heavy ion beams through the reactor cavity to the target. The problems associated with HI channel transport include collapse of channel due to pinching, motion of plasma within the solenoidal magnetic field, recirculating neutralization currents, attraction of elections, repulsion of ions, etc. In addition, it will be necessary to know the betatron period vs. the ionic charge state. Development of instabilities such as "kink" and "sausage" need to be understood, both experimentally and theoretically.

There are several critical issues which will require validation through experimentation and modeling before self-formed transport channels can be considered truly viable. Foremost among these is a laboratory demonstration of a self-pinched heavy ion beam transport channel. The transport characteristics of the channel must then be assessed including: (1) fraction of the beam ions initially captured in the channel, (2) fraction of the beam energy lost due to background collisions and back EMF, (3) fraction of the beam energy lost near the target where opposing side channel currents begin to cancel the confining azimuthal field, (4) fraction of the prepulse energy eroded during channel formation, (5) capability of the channel to re-image the focal spot at the channel entrance onto the target, (6) limitations on beam focal spot size at the channel entrance, (7) demonstration of sufficient control over the channel to accurately position the focal spot on the target, and (8) characterization of background gas conditions/limitations for stable channel formation.

Reactor Concept - Prometheus-H

Potential Impact - RP, IC, RS, RL

Design Specificity - DHI (Driver, Heavy Ion)

Overall Level of Concern - High
The capability to form a stable, self-pinched transport channel to re-image a heavy ion beam focal spot on a target would have significant positive economic and technical impact on design of a heavy ion-driven inertial fusion power plant.

Operating Environment

P	-	Background Gas Density	T	-	Temperature
Q	-	Power Density	E	-	Beam Energy
IB	-	Beam Current	EI	-	Ion Energy
G	-	Geometry	p	-	Pulse Shape
N	-	Cyclic Operation	HI	-	Heavy Ion

Relevance to MFE - Low
This development issue is not directly relevant to MFE.

Issue B.b.4 Stripping of HI Beam

Description - The stripping of the HI beam in a thin foil needs to be understood in terms of the momentum vector of the completely stripped beam. In addition, if an ionizing laser is used to generate a channel, the interaction of the stripped HI beam with the weakly ionized channel through the gas needs to be thoroughly investigated. The precision with which the HI beam follows the laser beam needs to be established accurately since it strongly impacts the accuracy with which the HI beams can be delivered to the indirect drive target. In addition, a reliable method is required for the introduction of the laser beam through the foil area and into the impact region for the injected indirect-drive target. In addition, the phenomenon of self-focused beam capture inside the pre-formed channel needs to be investigated experimentally.

Issue B.b.5 Alignment of Indirect HI Target

Description - Although the alignment stringencies of the HI beams to the indirect drive target are less severe than those placed on the excimer laser driver irradiating a direct-drive target, it is necessary to combine the 16 HI beams into a bundle of sufficiently small size (~1 mm) to permit the efficient irradiation of the target without damaging the capsule. This problem is therefore intimately related to the channel transport issues raised above in sections 3.3 and 3.4.

Issue C Vacuum System and Evacuation

Issue C.1 Vacuum Seal Compound Survival in Nuclear Environments

Description - Elastomers such as Viton, Buna and teflon are frequently used for seals in vacuum designs. These as well as other candidate elastomeric compounds may be quite susceptible to degradation and alteration of properties in a nuclear environment.

Reactor Concept - Laser and Heavy Ion

Potential Impact - Alternative, more expensive and labor intensive designs utilizing metal seals will be required if nuclear hardening of elastomeric seal materials is not accomplished.

Design Specificity - This issue is generic to all reactor concepts.

Overall Level of Concern - Low. This problem will have to be solved and may add to remote maintenance costs. the problem has been encountered before and existing seal designs are available.

Operating Environment -

Degree of Relevance to MFE - High. Magnetically confined fusion devices have encountered this problem and have sponsored studies to determine applicable alternative seal designs.

Analysis - None.

Issue C.2 Cryogenic Pump Hydrogen Capacity

Description - The largest design factor affecting the vacuum system is cryopump hydrogen capacity. Current pumps have relatively limited capacity which drives designers to choose between large numbers of pumps or frequent pump regeneration. Increases in hydrogen capacity may be accomplished through pump design trade-offs, sacrificing the ability to pump large amounts of heavier gas species.

Reactor Concept - Laser and Heavy Ion

Potential Impact - Vacuum system design may be changed due to increases in hydrogen capacity. Reductions in the number and/or size of cryogenic pumps has impact on remote maintenance systems, shielding requirements, reactor exhaust reprocessing system as well as the vacuum system.

Design Specificity - This issue is generic to all inertial confinement reactor concepts.

Overall Level of Concern - High. This issue could significantly reduce the size of the reactor vacuum system. As shown in the potential impact statement, the issue has a ripple effect through several reactor subsystems. Significant cost reductions are possible.

Operating Environment

Degree of Relevance to MFE - High. MFE reactors have significant gas loads and the vacuum system spatial restrictions are significant.

Analysis - See Section 6.6 of report.

Issue C.3 Chemical Stability of the Reactor Exhaust

Description - The carbon and hydrogen isotopes contained in the reactor exhaust could combine to form various hydrocarbon molecules. This chemical recombination could produce flammable and/or toxic compounds. Vacuum and reactor exhaust systems operation and design could be affected.

Reactor Concept - Laser and Heavy Ion

Potential Impact - Vacuum system design may be changed due to reduced atomic hydrogen gas loads as well as the potential health and safety hazards. The exhaust system design may also need alteration to allow separation of the hydrocarbons for potential cracking/reprocessing operations.

Design Specificity - This issue is generic to all inertial confinement reactor concepts that introduce carbon into the reactor.

Overall Level of Concern: - Medium. This issue could significantly reduce the size of the reactor vacuum system. It also has the potential to increase safety problems and to add to the fuel reprocessing complexity. This issue will have to be addressed prior to design of the first reactor.

Operating Environment - High temperature carbon and hydrogen exhaust gases.

Degree of Relevance to MFE - None. Carbon and other chemically reactive compounds are probably present in only insignificant amounts in an MFE reactor.

Analysis - None.

Issue D Tritium Processing System

Issue D.1 Tritium Inventory

Description - The Tritium Fuel Cycle System is required to manage and process all tritium containing streams in the IFE plant. These include supply of tritium to target fabrication, processing of reactor chamber exhaust to remove protium and impurities, and treating tritiated impurities to recover tritium. In addition, tritium is to be recovered from the breeder blanket to ensure self-sufficiency. Also, various systems such as coolant, beam lines, reactor building atmosphere and waste water need to be decontaminated to remove tritium.

The key issue in the Tritium Fuel Cycle System is the tritium inventory and mean residence time of tritium in the subsystems and tritium losses from the subsystems, due to the radiological hazard posed by tritium. Tritium is a weak beta emitter with a half life of 12.3 years. It is a particular biological hazard because hydrogen is an important chemical component of the life cycle and the hydrogen isotopes are extremely mobile.

Reactor Concept - Laser and Heavy Ion. The design of the Tritium Fuel Cycle System is relatively independent of the driver design and is similar whether the Heavy Ion or Laser driver is selected.

Potential Impact - (RS) Containment and control of tritium present some special problems because tritium can permeate through materials and form volatile species. Tritium cleanup and safety systems are provided to protect the plant staff, the public and the environment from exposure to too much tritium, by effectively limiting the escape of tritium. They must also quickly recover all the tritium deposited in reactor systems to limit inventories and prevent decay losses.

Design Specificity - (B, T, TF) There are three subsystems of the Tritium Fuel Cycle System in an IFE plant with potentially large tritium inventories, i.e. the blanket, the exhaust processing system and the target factory.

Level of Concern - (Medium) Several strategies are suggested for controlling tritium to very low concentrations and for limiting the escape of tritium to the environment. By proper selection of material combinations, highly reliable processing systems and their operating conditions and multiple barriers, the tritium inventories and leakage can be minimized. Tritium escaping to the plant containment can be removed by gas cleanup systems.

Operating Environment -

Relevance to MFE - The tritium issue is virtually identical for IFE as for MFE with the exception of a large tritium inventory associated with the target fabrication for IFE.

Analysis - A critical issue is a serious problem which only R&D can resolve. A problem which can be resolved through conservatism in design and where R&D has only economic justification, could be termed a technical issue.

For DT fuel cycle self-sufficiency the blanket performance is a critical issue. The tritium breeding required defines a number of concerns of which only a few quality as issues. For example, the tritium inventory in the blanket is one of the parameters of the blanket issue. Tritium recycling from the chamber is, for steady state conditions, not an issue. The chamber tritium inventory (at steady state) may be an issue which could be packaged with another parameter; i.e., the tritium content of the first wall protection material, into a broader issue. Tritium inventories in the fuel processing systems are not an issue. for the given design the amount of tritium in the system is known and is acceptable. If however, the reference design changes to some different concept, this may become an issue. The time required for target fabrication and target storage could be packaged into a broader target fabrication issue.

Based on the above comments and on the present design, there is no critical issue in the Fuel Cycle Design.

Issue D.2 Tritium Permeation from the First Wall Coolant - Liquid Pb

Description - Approximately 40% of the heat produced in the reactor will be removed by liquid lead and transferred into the ultimate heat transfer medium steam which will convert this into energy in a steam turbine. The permeation rate from the Pb side of the heat exchanger is of serious concern. Any permeation rate in excess of the release limit is unacceptable for direct heat exchange in a steam generator for directly driving the turbine. The following theoretical mitigating options exist:

(1) Double wall [1.1] or composite heat transfer tubes [1.2]. Option [1.1] could have an interspace between tubes which would be purged and evacuated. Alternatively, option [1.2], would feature a composite heat transfer tube wall which would have tailored permeation barriers consisting of dissimilar metals and/or oxide barriers.

(2) Use of an intermediate coolant loop. Such loop would transfer heat between Pb and steam, and provide opportunity for recovering permeated tritium.

Option 1.1 is, from the fuel cycle design point of view, very simple. In this case a purge gas would sweep the interspace under vacuum. The gas would be processed in one of the main fuel processing loops such as PSA (if He is used) or fuel purification loop if hydrogen is used. However, from the heat transfer point of view this option may be very difficult to implement as the heat transfer from liquid lead to steam may be severely restricted.

Option 1.2 would have no impact on the fuel cycle since the permeation would be restricted to values below noticeable levels. There would be no additional processes required.

Option 2 would, due to the high temperatures, involve a medium other than water. Such medium would most likely have to be liquid metals (or steam) since even known organic coolants could be used only to some 420°C.

In order to see if the concern is relevant the permeation rate was attempted to be calculated:

Solubility of T in Liquid Lead - Upper Permeation Limit - Ghoniem[1] suggests solubility values of 0.11-0.25 [cc T/100 mg Pb] at 500 and 600°C respectively. Such high figures appear to be in agreement with Opie and Grant[2] which were never experimentally duplicated;[4] and Hofman and Maatsch[3] could not measure figures above 0.01 which apparently was the detection limit of their instruments. Even this lower figure, when extrapolated for the high Pb flow of 20,311 kg/s [1] (or 7.3×10^{11} [g/h]), will yield tritium transport figures in excess of the 29.29 mol/h fueled into the chamber. However, a more useful source of solubility dependency on pressure is shown in Reference 4 and Figure 5.4-1. From this the solubility is 1.2×10^{-2} [appm H in Pb/torr$^{1/2}$]. The simplifying news is that the solubility appears not to be temperature dependent. Consequently cooling of Pb will not release any T in the heat exchanger. This leads to an assumption that the partial pressure of T on the Pb side of the heat exchanger is equal to the pressure at which the equilibrium solubility was established in the chamber. The chamber pressure[6] appears to follow a decay exponential from 10^4 Pa to 0.2 Pa during each of the 0.25 sec interval between explosions. An approximate integration of that pressure indicates that the average pressure is in the 130 Pa region. If the mole fraction of T_2, mt $_T$ is 0.208, the partial pressure of T_2 is:

$$p_T = mfT \times 130 = 0.208 \times 130 = 27 \text{ [Pa] or } 0.205 \text{ [torr]}.$$

The amount of tritium dissolved in Pb transferred to the heat exchanger is:

$$T_2 = \frac{p_T^{1/2} \times K_6}{10^6} \times \frac{A_T}{A_{pb}} \times Q\left(\frac{gT}{h}\right)$$

where:

p_T	=	partial pressure of Tritium in the chamber [torr];
K_3	=	Solubility = 1.2×10^{-2} [appm H in Pb/torr$^{1/2}$];
A_T	=	atom number for tritium = 3;
A_{pb}	=	atom number for lead = 207.2;
Q	. =	Flow of lead to the heat exchanger 20311 kg/s or 7.3×10^{10} [g/h]

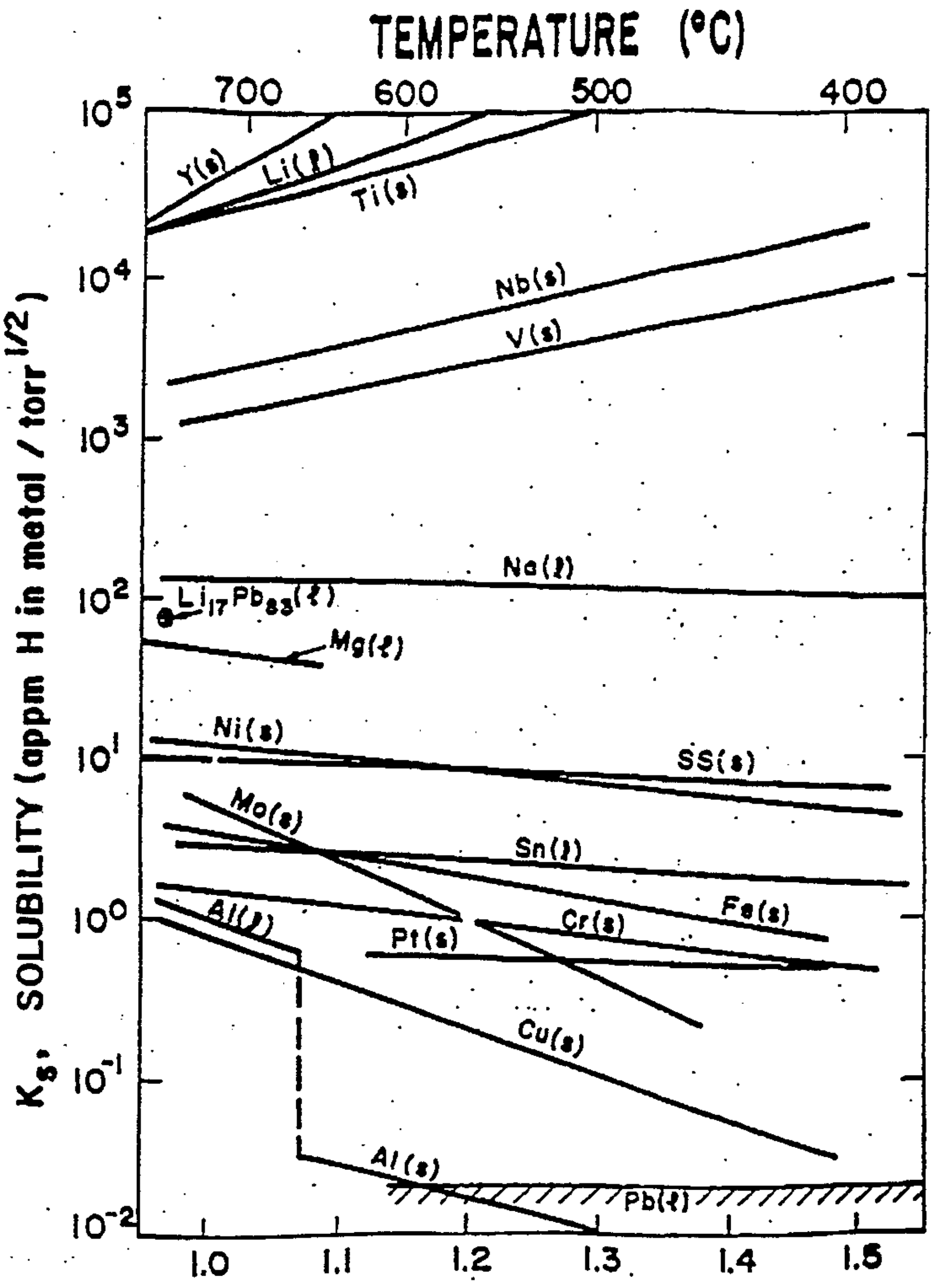

Figure 5.4-1. The Solubility of Hydrogen in Selected Metals and Alloys[4]

The resulting tritium flow in solution is:

$$T_3 = \frac{(0.205)^{1/2} \times 1.2 \times 10^{-2}}{10^6} \times \frac{3}{207.2} \times 7.3 \times 10^{10} = 5.7\left(\frac{g}{h}\right)$$

This represents the upper limit for the permeation, since no more tritium can be carried out of the chamber.

Tritium Permeation - From Reference 5, the following correlation applies for a group of steel based materials:

$$\text{perm} = 0.5 \times \exp\left(\frac{-15000}{RT}\right) = 1.41 \times 10^{-5}; \text{cm}^3 \text{ (STP)} \times \frac{\text{mm}}{\text{cm}^2 \times \text{min} \times \text{torr}^{1/2}}$$

if: perm = Permeability (see above);

and for Gas constant R = 1.98, wall temperature T = 723 K, and:

A = Heat transfer area 1.5×10^6 [cm^2]

t_p = Wall thickness of the heat transfer tubes = 2 [mm];

p_T = Partial pressure of Tritium = 0.205 [torr];

The T permeation rate is:

$$T_{perm} = \frac{60 \times \text{perm} \times A \times (p_T)^{1/2} \times M_T}{2 \times 1000 \times 22.4} =$$

$$\frac{60 \times 1.2 \times 1.41 \times 10^{-5} \times (0.205)^{1/2} \times 6}{2 \times 1000 \times 22.4} = X \times (0.205)^{1/2} = 16.8 \times 0.25 = 7.56 \left(\frac{g}{h}\right)$$

It is apparent that the permeation flux through clean tubes in the Pb heat exchanger is exceeding the amount of tritium dissolved in Pb. From the mass balance, the amount of tritium "dropped out" of the solution must be in balance with the amount permeated. From the material balance, the permeation rate must be equal to the amount of tritium left in the heat exchanger. This balance will be reached at a lower partial pressure where the dissolved tritium is equal to the permeation flow. For such balance, the following applies:

T permeated = T supplied with Pb - T returned in Pb

or:

$$\frac{7.56 \times (px)^{1/2}}{(0.205)^{1/2}} = 5.7 - \frac{5.7 \times (px)^{1/2}}{(0.205)^{1/2}}$$

Consequently:

$$(px)^{1/2} = 0.194; \text{ and } p_x = 0.037 \text{ torr};$$

The new permeation rate is:

$$T_{3x} = 5.7 \times \frac{(px)^{1/2}}{(p_{chamber})^{1/2}} = 5.7 \times \frac{(0.037)^{1/2}}{(0.205)^{1/2}} = 2.45\left(\frac{g}{h}\right)$$

And the tritium flow returning to the chamber will be:

$$T_{sr} = 5.7 - 2.45 = 3.25\left(\frac{g}{h}\right)$$

Permeation with Oxide Barriers - Bell[5] offers permeation impedance factors ranging from 100 to 1000 for stainless steel conditioned by water oxidation at 600°C. For Incaloy 800 the corresponding figures are ranging from 167 to 319. This still leaves permeation flux in the range of 7 to 70 [mg/h] or in terms of Ci/h 70 to 700 Ci/h. Even the lower of the two figures could still cause a tritium extraction problem. With composite walls and or space the permeation flux could be reduced by 4 orders of magnitude which could bring the permeation into the range of 7 Ci/h or 167 Ci/day which is still hardly acceptable. It appears that the permeation control may have resorted to much more drastic steps such as oxidizing the permeated tritium in the tube interspace (or in the intermediate loop or on the Pb side of the heat exchanger) which should lower the permeation rate.

Tritium Inventory for the Fuel Cycle Components - As the design progresses, the earlier preliminary estimate of tritium inventories for the fuel cycle has been updated from the earlier figures extrapolated from ITER. These are shown in Table 5.4-1.

Table 5.4-1: Tritium Inventories for Fuel Cycle Systems

Service or System	Process	T Inventory [g]
Isotope Separation (ISS)	Cryo-distillation	56
Impurities from Fuel	Permeation	5
Tritium from Impurity reject	HITEX	0.5
Tritium from Solid Breeder	Pressure Swing Adsorption	2.8
Tritium from Water	Distillation + VPCE	0.3
Tritium from Atmospheres	Recombiner/Dryer	25
Solids removal from Pb	TBD	0
Fuel Management and Storage	Zr/Co or U beds	600-800
Breeding Blanket	Solid, He purged, He cooled	50-500
Coolant	Helium	0
Solid Waste De-tritiation	TBD	TBD
Total		740-1400

References

1. N. M. Ghoniem, UCLA, "Laser Reactor Chamber Design," IFE Reactor Design Studies Project Meeting, 6 August 1991.

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3. W. Hofman and J. Maatsch," Loslichkeit von Wasserstoff in Aluminum," Blei-und Zinkachmelzen , Z. Metallkunde 47, 89-95 (1956).

4. E. M. Larsen, M. S. Ortman, K. E. Plute, University of Wisconsin, "Comments on the Hydrogen Solubility Data for Liquid Lead, Lithium, and Lithium-Lead Alloys and Review of a Tritium-Solubility Model for Lithium-Lead Alloys," UWFDM-415 (1981).

5. J. T. Bell, J. D. Redman, Chemistry Division, Oak Ridge National Laboratory, "Tritium Permeation Through Steam Generator Materials," American Chemical Society, 8412-0513- 2/79/0779-331, 1979.

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Issue E. Cavity

E.a Wall Protection

Issue E.a.1 Cavity Vapor Hydrodynamics

Description - Vapor hydrodynamics following the blast affects both the pressure loads seen at the wall and also the condensation rate for cavity clearing, both of which are serious issues. Hydrodynamic phenomena in the cavity are very complex, involving temporally and spatially dependent energy deposition, shock propagation and vapor mass transfer. The hydrodynamics is also intimately coupled to cavity heat transfer, which is itself very complex.

Reactor Concept - Laser and Heavy Ion

Potential Impact - (DW, UL) Vapor hydrodynamics strongly affects recondensation and cavity clearing; if the cavity clearing rate is too slow, the reactor concept is not feasible. Unacceptably high pressures at the first wall would cause early failures or result in conservative designs that increase cost and lower performance.

Design Specificity - (Generic) Dry wall protection schemes use cover gases, whereas liquid protection schemes fill the cavity with evaporated liquid. In either case, this is an important issue.

Overall Level of Concern - (Critical)

Operating Environment - (S, A, G, TWI, Q, t, q, P) Many factors affect cavity hydrodynamics. Initial conditions are set by the blast yields and spectra. Vapor and surface conditions are important, including temperature, pressure, power density and heat flux. Dimensions, geometry, and wall interactions also affect the phenomena.

Degree of Relevance to MFE - (None) This work is only slightly related to plasma disruptions.

Issue E.a.2 Cavity Structure Mechanical Response to Blast

Description - The main sources of loading on the first wall are due to: (1) impulse from rapid evaporation, (2) shock waves in the cavity gas, and (3) weight of the Pb. If the resulting stresses and strains are too large, then the fatigue life of the first wall may be unacceptably short, or the cavity will have to be designed more conservatively. Many failure modes will depend on the mechanical responses in the first wall structures. Mechanical response is very design dependent, and is difficult to predict currently due to the unique material design, component configuration and attachment scheme, as well as the complex loading conditions. Innovative design approaches can be envisaged to reduce the peak stresses; these require analysis and testing to determine the extent to which they are successful.

Reactor Concept - Laser and Heavy Ion

Potential Impact - (UL, RP, IC) If the resulting stresses and strains are too large, then the fatigue life of the first wall may be unacceptably short, or the cavity will have to be designed more conservatively.

Design Specificity - (All IFE reactors must address this issue.)

Overall Level of Concern - (High)

Operating Environment - (F, T, σ, A, TWI, G, Q, q, P, N, s) Mechanical responses depend very strongly on the local conditions in the first wall, including temperature, stress state, etc., and are strongly influenced by geometric factors. In addition, simulation of proper loading conditions is important, such that the requirements on the environmental conditions are very difficult.

Degree of Relevance to MFE - (Low) This problem resembles the response to disruptions, and to some extent the mechanical response of large components (such as the blanket) under cyclic operating conditions.

Issue E.a.3 Vapor Condensation Rate

Description - For liquid-protected first walls, evaporated material must be removed from the cavity quickly to allow rapid firing of the targets and beams. In most designs, this requires condensing the vapor on the wall or on separate condensing surfaces. Noncondensables must be pumped separately. The condensation rate is limited by processes in the cavity and by heat transfer to the cooling medium. The condensing surface must be adequately cooled to a temperature lower than the saturation temperature at the desired cavity base pressure. The basic heat and mass transfer processes under ideal conditions are relatively well known, but insufficiently studied at present. Lack of experimental data makes the modeling predictions very uncertain. More seriously, non-ideal effects, such as nucleate recondensation, aerosol transport, droplet generation and transport, 3D effects contribute very large uncertainties.

Reactor Concept - Laser and Heavy Ion

Potential Impact - (DW, RP, IC) Inadequate cavity clearing lowers the allowable repetition rate, raising the yields and/or lowering the power produced. If the yields become too high, the driver energy and wall loads may become prohibitively high. Alternatively, one could reduce the net power produced, although this would almost certainly destroy the economics.

Design Specificity - (Most wall protection schemes)

This issue is relevant, with the possible exception of a few schemes such as HYLIFE-II, in which the cavity is cleared by liquid slugs.

Overall Level of Concern - (Critical)

Operating Environment - (T, A, TWI, G, t, q, P) The main parameters which dominate recondensation are the temperature and pressure in the cavity and at the first wall.

Degree of Relevance to MFE - (None) Some possible relationship to plasma disruptions.

Issue E.a.4 Radiation Heat Transport in Partially-Ionized Gas

Description - The x-ray and debris energy is absorbed in the cavity background gas or in the vapor shield which arises from film evaporation. This leads to vapor temperatures up to several eV. In this partially-ionized regime, emission and transport of thermal radiation is very difficult to model. Thermal radiation is particularly important for the analysis of dry spots (or dry walls), but also contributes to the determination of the cavity clearing time.

Reactor Concept - Laser and Heavy Ion

Potential Impact - (RP, RL) Thermal radiation affects vapor recondensation and cavity clearing time, although its importance in this regard is uncertain (the time constant may be fast enough such that thermal conduction and mass transport dominate). It is more important when dry spots occur; when no liquid is present, evaporation of the dry wall due to thermal radiation is more important.

Design Specificity - (Generic)

Overall Level of Concern - (High)

Operating Environment - (T, A, TWI, G, Q, t, q) Target yields and spectra determine the initial conditions. The background gas pressure and temperature and wall temperature are the most important parameters.

Degree of Relevance to MFE - (Low) Thermal radiation in partially-ionized gases shares some similarities with the plasma edge region of an MFE reactor, although the materials are different.

Issue E.a.5 Film Flow Control: Injection, Uniform Thickness, and Drainage

Description - Any solid surface exposed to the blast will rapidly deteriorate; complete wall coverage is mandatory. Further, if the thickness of the film varies too much, then the wall temperature will vary, limiting recondensation. Excessive variation of film thickness will lead to overly conservative design, driven by the hot spots. Many problems have been identified with control of the film thickness. One of the most difficult problems is protection of inverted (upper) surfaces. Any finite-thickness film is subject to Rayleigh-Taylor instability and will drip down into the cavity. Proposals to aid in upper end-cap protection include inertial jet injection and magnetic guiding. Drainage is another serious concern, as large pools at the bottom of the cavity would become hot and limit recondensation.

Reactor Concept - Laser and Heavy Ion

Potential Impact - (DW) Inability to adequately protect the solid surfaces makes this design concept impractical.

Design Specificity - (Generic to thin film wall protection.)

Overall Level of Concern - (Critical)

Operating Environment - (A, G, v) Most aspects of this issue are independent of the radiation and blast environments.

Degree of Relevance to MFE - (Low) Some similarity to free-surface films as innovative divertor protection.

Issue E.a.6 Film Flow Stability and Response to Impulsive Loading

Description - The ability to maintain a constant film supply through a porous wall under impulsive loading is highly uncertain. Resolution of this issue requires a good understanding of the time-dependent surface pressure and the interaction of the fluid and structure. Rapid heating from the blast, sometimes called isochoric heating, can cause liquid to eject into the cavity. In this event, beams and targets would not propagate into the chamber.

Reactor Concept - Laser and Heavy Ion

Potential Impact - (DW) If liquid is ejected into the cavity, then beams and targets would not propagate and the film concept would be impractical.

Design Specificity - (Thin film protection schemes.)

Overall Level of Concern - (High)

Operating Environment - (A, G, v) Requires simulating both the film conditions as well as the blast conditions which establish the time-dependent loads.

Degree of Relevance to MFE - (Low) Some similarity to free-surface films as innovative divertor protection.

Issue E.a.7 Pb/SiC Wettability

Description - Good wetting between Pb and SiC is necessary to provide reliable supply and coverage of Pb to the first wall. Preliminary experiments indicate that the two materials do not wet, even in a very pure atmosphere. Wetting is particularly important at inverted surfaces, where capillary action is needed to help support the film. Chemical additives to the SiC matrix (e.g. metals) may be necessary to encourage wetting.

Reactor Concept - Laser and Heavy Ion

Potential Impact - (RP, RL, IC) If good wetting can not be obtained, then the film supply system would become very complex and more subject to failures.

Design Specificity - (Specific to this design, using Pb and SiC in a thin-film configuration.)

Overall Level of Concern - (Medium) Wetting is important, but it is predicted that solutions to this problem can be obtained without a huge R&D investment.

Operating Environment - (C, I, s) This is primarily a materials issue, with little effect from the operating environment.

Degree of Relevance to MFE - (Low) Possible relationship to LiPb breeders in SiC blankets, although this combination is not one of the principal MFE design concepts.

Issue E.a.8 Pb Compatibility with Steel

Description - The maximum bulk outlet temperature of the Pb first wall coolant is limited by compatibility with steel in the pipes and heat exchanger. Dissolution of steel is controlled primarily by temperature. Previous studies have set limits of the order of 10 mm/yr erosion to prevent heat exchanger plugging. This translates to a coolant bulk outlet temperature limit of approximately 500–550°C. These estimates are based on extrapolation from data obtained for sodium-steel interactions, and may not be valid for Pb-steel. Since the bulk coolant temperature is important in determining the thermal cycle efficiency, accurate measurements are important. Impurity control methods, such as cold trapping may allow an increase in the allowable temperature, and should be explored as well.

Reactor Concept - Laser and Heavy Ion

Potential Impact - (RP, RL, RS) - Lower temperatures result in lower thermal cycle efficiencies. If the corrosion rate is too high, heat exchanger plugging may result. Transport of steel constituents into the reactor cavity would result in additional radioactivity.

Design Specificity - (Specific to Pb-steel systems.)

Overall Level of Concern - (Medium)

Operating Environment - (T, C, v) The concern is outside the radiation environment. The major parameters are temperature, impurity content (especially oxygen), and coolant velocity.

Degree of Relevance to MFE - (Medium) Material compatibility is a generic issue. Pb corrosion is related to LiPb corrosion, which is an important issue for MFE.

E.b Blanket Issues

Key technical issues for blankets can be listed in the following categories (major sources of uncertainties for each issue category are also shown).

1. Tritium self-sufficiency
    - Uncertainties in achievable breeding ratio (inventory)
    - Uncertainties in required breeding ratio (production rate, burn up)
2. Tritium inventory and recovery
    - Tritium transport mechanisms
    - Solid breeder micro-structure
    - Chemical trapping
    - Surface processes
    - Irradiation effects
    - Temperature limits
3. Breeder/structure mechanical interactions
    - Swelling

- Interface heat transfer

4. Off-normal and accident conditions
   - LOFA, LOCA
   - Tritium behavior during transients
   - Module pressurization
5. Structural response and failure modes
   - Uncertainties
6. Corrosion and mass transfer
   - LiOT formation and vaporization
   - Breeder/clad corrosion under irradiation and temperature
   - Coolant impurities
7. Tritium permeation
   - Surface kinetics
8. Fabrication & Assembly
9. Heat generation and power production
   - Nuclear heating rates and energy multiplication

Each issue is described in more detail below.

E.b.1 Tritium Self-Sufficiency

Description - Tritium self-sufficiency is a necessary goal for fusion, which is satisfied when the achievable tritium breeding ratio equals or exceeds the required tritium breeding ratio. Blanket-related uncertainties in the achievable tritium breeding ratio include uncertainties in tritium production rates due to limitations in neutronics predictive capability and data base and to material and configuration choices. Uncertainties in the required tritium breeding ratio relate mostly to the blanket inventory.

Reactor Concept - L/H

Potential Impact - (DW) Tritium self-sufficiency is a critical issue that may close the design window since it is a required goal for a fusion reactor.

Design Specificity - Generic

Overall Level of Concern - Critical

Operating Environment -

Neutron: H, D, R

Parameters: F, ϕ, S, T, C, I, TG, A, G, Q, t, P_t, N, γ

Degree of Relevance to MFE - High

E.b.2 Tritium Inventory and Recovery

Description - Tritium inventory and recovery in the solid breeder blanket is important for two reasons. First, the feasibility of the blanket depends on whether or not it can breed enough tritium to satisfy the tritium self-sufficiency requirement. The required tritium breeding ratio increases with increasing breeder inventory. Secondly, this tritium inventory may be a large safety risk, depending on its magnitude and mobility. Uncertainties in the tritium transport mechanisms are large and are associated with both lack of fundamental property data and with the effect of integrated operation in a fusion environment. Achieving acceptable levels of tritium inventory and recovery would also impose temperature limits on the breeder and blanket and affect design configuration and operating flexibility.

Reactor Concept - L/H

Potential Impact - (DW, US, IC) The impact of tritium recovery and inventory on tritium self-sufficiency makes it a critical issue as it may be responsible for closing the design window. In addition, a large tritium inventory is a major safety concern because of hazard during accidents, as well as an economic penalty because of the larger initial tritium supply required before the device becomes self-sufficient.

Design Specificity - Solid breeder blankets

Overall Level of Concern - Critical

Operating Environment -

Neutron: H, R
Parameters: F, ϕ, S, T, C, I, A, G, Q

Degree of Relevance to MFE - High

E.b.3 Breeder/Structure Mechanical Interactions

Description - The mechanical interactions between the solid breeder material and the structural material can lead to either degradation of the performance or seriously limit the useful lifetime or safe operation of the blanket module. These interactions are driven by differences in thermal expansion, creep and swelling behaviors.

Reactor Concept - L/H

Potential Impact - (RP, RL) Material property changes such as melting points, and compatibility between structure and breeder under irradiation and temperature and in the presence of impurities may limit the lifetime or performance of the blanket.

Design Specificity - Solid Breeders/SiC

Overall Level of Concern - High

Operating Environment -

Neutron: H, R
Parameters: F, T, C, I, A, t, N, σ, P

Degree of Relevance to MFE - High

E.b.4 Off-Normal and Accident Conditions

Description - The reactor would have to be designed to withstand several types of accident transients with no (or minimum) loss of investment. These transients include loss of flow and loss of coolant accidents and tube sheet failure inside the blanket module. Adequate ability to predict system response to such transients, including tritium behavior and module pressurization effects, is needed.

Reactor Concept - L/H

Potential Impact - (IC, RS) Inaccurate predictions could lead to either over-design with associated costs, or under-design with potential for serious fault conditions.

Design Specificity - generic, SiC

Overall Level of Concern - High

Operating Environment -

Neutron: H
Parameters: T, s, G, Q, t, P_t, v, P, N, TG

Degree of Relevance to MFE - High

E.b.5 Structural Response and Failure Modes

Description - Knowledge of failure modes and rates in blanket components is necessary because of their critical impact on the economic potential and safety. Virtually no data exist on failure modes and rates of components in a fusion environment. Possible failure modes that need to be examined experimentally are crack growth under cycling and irradiation, and cracking at welds and discontinuities. However, the most important information from experiments is expected to be the identification of unforeseen failure modes.

Reactor Concept - L/H

Potential Impact - (RS, UL) Understanding of structural response and identification of failure modes are critical to the economic potential and safety of a fusion reactor.

Design Specificity - Generic, SiC

Overall Level of Concern - High

Operating Environment -

Neutron: H, D, R
Parameters: F, T, σ, C, I, A, G, Q, t, N, P

Degree of Relevance to MFE - Medium

E.b.6 Corrosion and Mass Transfer

Description - With helium as coolant, the key concern are the impurities and their effect on the structural material. Of concern also is the material interaction at the breeder/clad interface including the effect of burnup, and the formation of LiOT enhanced by moisture impurity and formation which could lead to LiOT vaporization and Li mass transfer, as well as enhanced corrosion.

Reactor Concept - L/H

Potential Impact - DW (particularly for Li_2O) LiOT formation and vaporization is of particular concern for LiOT. Mass transfer of LiOT to cooler regions could result in plugging purge flow paths and loss of breeder material.

Design Specificity - Solid breeder (Li_2O), SiC

Overall Level of Concern - High

Operating Environment -

Neutron: H, R
Parameters: F, T, C, I, t, P_t, N

Degree of Relevance to MFE - High

E.b.7 Tritium Permeation

Description - Tritium permeation from the breeding material into the coolant may be a problem at interfaces where large areas of relatively thin walls separate breeder and coolant. In the absence of cracks, tritium will diffuse through structural components at a rate determined by surface kinetics, tritium vapor pressure and permeability. Corrosion/chemistry at both interfaces of structural components may either inhibit or enhance tritium permeation. Alternately, cracking of engineered or natural barriers will strongly affect permeation.

Reactor Concept - L/H

Potential Impact - (US, UL) Tritium permeation into the coolant is a substantial safety penalty since it may be difficult to prevent further tritium transfer outside of the primary coolant. A major tritium permeation problem would require replacing the faulty blanket module(s).

Design Specificity - Generic

Overall Level of Concern - High

Operating Environment -

Neutron: D, R
Parameters: F, T, I, P_t, N

Degree of Relevance to MFE - High

E.b.8 Fabrication

Description - Manufacture and assembly of the SiC tube sheets and modules are uncertain and need to be demonstrated. In addition, the fabrication of the solid breeder is uncertain. The basic material must be produced and assembled into the desired form with the desired microstructure and packing fraction. Precautions with Li_2O are necessary because it is hygroscopic and LiOH is corrosive.

Reactor Concept - L/H

Potential Impact - (IC, UL) Blanket cost and reliability are dependent on ease of fabrication and assembly.

Design Specificity - Solid Breeder, SiC

Overall Level of Concern - High

Operating Environment -

Neutron:
Parameters: A, G

Degree of Relevance to MFE - Medium, depending on MFE blanket design similarity

E.b.9 Heat Generation and Power Production

Description - Uncertainties in the prediction of nuclear heating rates due to inaccuracies in neutronics data and/or transport code affect temperature levels and gradients, which govern most blanket phenomena. Uncertainties in predicting the energy multiplication factor for the blanket affect the power production. In addition, uncertainties associated with decay heat production would affect accommodation of afterheat under normal and accident conditions.

Reactor Concept - L/H

Potential Impact - (RP, RS) Poor prediction of heat generation during operation has implications on the design limit and the performance of the blanket.

Design Specificity - Generic, solid breeder

Overall Level of Concern - High

Operating Environment -

Neutron: R, H
Parameters: ϕ, S, G, Q, t, γ

Degree of Relevance to MFE - High

E.c Shielding

Issue E.c.1 Effective of Bulk Shield

Issue E.c.1.1 Biological Dose During Operation and After Shutdown for Maintenance

Description - During reactor operation, the occupational exposure limits outside the reactor site (outside reactor building) must be maintained. The bulk shield thickness/material outside the FW/Blanket system and the reactor building thickness/material must be designed to ensure meeting these exposure limits during reactor operation. After shutdown, the activation level attained in the bulk shield due to prolonged irradiation during reactor operation determines the waiting period before accessing reactor building. This also applies to the shielding materials of the laser beam lines and the beamlets (including the prepulsed beams) in HI reactors. Extra shield may be required at localized zones to ensure maintaining the exposure limits (e.g. around the laser windows at the inlet of laser beams to reactor building and at the far ends of the HI beams). Primary uncertainties in actual dose levels arise from tolerances in bulk shield assemblies, distortion resulting from thermal and radiation effects, and neutron streaming through gaps and penetrations.

Reactor Concept - Laser and Heavy Ion.

Potential Impact - (RS, UL) If shielding is insufficient, this will require additional shield and/or components rearrangement. This could lead to delayed plant operation and/or reduced period of operation, imposing economical and availability penalties.

Design Specificity - (Generic)

Overall Level of Concern - (High)

Operating Environment - (R, D; ϕ ,F, S, G) Fusion neutrons are required to interact with bulk shield/reactor building as the source of radiation. Dose levels are governed by the material selection (for both during operation and after shutdown cases), neutron and gamma fluxes and spectra, and the actual geometry and arrangement of the bulk shield. Heat deposition and removal in bulk shield (due to neutrons/gammas interactions during operation and due to decay heat after shutdown) is an important design issue which has safety/reliability implications.

Relevance to MFE - (High)

Issue E.c.1.2 Radiation Streaming

Description - Neutrons stream through: (a) the relatively large opening of the laser and HI beams, and (b) the gaps/slits between shield assemblies (of the bulk shield, shielding of the beamlines, shielding of vacuum ducts, etc.). Neutrons/gammas reaching the ends of the beamlines will increase local exposure dose and radiation damage to components in the vicinity. Neutrons/gammas streaming through gaps/slits impeded in the bulk shield design also increase local flux levels which will require safety factors to be impeded in the design of shielding segments.

Reactor Concept - Laser and Heavy Ion

Potential Impact - (RS, UL) Accurate estimates of neutrons streaming through the relatively large openings of the laser and HI beamlines penetrating the bulk shield is essential for protecting laser windows and sensitive components and for the designing of the extra local shield around these components.

Design Specificity - (Generic for both laser and HI)

Overall Level of Concern - (High)

Operating Environment - (R, D; ϕ, F, S, G) In general, level of neutrons/gammas at the end of openings/gaps/slits depends on the energy, spectrum, and the fluence of the primary neutrons streaming through these opening. The size and shape of the openings/gaps/slits (e.g. Diameter/Length of large openings, straight vs. irregular or stepped shape for gaps/slits) is a determining factor to the flux level at the ends of these penetrations.

Relevance to MFE - (High) Large laser and HI beamline openings are similar to the openings of the neutral beam injectors/ vacuum ducts in MFE.

Issue E.c.1.3 Analytical Techniques and Data Base

Description - Neutron and gamma transport codes and nuclear data base are used to predict the nuclear performance of the bulk shield and dose level behind it during operation and after shutdown. The adequacy of these codes/data in predicting this performance as well as neutrons/gammas streaming through penetrations impeded in the bulk shield is an important design issue not only pertaining to bulk shield design but to the design of all other nuclear components. Uncertainties in estimating the operating environment of sensitive components are best relieved by additional conservatism in bulk and penetrations shield thicknesses.

Reactor Concept - Laser and Heavy Ion

Potential Impact - (RS, UL) The additional conservatism in designing the bulk and penetrations shield (or safety factors) to cover the current uncertainties in nuclear data (transport and response data) and the approximations used in the transport calculations has an adverse impact on the overall cost of the reactor. Integral experiments are needed to test and validate the design safety margins and/or to improve the data base used in design.

Design Specificity - (Generic)

Overall Level of Concern - (High)

Operating Environment - (R, D; ϕ, F, S, G) Integral experiments dedicated to test and validate the neutron/gamma transport codes/data used in shielding design will require either a 14.1 MeV point source or a simulated line source. The latter is more suitable for streaming experiments.

Relevance to MFE - (High)

Issue E.c.2 Shield Compatibility with Cavity and Vacuum Boundary, Including Assembly/Disassembly

Description - Shields are generally heavy, weighting more than a 50 tons apiece. They must be fitted together with such accuracy that the slit width between them is small enough to maintain the level of radiation streaming through these slits/gaps below a certain specified level. The design of support mechanism for the blanket and shield must consider various factors such as competition for space, differences in the amount and direction of thermal expansions, clearance against earthquakes, etc. In the process of assembling/disassembling the shield, activation level of shield materials may require remote handling.

Reactor Concept - Laser and Heavy Ion

Potential Impact - (RS, UL) Mechanical interactions between the various segments of the shield and/or other components may lead to mechanical failures. Additionally, the type of maintenance (vertical vs. horizontal) is a determining factor to reactor reliability/availability. From a safety stand viewpoint, if the precision of the assembly/disassembly is not enough, neutrons/gamma streaming could occur leading to unacceptable radiation dose levels.

Design Specificity - (Generic)

Overall Level of Concern - (High) Because of the complexity and serious consequences of mechanical failures with regard to shield compatibility with cavity and vacuum boundary, the level of concern is high in this case. Furthermore, although radiation streaming through slits/gaps between the shield segments seems to be inevitable, reduction in the streamed neutrons/gammas could be achieved by considering stepped slits/gaps or by adding additional shielding when feasible.

Operating Environment - (R, D, ϕ, F, S, G)Although irradiation creep has some effect on mechanical failures, neutrons and transported gammas have the dominant role in generating bulk heating in the shield segments and thus causing thermal expansions. Neutrons are also the source of concern with regard to streaming and activation issues.

Relevance to MFE - (High)

Issue E.c.3 Activation of Reactor Building Components Outside the Cavity

Description - The combined thickness of the blanket and bulk shield is an important contributing factor in determining the fusion power and economics of a reactor. The bulk shield thickness should be chosen such that activation of components located in the reactor building and outside the cavity is kept minimal (e.g. activation of heat exchangers, vacuum pumps, etc., if the design calls for installing them in the reactor building). The situation in laser and HI reactors are more relaxed compared to MFE since no inboard shield is required to protect the superconducting magnets in these reactors. However, the protection of the final mirrors and the quadrupole magnets (see issues # D.3.4 and D.3.5) are key design issues for IFE.

Reactor Concept - Laser and Heavy Ion

Potential Impact - (RS, UL)

Design Specificity - (Generic)

Overall Level of Concern - (Low)

Operating Environment - (R, D ; ϕ, F, S, G) Neutrons/gammas are required to interact with components located outside the cavity. Level of activation of these components depends on their location, size, and materials.

Relevance to MFE - (High)

Issue E.c.4 Shielding of Final Mirrors

Description - Neutrons and gammas stream through the laser beam ducts from the center of the cavity all the way to the Grazing Incidence Metal Mirrors (GIMM), the turning mirrors, and the laser windows. Streamed neutrons can also end up in the laser building and hence cause damage to the sensitive optical components. Because the beam duct from the GIMM to the cavity is conical in shape, most of the radiation damage to the GIMM (quantified in terms of dpa/FPY) is caused by the uncollided neutrons streaming directly from the cavity center to the GIMM. In addition to these neutrons and the collided ones in the shielding materials located in the vicinity of the GIMM , neutron-induced gammas deposit substantial part of their energies in the GIMM . This impact the life-time of the GIMM. To minimize neutrons' damage effect in the GIMM, a neutron trap zone is normally located behind the GIMM to absorb transmitted neutrons and lessen neutron reflection to the GIMM. Damage to the turning mirrors are primarily caused by collided neutrons in the liner/shield materials around the beam duct. Excessive dose absorbed in the laser windows leads to their damage.

Reactor Concept - Laser

Potential Impact - (UL,RP,RL,IC) GIMM transmission characteristics adversely affected by radiation damage caused by neutron streaming leading to short life-time. Thermal stresses cause deformation and reduced performance. Frequent replacement of the GIMM impacts system cost and the overall reactor availability. This applies as well to the turning mirrors and the laser windows whose life-time are generally longer than the GIMM's.

Design Specificity - (Mirrors)

Overall Level of Concern - (High)

Operating Environment - (R, D, H; ϕ, F, S, G) High-energy neutrons (~12 MeV) for GIMM, relatively moderated neutrons (several MeV) for the turning mirrors and laser windows are the main cause for reduced performance due to radiation damage. Geometry of the mirrors impacts life-time (e.g. flat vs. paraboloid or ellipsoid mirrors, grazing incident angle, mirror thickness, etc.)

Relevance to MFE - (None)

Issue E.c.5 Shielding of Quadrupole Magnets

Description - Focusing magnets in a HI beam driven reactor are damaged by neutrons streaming through the beam ducts unless adequate shielding is provided to protect these superconducting magnets. The damage is quantified in terms of the dpa/FPY to the Cu stabilizer, the peak radiation dose to the insulator, the fast neutron (> 0.1 MeV) fluence and peak power density in the magnet. Radiation damage is more serious in the quadrupole magnets closer to the cavity where shielding is needed most.

Reactor Concept - Heavy Ion

Potential Impact - (UL,RP,RL,IC) Radiation damage to the epoxy (or to the more radiation-resistant polyimide) insulator is not reversible. Frequent repair has the most impact on the driver cost. Shielding should protect excessive radiation dose to the insulator such that the insulator could last the life-time of the reactor. Peak radiation damage to the Cu stabilizer (reversible) should be kept below a specific design limit to allow for few (if not at all) annealing processes during the plant life-time and, hence, increasing the plant availability. Total heat deposited in the magnet should also be kept below a specific integrated value to avoid magnet warm-up.

Design Specificity - (Magnets)

Overall Level of Concern - (High)

Operating Environment - (R,D,H ; ϕ, F, S, G) Neutrons streaming through the HI beam ports at the FW and colliding in the beamline shielding materials are the main cause of magnet damage. Neutrons and gamma heating in the insulator, when excessive, is a life-limiting factor.

Relevance to MFE - (Medium) Although there is a degree of relevance exists to MFE but the geometrical arrangement of the magnet relative to the primary neutron source in HI IFE reactor is different from MFE. In the latter, neutrons streaming through the beamlines are incident with a glancing angle to the magnet shield, relaxing the shielding requirements in this case.

Issue F. Material

Issue F.a Viability of SiC Structures

Description - The viability of using SiC structures in the first wall and blanket is key consideration of the laser and heavy ion designs. If these concepts are to be believable, efforts should be made to assess the factors involved in determination of acceptable lifetimes, and to determine the appropriate manufacturing methods and their economics. Anticipated lifetimes for FW/B components are not well known. Limited resources allocated to this area precluded a realistic assessment of the anticipated lifetimes. Without this knowledge, system reliability, maintenance and economics would be seriously challenged. In order to perform this task, several investigations need be considered. It is too simplistic, and perhaps misleading, to use the accumulated fluence, or displacements per atom, to make projections of lifetimes. The determination of such lifetimes would need knowledge of the various effects of radiation. The most prominent of those are neutron induced swelling, embrittlement, fiber shrinkage, and/or detachment from the matrix, creep and fatigue crack propagation at high temperatures, and crack bridging mechanisms during irradiation.

On the other hand, the technology to process and manufacture SiC composites is at its infancy. An evaluation of manufacturing methods, potential, and costs is needed. Manufacturing methods are classified into fiber production techniques and matrix processing technologies. A variety of possibilities exist, with potential consequences on the economics and design.

Reactor Concept - Laser and Heavy Ion. The work is applicable to both Laser and Heavy Ion designs.

Potential Impact - (RP, RL, UL) Short lifetime of the SiC structure would result in an unacceptable reliability and/or availability. Additionally, reduced performance and reduced component lifetimes are expected.

Design Specificity - (FW, B) SiC structures are used in both the First Wall and Blanket components.

Overall Level of Concern - (High) Without reasonable and reliable lifetime of structural components, the entire design is compromised.

Operating Environment - (D, R; γ, T, σ) Neutron and gamma radiation, high temperatures, and moderate stress levels.

Degree of Relevance to MFE - (High) The development of low activation SiC composites is one of the important technology goals of magnetic confinement fusion.

Analysis -

(1) Radiation Effects: Assessment of the effects of radiation on SiC has not been thoroughly made. Experimental data and theoretical analyses will be available in the near future through the MFE materials program. Assessment will include mechanical properties, swelling, and high temperature creep.

(2) Fatigue Life: Fatigue analysis of the FW/B structure can be very involved. It requires accurate determination of the mechanical loading imposed by ablasion and repetitive reflections of pressure shock waves. A study of fatigue crack initiation and propagation in the structure is necessary. Reasonable assessments on this basis will require, at least, 2-D finite element analysis of the FW/B front and side walls. Considerations of the effects of radiation on fatigue crack growth will have to be on the basis of theory/extrapolation.

(3) Manufacturing of the FW/B: Existing manufacturing techniques involve CVD, and CVI processing technologies for the production of the composite's matrix. The fibers can be produced by the Yajima method (Nicalon), the Rice hulls method (US), the Los Alamos method (Whiskers). Combinations of fiber and matrix processing produces the composite. Assessment of the cost, reliability, and the capability for large component fabrication is desirable.

Issue F.b Thermomechanical and Materials Design of Laser Optics

Description - The mirror designs which we introduced in this study have been successful, at least conceptually. Nevertheless, greater improvements can be achieved, and more certainty and recognition may be realized, once we perform the proper thermostructural analysis. This will include materials selection data base, possible various configurations which would minimize surface deformations, laser energy density limits, and thermal fatigue limits. More work is needed on the dielectric tuning mirror, since it is quite sensitive to radiation effects.

Reactor Concept - Laser. The work is applicable only to the KrF Laser design.

Potential Impact - (DW, RP) The lifetime and design of the optics system in the neutron environment systems has long been identified as key to the performance of the system. The window may actually be closed if the lifetimes of the turning and grazing incidental mirrors are too short for economic feasibility. Additionally, the reliability of the entire system hinges on the reliability of the optics system.

Design Specificity - (DL) This issue is specific to the Driver Laser (DL).

Overall Level of Concern - (High) Without reasonable and reliable performance of the optics system, the laser concept is at risk.

Operating Environment - (D, R, H; γ, T, σ) Neutron and gamma radiation, high temperatures, and moderate stress levels.

Degree of Relevance to MFE - (Low) Optical components are used in MFE designs for RF heating and for diagnostics. However, the environment is not as severe, and the problem is not perceived to be a concern to the MFE community.

Analysis - Research is expected to be along two major fronts; Materials selection and thermomechanical design. This research will be concerned with the detailed design of the two final mirrors; the turning and the grazing incidence. The turning mirror will likely be selected of a dielectric material, which will be very sensitive to the effects of both neutron and gamma radiation. The neutron fluence limit is generally on the order of 10^{16} n/cm^2. The effort will involve shielding design to reduce neutron and gamma fluence, material selection for better solutions to the problem and analysis for accurate determination of the radiation limits. Further innovative thermomechanical designs of the GIMM may reduce its size and bring it closer to the cavity.

Issue H Maintenance and Configuration

Issue H.1 Computer Reliability

Description - Current guidelines on the relative safety of plant operation equate manual operation, mechanical interlocks, double electrical interlocks and triple computer interlocks. These guidelines date from the early days of the fission industry and need to be updated to reflect technological advances since that time. In other industries single computer systems are proving more "safe" than both mechanical and electrical interlocks when used in complex manufacturing plants. New guidelines are needed to put requirements for different levels of safety criticality and task complexity with approval procedures that equalize approval requirements for computers with other technology. IAEA study on this issue started in mid-1991 with seminar in Vienna in July.

Reactor concept - This issue applies equally to Laser and Heavy Ion options.

Potential Impact - (UL) This issue will result in unacceptable reliability and availability through the use of older less suitable technological solutions in areas where regulation hinders the adoption of computer based solutions.

Design Specificity - (Generic) This issue is generic and has impact to various degrees in all current power production options with increasing impact with plant size.

Overall Level of Concern - (Low) The level of concern ascribed to this issue is low based on the current level of action from the International Atomic Energy Authority among others.

Operating Environment - (t) Operating environment for this technology is assumed to be STP with the only key parameter time although current work on radiation hardness of electronics could bring in far more onerous conditions on a limited proportion of computer equipment.

Degree of Relevance to MFE - Due to its generic nature this issue is equally applicable to MFE.

Analysis - The current treatment of computer systems in the nuclear industry is thought to be overly restrictive given the current proliferation in many industries of computers with increasing power and reliability. While the need for verification of computers is not questioned, the current procedures are restrictive. In software QA, the seven-level process model for software development, starting with specification requirements and ending with traceable software code, is thought by many to be unusable and costly without guaranteeing software reliability. The International Atomic Energy Agency recognizes computer systems can play a significant role in improving nuclear plant safety and economics but this needs to be supplemented with an update of the current implementation standards.

Issue H.2 Total Remote Maintenance

Description - The design of plant to only have services for robotics and not humans is not something done in 1992 unless radiation levels or regulation force the issue. Given the overall trends in automation, it is probable that this tenth-of-a-kind plant should be designed for exclusive use of automation in key areas.

Reactor Concept - (Laser and Heavy Ion) This issue could bring in significant cost savings and design advantages if total remote maintenance (TRM) is used.

Potential Impact - (DW, UL) This issue could bring in significant cost savings and design advantages if TRM is used.

Design Specificity - (Generic) This issue is generic and applicable to all design options with toxic and/or radioactive elements or compounds and high radiation environments.

Overall Level of Concern - (Low) The level of concern on this issue is low, based on the assumption that TRM will be accepted in future decades.

Operating Environment - (F, S, T, C, H, B)

Degree of Relevance to MFE - (High) Due to its generic nature this issue is equally applicable to MFE.

Analysis - Designing the reactor building to accommodate robots and not humans is a contentious point though by 2030 the 'risk' in planning to keep humans out of all hazardous areas should be accepted. Even with no HVAC or human walkways, human access for emergency purposes can be accomplished with suited workers on mobile platforms.

Issue H.3 Material Joining

Description - The joining of and to silicon carbide is a largely untried process particularly at elevated temperatures.

Reactor Concept - This issue applies equally to Laser and Heavy Ion options.

Potential Impact - (DW, IC) This issue has the potential to close the design window though with R&D it is probable it can be solved.

Design Specificity - (Generic) This issue is general to all design solutions using ceramic composites which, by 2030 will probably mean a majority.

Overall Level of Concern - (High) High due to the lack of knowledge in this area.

Operating Environment - (F, S, T, C, H, B)

Degree of Relevance to MFE - (High) Due to its generic nature this issue is equally applicable to MFE.

Analysis - Joining of silicon carbide structural parts is not well understood. This will also be affected by the presence of lead coolant. Composite joints are often handled using metal implants though in this case further problems due to differential expansion would occur. Joining of composites to metals is an area needing research, especially with differential expansion issues at flanges, etc., particularly the joint between the silicon cooling pipes to stainless steel in the helium cooling lines.

Issue H.4 Lead Flushing

Description - When the reactor vessel is allowed to cool the lead coolant will solidify in the first wall requiring some sort of draining or flushing process to remove lead and allow the first wall tiles to be taken out individually. Any lead that remains will cause severe sealing problems on reassembly in the key primary cooling tubes.

Reactor concept - This issue applies equally to Laser and Heavy Ion options.

Potential Impact - (IC) This problem could have a significant cost impact as well as potentially decreasing the availability of the reactor.

Design Specificity - (Generic) This issue is specific to designs using a liquid metal coolant.

Overall Level of Concern - (Medium) Concern on this issue is high primarily due to the lack of information on the use of lead coolants particularly in silicon carbide structures.

Operating Environment - (F, T, H)

Degree of Relevance to MFE - (Low)

Analysis - Due to the high melting point (325°C) of lead, the presence of lead in pipes etc., will be a problem during maintenance. Flushing the lead out also brings more problems from the flushing medium.

Issue H.5 Seal Life

Description - The life of seals on the vacuum duct between the vacuum pumps and the reactor vessel is anticipated to be a problem, particularly as each vacuum pump needs an isolation valve at its junction with the duct. The issue is also applicable to a lesser degree to helium cooling pipes.

Reactor Concept - This issue applies mainly to laser options though as the issue applies to helium cooling pipes as well it does impact heavy ion.

Potential Impact - (DW, IC) This issue could severely close the design window as well as reducing availability and increase costs.

Design Specificity - (Generic) This issue is not specific to designs in general though liquid first walls and use of cryopumps increase the problem.

Overall Level of Concern - (High) Level of concern is high as the temperature range and types of materials which seals encounter are at the limit of current technology.

Operating Environment - (F, S, T, C, H, B) Key environmental parameters in this issue are temperature range and the materials (like helium) which come into contact with the seals.

Degree of Relevance to MFE - (High) Due to its generic nature this issue is equally applicable to MFE.

Analysis - Seals in vacuum pumps on the vessel only have a two-hour life in ITER MFE conditions, this will also be a problem on IFE on all flanges and valves near the reactor vessel. In the heavy ion option the problem is less severe as roots vacuum pumps are far less rigorous in environment than cryo or turbomolecular vacuum pumps. The life of seals in helium pipe is an accepted problem which none the less needs a solution if problems with this reactor are to be minimized.

Issue H.6 Embrittlement Temperature

Description - Material embrittlement problems are decreased if the temperature of much of the reactor pipework is kept above 150°C at all times, including during maintenance. This will be a maintenance challenge to operate at this elevated temperature.

Reactor Concept - This issue applies equally to laser and heavy ion options.

Potential Impact - (DW, IC) This issue will both close the design window for the reactor maintenance equipment and cause an increase in cost.

Design Specificity - (Generic) This issue is generic as it applies to a feature that will be found in most designs.

Overall Level of Concern - (Medium) This issue is of medium concern mainly due to the potential cost impact.

Operating Environment - T (Tritium)

Degree of Relevance to MFE - Due to its generic nature this issue is equally applicable to MFE.

Issue J Safety and Environmental

Issue J.1 Overall Plant Tritium Inventory

Description - The overall plant tritium inventory will directly impact the potential for large radioactivity releases, with their associated off-site exposures. Also, large amounts of tritium within the plant will require more complex engineered barriers to minimize occupational exposures. In addition to the amount, the form (i.e., whether HT or HTO) and location within the plant of the tritium will directly impact the design.

Reactor Concept - Laser and Heavy Ion

Potential Impact - (IC, RS)

This issue is an Attractiveness Issue, since there are engineered feature which can be implemented to mitigate the impacts of tritium, once its amount form, and location has been identified.

Design Specificity - T (Tritium)

Overall Level of Concern - Medium. Since there are engineered features to mitigate the impacts associated with this issue, an overall level of concern of medium has been specified.

Operating Environment - H (Tritium)

Degree of Relevance to MFE - Medium. The methods developed to mitigate the impacts of tritium for this plant are directly applicable to MFE, however, the amount, form and location will differ.

Issue J.2 Permeation of Tritium

Description - Tritium will be carried by the liquid lead first wall coolant and will readily permeate through the walls of the heat exchanger. Unless engineered design features are provided, the permeated tritium will be released to the environment, resulting in unacceptable off-site exposures.

Reactor Concept - Laser and Heavy Ion

Potential Impact - (RP) This issue is an Attractiveness Issue, since there are engineered feature which can be implemented to mitigate the permeation of tritium, (e.g., secondary loop, permeation barrier, duplex heat exchanger, etc.).

Design Specificity - T (Tritium)

Overall Level of Concern - (Medium) Since there are engineered features to mitigate the impacts associated with this issue, an overall level of concern of medium has been specified.

Operating Environment - H (Tritium)

Degree of Relevance to MFE - Medium. The methods developed to mitigate the impacts of tritium for this plant are directly applicable to MFE, however, the amount form and location will differ.

Issue J.3 Normal Operation Tritium Release

Description - This issue is closely linked to the previous issue, however, this issue extends the scope to controlling tritium releases from all portions of the plant.

Reactor Concept - L/HI

Potential Impact - IC. This issue is an Attractiveness Issue, since there are engineered feature which can be implemented to mitigate the release of tritium, (e.g., desiccant systems).

Design Specificity - T (Tritium)

Overall Level of Concern - (Medium) Since there are engineered features to mitigate the impacts associated with this issue, an overall level of concern of medium has been specified.

Operating Environment - H (Tritium)

Degree of Relevance to MFE - Medium. The methods developed to mitigate the release of tritium for this plant are directly applicable to MFE.

Issue J.4 Neutronic Cross Sections/Data Library for Activation Analysis

Description - As emphasis on safety and environmental impact of fusion reactor has greatly increased, an accurate predictive capability of radioactivity and its related parameters such as decay heat has become necessary. The basic elements of such predictive capability are a computer code based on an accurate mathematical model and a library of basic nuclear data including decay data and transmutation cross sections. Recent studies[1] point out that inadequate reaction cross section and decay data exist in the codes and data libraries widely used in fusion community. Example calculations show that the inadequacy in the RACC libraries underestimates the photon yield by a factor of as large as 1000 in the ITER first wall tungsten zone during operation and at times after shutdown. The study concludes that the accuracies of neutronic cross sections and data library are essential for activation analysis.

Reactor Concept - Laser and Heavy Ion. The work is applicable to both Laser and Heavy Ion designs.

Potential Impact - (US) Inadequate prediction of radioactivity and decay heat for a fusion reactor design may result in unacceptable safety risk.

Design Specificity - (Generic) All components exposed to radiation environment are affected.

Overall Level of Concern - High

Operating Environment - (R; ϕ, F, S, Q, γ)

Degree of Relevance to MFE - High

Reference

1. I. Jun, "Comparison Study Between Computed and Measured Radioactivity Decay Rates from Neutron Irradiation of Zirconium and Tungsten in a Simulated Fusion Environment," UCLA-FNT-55, November 1991

Issue J.5 Removing Decay Heat From Lead Coolant Under Accident Conditions

Description - Following the accident conditions, such as a loss of coolant due to a lead cooling tube rupture, the radioactive lead coolant spills and might pose a threat to the safety and environment. One of the design criteria requires that under this condition, the radioactive lead will be collected into a "containment" through gravity driven lead drain paths. If such a collection is fully successful, the lead can be cooled either actively or passively. However, some amount of lead might stay inside the reactor and knowing the location of lead is needed to mitigate the safety concern. Analysis indicates that if a failure of removing lead coolant decay heat occurs, the lead coolant (for the case of after two full power year operation) can reach about 1000°C at 8 hours following the accident. This temperature might damage the local structure and results in the migration of lead radionuclide into other plant components. Design reactor chamber with residual heat removal system (such as containment fan cooling) and/or with the development of lead detecting devices increase the plant cost.

Reactor Concept - Laser and Heavy Ion. The work is applicable to both laser and heavy ion designs.

Potential Impact - (US, IC, RS) Inadequate cooling in lead decay heat may result in unacceptable safety risk. Design inclusion of residual heat removal system increases the plant capital cost.

Design Specificity - FW

Overall Level of Concern - Medium.

Operating Environment - (R; ϕ, s, Q, γ)) The levels of decay heat following the reactor shutdown due to short lived radionuclides depend on the amount of neutron flux prior to the accident occurs, which is sensitive to the reactor power. The magnitude of long term decay heat is determined by the total neutron fluence regardless of the temporal variation of flux.

Degree of relevance to MFE - Medium. This issue is only preferentially relevant to MFE if lead is considered as the multiplier in the blanket design. Developing active means for lead decay heat removal under a cooling tube rupture (LOCA) is important for MFE blanket design.

Issue J.6 Hydrogen Burn Due to Rupture of Diffusion Vessel

Description - The diffusion vessel in the Target Factory could rupture resulting in either an explosion or burning of the tritium and deuterium contained within the vessel. Such an explosion could result in the environmental release of, and associated off-site exposures to, HTO unless proper engineered barriers are provided.

Reactor Concept - Laser and Heavy Ion

Potential Impact - (RP, IC) This issue is an Attractiveness Issue, since there are engineered feature which can be implemented to mitigate the impacts of a hydrogen burn, (e.g., dividing the inventory into smaller vessels, increasing the robustness of the building walls, etc.).

Design Specificity - TF (Target Factory)

Overall Level of Concern - (Medium) Since there are engineered features to mitigate the impacts associated with this issue, an overall level of concern of medium has been specified.

Operating Environment - (H, P_t)

Degree of Relevance to MFE - None

Issue J.7 Detection of Local Dry Spots Prior to Failure

Description - The dry spots on the first wall may be created due to the following mechanisms: (1) poor wetting of lead on the SiC material; (2) hydrodynamic instability of film subjected to pressure impulses; and (3) integrity of fibrous SiC material which is immersed in lead metal and subjected to a severe radiation environment. Once a dry spot is formed on the surface, the heat deposited on the SiC may result in a wall sublimation if at which the heat can not be adequately conducted away. Analysis shows that the sublimation rate of SiC is about 0.67 Kg/m^2 per shot, which corresponds to a layer of thickness of 1.1 mm per shot. If the film can not be reestablished and the dry spot remains, the time to failure (or a hole formation on the SiC wall) for a wall thickness of 0.5 cm is about 17 minutes. A failure of first wall reduces the plant availability, in addition it raises a safety concern if a hole is created and lead floods the chamber. This result indicates that the ability of local dry spot detection and remedy of removing dry spot is needed to reduce this issue.

Reactor Concept - Laser and Heavy Ion. The issue is applicable to both laser and heavy ion designs.

Potential Impact - US, IC

Design Specificity - Cavity FW

Overall Level of Concern - High. The abilities to detect and remedy the first wall dry spot are essential for the first wall structural integrity and reactor safety.

Operating Environment - (F, ϕ, S, T, Q, σ)

Degree of relevance to MFE - (High) Analytical method (or numerical modeling) for the SiC sublimation is relevant to the modeling used in the plasma disruption phenomenology studies, when the FW or high heat flux components undergo melting and subsequent vaporization. Technology for detection of dry spot is needed for the liquid film divertor concepts.

Analysis - The rate of SiC sublimation due to radiation re-emitted to the surface by the cavity gas depends on the gas conditions (pressure, temperature, charge state) as a function of time. The vapor entering the cavity from the X-ray deposition following the explosion is expected to be at a temperature of several eV. With gas at a temperature of several eV, the gas becomes ionized and excited. The gas temperature is estimated by knowing the equation of state properties, which are calculated by assuming the interparticle potentials are small.[1] The internal energy for an ion is computed relative to the ground state energy of the neutral atom and is given as:

$$e(Z) = \frac{3}{2}(1 + \langle Z \rangle)\, KT + Q(Z)$$

where Q is the energy required to remove the Z electrons from the neutral atom and is written as:

$$Q(Z) = S\, I_i\,; \qquad \text{for} \quad i=1,---, Z$$

I_i= ionization potential for the ith charge state.

The degree of gas ionization and excitation (ignored in the present analysis) depends on the gas temperature and number of density and is obtained from LIBRA.[2] The cooling rate of the ionized gas is calculated based on the analytical method developed by Zel'dovich et al.[1] This is given as:

$$q''' = \frac{4sT^4}{l_1}$$

where s is the Stefan-Boltzmann constant and l_1 is the radiation mean free path and is given as:

$$l_1 = \frac{1.1 \times 10^{23}\, T^{3.5}}{n^2 \langle Z\rangle (\langle Z\rangle + 1)^2 \frac{I}{KT}}$$

where n is the number of density and T is gas temperature.

The aforementioned model is only valid for optically thin gas. If the photon mean free path approaches the characteristic length of the cavity, the gas is assumed to act as a black body. Under the circumstance that the radiative energy flux into the SiC exceeds the rate at which the conduction carry away, some amount of SiC is sublimated. The heat of sublimation is estimated by averaging the potential energy of both Si and C in the SiC lattice based on Pearson et al.[3] This is found to be equal to 1.91x107 J/kg. The amount of SiC sublimated is about 0.67 Kg per shot per m^2. This corresponds to a layer thickness of 1.1 mm.

Present calculation assumes thermal-hydrodynamic equilibrium, further analysis shall include the effect of nonthermal-hydrodynamic equilibrium, gas excitation, self-shielding, etc. Better modeling of radiative heat flux shall be incorporated to the cases where the optically thin gas theory breaks down.

References

1. Y. B. Zel'dovich et al., "Physics of Shock Waves and High Temperature Hydrodynamic Phenomena", Volume I, Academic Press, New York, 1966

2. "LIBRA, A Light Ion Beam Fusion Conceptual Reactor Design," UWFDM-800, July, 1989

3. E. Pearson et al., "Computer Modeling of Si And SiC Surfaces and Surface Processes Relevant to Crystal Growth From the Vapor", J. of Crystal Growth 70 (1984) 33-40.

Issue J.8 Detailed Accident Analysis

Description - A number of accident scenarios/initiating events have been identified for Prometheus (see Table 5.4-2). However, due to limitations on the scope of this study it is not feasible to perform a detailed analysis of each of these accidents to determine what detailed design features are necessary to prevent/mitigate each of the identified accidents. Nonetheless, the viability of design which has been proposed is not expected to be negated by the detailed analysis of these, or other, accidents.

Reactor Concept - Laser and Heavy Ion

Potential Impact - (IC, RS)

Design Specificity - (All) Accident initiating events have been postulated that involve many (all) of the plant's systems.

Overall Level of Concern - (High) The potential exists for some of the yet unanalyzed accidents to require extensive and complex engineered features to mitigate their effects, however, it is not believed that any of the identified accident scenarios will negate the viability of the basic plant design.

Operating Environment - (All) Accident initiating events have been postulated that involve many (all) of the plant's parameters.

Degree of Relevance to MFE - (Medium) A number of the identified accident scenarios have direct applicability to MFE, (e.g., accidents in the blanket or the tritium systems).

Table 5.4-2 Potential IFE Reactor Accidents by Subsystem

Accident	Concern
A. Laser System	Reliability
1. Partial Input Beam Blockage	
2. Single Raman Accumulator Failure	
3. Single SBS Pulse Compressor Failure	
4. Loss of Inerting Gas	
a. Inadvertent Personnel Entry	Personnel Health
b. Loss of Containment	
5. Laser Misalignment	
a. Single Beam Misses Target	
b. Multiple Beams Miss Target	
6. Fluorine Release	Toxic Chemical Release
B. Reactor System	Reliability
1. Loss of Vacuum	
a. Vacuum Pump Failure	
b. Laser Building "Window" Failure	
c. Break in Instrument Line	
2. First Wall Unlocking	
3. Target Manufacturing Errors	
a. Contains Excess Tritium	
b. Contains Shortage of Tritium	
4. Loss of Wet Wall	
C. Blanket Coolant System	Reliability
1. Heat Exchanger Tube Rupture	
2. Pump Failure	
3. Increase in Coolant Flow Rate	
D. Driver Coolant System	
1. Heat Exchanger Tube Rupture	
2. Pump Failure	
3. Increase in Coolant Flow Rate	
E. First Wall Protection System	Toxic Material (Pb) Release
1. Plugged SiC Tube	
2. Pump Failure	
3. Increase in Coolant Flow Rate	
F. Secondary Coolant System	Reliability
1. Steam Line Break (Break Size Equal to Area of Safety Valve Throat)	
2. Decrease in Heat Removal (e.g. Pump Failure)	
3. Increase in Heat Removal (e.g. Decrease in Feedwater Temperature	
G. Target Delivery System	Reliability
1. Failure to Deliver Target	
2. Target Misalignment	Toxic Material (Pb) Release
a. Target Arrives Too Soon/Late	
b. Target Off-Center	
H. Target Factory	Tritium Release
1. Loss of Cryogenics	
2. Storage Tank Failure	
I. Containment Cooling (HVAC) System	Tritium Release
1. Loss of Cooling	
2. Loss of Containment Integrity	
J. Radwaste System	Tritium Release
1. Gas Collection Tank Failure	Methane Release
2. Liquid Waste Tank Failure	
K. Turbine-Generator System	Reliability
1. Loss of Load	
2. Loss of Condenser Vacuum	
L. Maintenance Systems	Personnel Exposures
1. Blanket Section Change-Out Accidents	
a. Stuck	
b. Dropped	
c. Broken	

Issue J.9 Removal of Contaminants from the Liquid Lead

Description - The Prometheus design includes the use of liquid lead for first wall protection. This lead, and any impurities within it, will become activated and contaminated with target debris, and will have to be processed to remove these contaminants. Since this is a new and innovative use of lead, these cleanup processes have not been developed.

Reactor Concept - Laser and Heavy Ion

Potential Impact - (RP, RS)

Design Specificity - WP (Wall Protection)

Overall Level of Concern - (Medium) The development of processes to remove contamination from lead is expected to be evolutionary, rather than innovative.

Operating Environment - I (Impurities)

Degree of Relevance to MFE - None

Issue J.10 Impact of Large Quantities of Lead on Waste Disposal

Description - The Prometheus design includes the use of liquid lead for first wall protection. This lead will become activated, and will have to periodically replaced, generating large quantities of radioactive lead for disposal. Because lead is a hazardous material, this waste must be disposed of as mixed waste (i.e.; both radioactive and hazardous) falling under NRC's 10CFR Part 61 and EPA's RCRA regulations. Finally, since the amount of radioactive lead which is currently generated is so small, it is not specifically identified in NRC regulations. However, if large quantities are to be generated, the NRC may modify their regulation to specifically address lead.

Reactor Concept - Laser and Heavy Ion

Potential Impact - (IC, RS)

Design Specificity - WP (Wall Protection)

Overall Level of Concern - Low. The NRC and EPA are currently developing procedures for addressing the disposal of mixed waste. It can be assumed that by the time Prometheus is operational (i.e., 2030), these procedures and regulations will be in place. Regardless, there will be a high unit cost associated with the disposal of all radioactive, hazardous and mixed wastes from Prometheus or any other source.

Operating Environment - I

Degree of Relevance to MFE - None

Analysis - An analysis of the disposal of fusion reactor materials, including radioactive lead (Pb-205) was presented in "Recycling and Shallow Land Burial as Goals for Fusion Materials Development," Carlo Ponti, Fusion Technology, January 1988. This analysis presents a proposed concentration limit of 1×10^6 (Bq/cm^3) for Pb-205.

K. Subsystem Interactions

Issue K.1 Laser System/Cavity Interface and Final Mirror Protection

Description - The Interface between the laser system and the reactor cavity represents a key development issue for the laser driver. The beam port walls and final optics must be protected from heating, blast and radiation damage effects. Furthermore, the protection mechanism(s) must not interfere with the laser beam propagation. The problem is complicated by the fact that the optics require a clean-room environment and special radiation-sensitive coatings to control their energy absorption while maintaining a direct line-of-sight to the target.

We investigated a multi-layer defense for the laser system/cavity interface that is illustrated schematically in Figure 5.4-2. The protection mechanisms include:

(1) The use of a flowing, liquid lead film to protect the port wall structure from surface vaporization. The port wall design employs a porous SiC first wall structure that slowly allows the liquid lead to seep through providing film replenishment around ports between shots.
(2) The residual lead vapor from the cavity walls which helps attenuate debris and x-rays before they even reach the wall boundary.
(3) A magnetic field in each beamline to deflect ions and electrostatically charged particles.

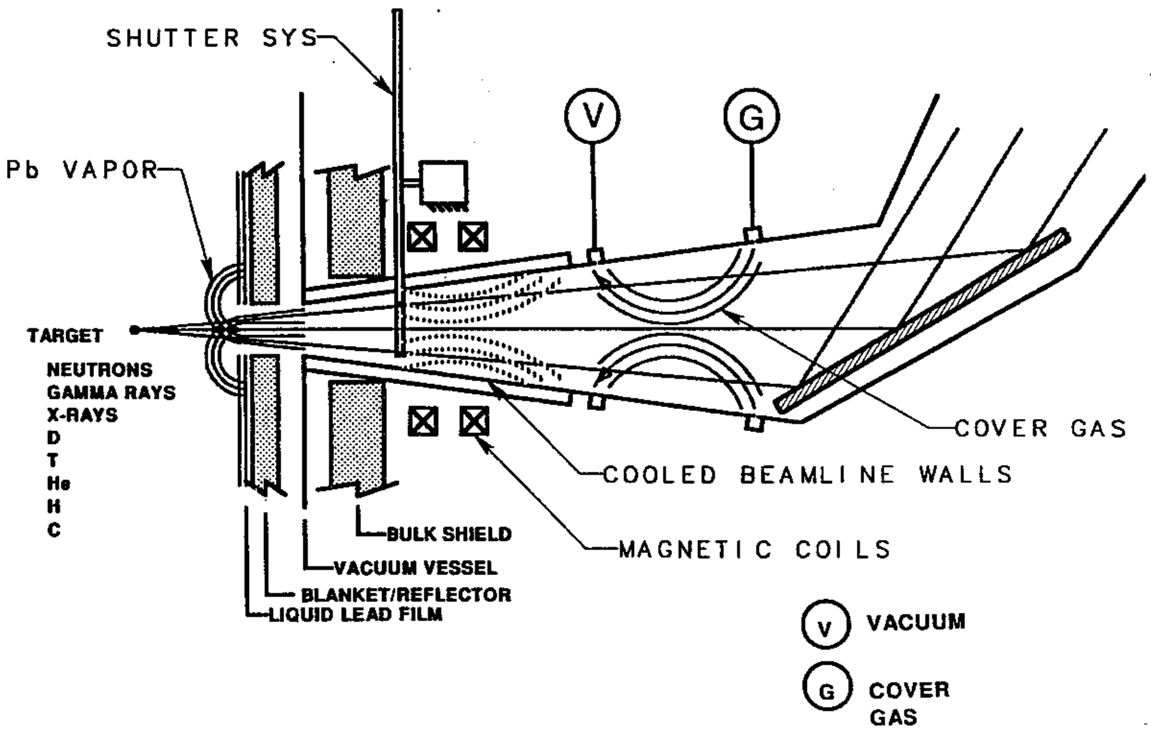

Figure 5.4-2. Protection Options for Final Optics Protection

(4) A flowing neon cover gas in each beamline, injected at one location and vacuum pumped at another to stop the remaining x-rays and sweep out vaporized gas. Alternatively, the beamline walls downstream of the GIMM can be heated to vaporize a portion of the protective liquid lead film providing a lead vapor protection gas. Any lead vapor recondensing on the GIMM surface will be vaporized by the laser prepulse beams.

(5) Cooling the beamline walls below the mirror surface temperature to assure that condensable gases stick to the walls instead of the optics.

(6) A low speed shutter system to intercept lead droplets that are blown off the walls and may make their way down the lower beamlines.

(7) Placement of the final optic element at a significant distance (25 m) form the target blast center to minimize shock waves and allow for $1/r^2$ attenuation of the heat flux and radiation.

(8) Use of a Grazing Incidence Metal Mirror (GIMM) as the final optic in each beamline to remove the dielectric-coated focusing mirrors from line-of-sight radiation. We feel that all of the above mechanisms are required to assure viable system performance. Lifetime is still an issue for the GIMM but swelling analysis indicates that it can be life-of-plant using the design approach we have developed. This topic is discussed as part of the GIMM critical issues.

Our baseline design employs all the protection methods above except the use of the neon cover gas and cooled beamline walls. The neon cover gas resulted in extremely difficult vacuum pumping requirements. Therefore, we chose to heat the beamline walls providing a Pb vapor cover gas and depending on the laser beams to remove recondensed vapor on the GIMM surfaces.

Reactor Concept - Prometheus-L

Potential Impact - (UL) The final optics are large area, expensive items subjected to a very harsh environment. If they are not properly protected, their lifetime will not be sufficient for economic power production.

Design Specificity - (DL) This issue is specific to the laser driver, but generic to the design of any laser-driven inertial fusion energy power plant.

Overall Level of Concern - (Critical) The design of the laser system/cavity interface is critical to the successful development of laser-driven inertial fusion energy power plants. The final optics are expensive and must repeatedly and reliably deliver their portion (~100 kJ) of the total energy to the target with microradian pointing accuracy for successful operation. These optics must furthermore have a multi-year lifetime for the plant to be economically competitive.

Operating Environment - (OF, F, S, C, T, n, γ, V, S, q)

Relevance to MFE - Low. This development issue is not directly relevant to MFE but there may be some aspects of the problem which have MFE relevance. For instance, some MFE plasma diagnostics may needs to operate in environments comparable to those expected for the final mirrors.

Analysis - Extensive literature reviews and analyses were conducted to substantiate the proposed laser system/cavity interface design. This activity is summarized in Table 5.4-3. This table indicates the sources of mirror degradation and the primary and secondary protection mechanisms for each source of degradation.

Table 5.4-3 Final Mirror Protection Summary

Source/Debris or Radiation	Debris or Radiation State	Range of Speed (m/s)	Protection Method*
Target			
X-rays	Radiation	$3x10^8$	SD; PBv; CG
Gamma Rays	Radiation	$3x10^8$	SD; PBv; CG
Neutrons	Particle	$3x10^8$	SD
Hydrogen	Ionized; Vaporized	(TBD)	PBv; M; CG; CBW; VP; S?
Deuterium	Ionized; Vaporized	(TBD)	PBv; M; CG; CBW; VP; S?
Tritium	Ionized; Vaporized	(TBD)	PBv; M; CG; CBW; VP; S?
Helium	Ionized; Vaporized	(TBD)	PBv; M; CG; CBW; VP; S?
Carbon	Ionized	(TBD)	PBv; M; CG; CBW
First Wall Film			
Lead	Ionized; Vaporized Liquid Droplets	(TBD) 9.8+	M; CG; CBW; S?

* Protection Methods

SD	Mirror Surface Design	CBW	Cooled Beamline Walls
PBv	Lead Vapor	VP	Vacuum Pumping
M	Magnetic Field Lines	S	Shutter System
CG	Cover Gas		

Issue K.2 SiC/Metal Piping Transition Interface

Description - The proposed Prometheus first wall and blanket are fabricated using low activation SiC/SiC composite materials to minimize the generation of high-level radioactive waste in these regions thus achieving an inherently safe design. However, the main heat transfer piping and steam generators can employ conventional high-temperature piping/structural materials since they are located outside the bulk shield where neutron activation is minimal. Furthermore, there is significant cost incentive to transition to conventional materials as soon as possible outside the bulk shield to achieve an economically attractive design. The transition interface between low activation SiC structure and conventional metal piping is therefore a key development issue for our Prometheus cavity design.

The transition from SiC to conventional piping involves large diameter piping that must be leak tight to 1.5 MPa (15 atm) helium and 23 MPa (20 atm) lead coolants and resistant to corrosion by impurities in the coolant streams. These joints must furthermore be capable of being broken and rejoined using remote handling equipment. Pipe diameters ranging from 1.0 m for the lead lines to 2.8 m for the helium lines are presently being considered. Therefore, both the material change and the pipe sizes make this a key development issue.

Reactor Concept - Prometheus-L and -H

Potential Impact - (IC) The primary heat transport/steam generator system(s) in a large nuclear power plant is complex and expensive. The bulk of this system is located in a low radiation environment and can therefore be fabricated from conventional materials to keep the cost for these items under control while still maintaining a low radioactive material inventory.

Design Specificity - (CS/CBOP) This issue is generic to any advanced nuclear reactor design employing ceramic reactor structures to achieve high levels of inherent safety but using conventional steam-cycle balance-of-plant systems to control costs. In the Prometheus design the transition interface involves the use of helium and lead coolants for primary heat transport.

Overall Level of Concern - Critical. The design of the piping transition interface is critical to the successful development of advanced, low-activation, ceramic structure nuclear power plants.

Operating Environment - (C, T, H, A, P, Q, I, v)

Relevance to MFE - High. This development issue is directly relevant to MFE designs that employ advanced ceramic structures.

Issue K.3 Heavy-Ion System/Cavity Interface and Beam Propagation, Focusing, and Optics Protection

Description - The interface between the heavy-ion system and the reactor cavity/target represents a key research and development area for the heavy ion-driver, heavy ion systems studies have typically proposed some form of ballistic focusing with varying degrees of and mechanisms for space-charge neutralization. Ballistic focusing requires large conical envelopes on two-sides of the target where multiple (typically 8 or more per side), large area (typically 1-m diameter) openings must be provided through the shield, breeding blanket and first wall. Since the beams converge at the target, this approach leads to significant line-of-sight radiation streaming down the center of the final focusing magnets which typically precludes the use of superconducting magnets for this purpose. This also complicates the wall protection system design since the interior walls of these beamlines must be protected from heating, blast and radiation damage effects. Furthermore the protection mechanism must not interfere with the propagation and focusing of the beams which must form a tightly-focused (<1-cm diameter) spot at the target. This typically requires background gas pressures of order 1 mtorr with Li vapor.

Our design instead proposes to use a self-formed transport channel to re-image the beam focal spot from outside the blanket onto the target. This has significant implications relative to the above issues for ballistic focusing. It moves the conical arrays of focusing magnets out of line-of-sight into the cavity minimizing the opening size in both the blanket and the first wall to something of order 10 cm diameter. This minimizes shielding concerns for these magnets, permitting superconducting coils to be employed. It also greatly simplifies the wall protection system design for the heavy ion-driver since the transport channels can be formed in a significantly higher (100 mtorr lead vapor) background gas environment than is possible using ballistic focusing. This enables us to consider using the same lead wetted-wall design for the laser and heavy-ion drivers.

Channel formation using light ion beams with pre-formed plasma channels is well documented and has even been considered for near-term applications such as the light-ion LMF, but self-formed channels are a different matter. Analyses indicate that stable, self-formed channels cannot be generated using light ions. These analyses are not valid for heavy-ions due to their higher energies (GeV as compared to MeV for light ions) and significantly greater mass (200 amu versus 7 amu). We have evaluated the first-order physics of heavy-ion channel formation and find no fundamental limitations. However, the dynamics of the problem are extremely complex and beyond the scope of our study. We have therefore targeted this as a key R&D area.

There are several critical issues which will require validation through experimentation and modeling before self-formed transport channels can be considered truly viable. Foremost among these is a laboratory demonstration of a self-pinched heavy-ion beam transport channel. The transport characteristics of the channel must then be assessed including: (1) fraction of the beam ions initially captured in the channel, (2) fraction of the beam energy lost due to background collisions and back EMF, (3) fraction of the beam energy lost near the target where opposing side channel currents begin to cancel the confining aximuthal field, (4) fraction of the prepulse energy eroded during channel formation, (5) capability of the channel to re-image the focal spot at the channel entrance onto the target, (6) limitations on beam focal spot size at the channel entrance, (7) demonstration of sufficient control over the channel to accurately position the focal spot on the target, and (8) characterization of background gas conditions/limitations for stable channel formation.

Reactor Concept - Prometheus-H

Potential Impact - (DW) The use of liquid lead for wall protection is probably not compatible with ballistic transport using our present design. An alternative, lower-Z wall protection material would be needed, or a different cavity design using a condensing vapor spray or a wall geometry with more exposed surface area.

Design Specificity - (DH, WP) This issue is specific to the heavy-ion driver coupled with a liquid lead wall protection scheme.

Overall Level of Concern - (High) The capability to form a stable, self-pinched transport channel to re-image a heavy-ion beam focal spot on a target would have significant positive economic and technical impact on design of a heavy ion-driven inertial fusion power plant.

Operating Environment - (ρ_g, Q, IB, G, N, T, E, EI, p)

Relevance to MFE - Low. This development issue is not directly relevant to MFE.

Analysis - Our study budgets/priorities did not permit any detailed analysis of heavy ion beam transport channel formation, stability and beam loss dynamics. We have assessed these issues and determined that there is no fundamental reason why self-formed transport channels will not work with heavy-ion beams. The potential technological and economic benefits of this mode of propagating the beams to the target warrants further investigation into their feasibility.