2.6 Key Technical Issues and R&D Requirements

Although significant progress has been made in inertial fusion energy research during the past decades, the field is still in its early stage of R&D and the present data base is very limited. Therefore, many uncertainties exist in the actual performance and operation of present fusion reactor conceptual designs. The expected consequences of these uncertainties vary in magnitude—on one extreme the uncertainties are so large that the feasibility of the reactor design is at stake, and on the other extreme, the uncertainties may simply require moderate redesign, reduced performance, or increased cost.

An extensive effort has been made in this study to identify and characterize the key physics and engineering issues for the two IFE conceptual reactor designs, Prometheus-L and H. However, many of the issues tend to be generic and are fairly independent of the specific design selections made in Prometheus. Therefore, the issues identified here are of general importance to IFE. Furthermore, an effort has been made in this study to indicate the relevance of the issues to MFE.

The key issues identified in this work are large in number and they cover specific technical issues ranging in complexity and importance. Each of these key issues impacts key aspects of feasibility, safety, and/or economic potential of inertial fusion reactors. Resolving these issues requires new knowledge through experiments, theory, and models. An attempt was made to identify the R&D required to resolve these issues. The R&D evaluation included a general description of required facilities, expected time duration, and costs.

The key issues are described in detail in Chapter 5. The description for each issue includes: potential impact, design specificity, level of concern, operating environment required in facilities to investigate the issue, the degree of relevance to MFE, and analysis to characterize the issue. As indicated earlier, the number of key issues is large, greater than one hundred. In order to provide a brief summary of the most important issues, a smaller number of issues (called critical issues) were identified. A critical issue is broader in score than a key issue; each critical issue may encompass several of the most important key issues for a number of components and technical disciplines.

Table 2.6-1 provides a list of the critical issues. These critical issues are presented in detail in Chapter 5. Following is a brief summary.

Table 2.6-1 List of Critical Issues

1. Demonstration of Moderate Gain at Low Driver Energy
2. Feasibility of Direct Drive Targets
3. Feasibility of Indirect Drive Targets for Heavy Ions
4. Feasibility of Indirect Drive Targets for Lasers
5. Cost Reduction Strategies for Heavy Ion Drivers
6. Demonstration of Higher Overall Laser Driver Efficiency
7. Tritium Self-Sufficiency in IFE Reactors
8. Cavity Clearing at IFE Pulse Repetition Rates
9. Performance, Reliability, and Lifetime of Final Laser Optics
10. Viability of Liquid Metal Film for First Wall Protection
11. Fabricability, Reliability, and Lifetime of SiC Composite Structures
12. Validation of Radiation Shielding Requirements, Design Tools, and Nuclear Data
13. Reliability and Lifetime of Laser and Heavy Ion Drivers
14. Demonstration of Large-Scale Non-Linear Optical Laser Driver Architecture
15. Demonstration of Cost Effective KrF Amplifiers
16. Demonstration of Low Cost, High Volume Target Production Techniques

(1) Demonstration of Moderate Gain at Low Driver Energy - The present U.S. national strategy envisions three major facilities for inertial fusion energy development at a cost of more than $1 billion per facility. Such a path makes the development of IFE very difficult in a constrained budget. Large capital expenditure requirements lead unavoidably to a long time scale. An alternative path that might potentially accelerate IFE development involves small to moderate size facilities with low fusion power. While such facilities may not be economically attractive they are most suitable for physics testing and engineering development. A key to the development of such small facilities is target designs that provide moderate gain (20-50) at low driver energy (1-2 MJ).

To help identify and quantify relevant target design goals, a system study was performed to define curves of required gain versus driver energy for a 100 MWe cost-limited demonstration power plant. Figure 2.6-1 shows the resulting gain requirement curves for a laser driver based on the Prometheus-L design at 10% and 15% efficiency for two different projected direct capital cost levels. Also shown is a comparison to possible pessimistic and optimistic physics limitations. The figure shows that target gains of 30-40 would provide a possible design window for 1-2 MJ driver energy. Such designs could likely be validated on Nova Upgrade. Figure 2.6-2 shows similar results for the Prometheus-H driver design. This figure shows that the higher heavy-ion driver efficiency leads to a possible design window with target gains of only 20-30 over the 1-2 MJ energy range. Thus, further design work on both heavy ion and laser targets appropriate for 1-2 MJ drive energy is clearly justified.

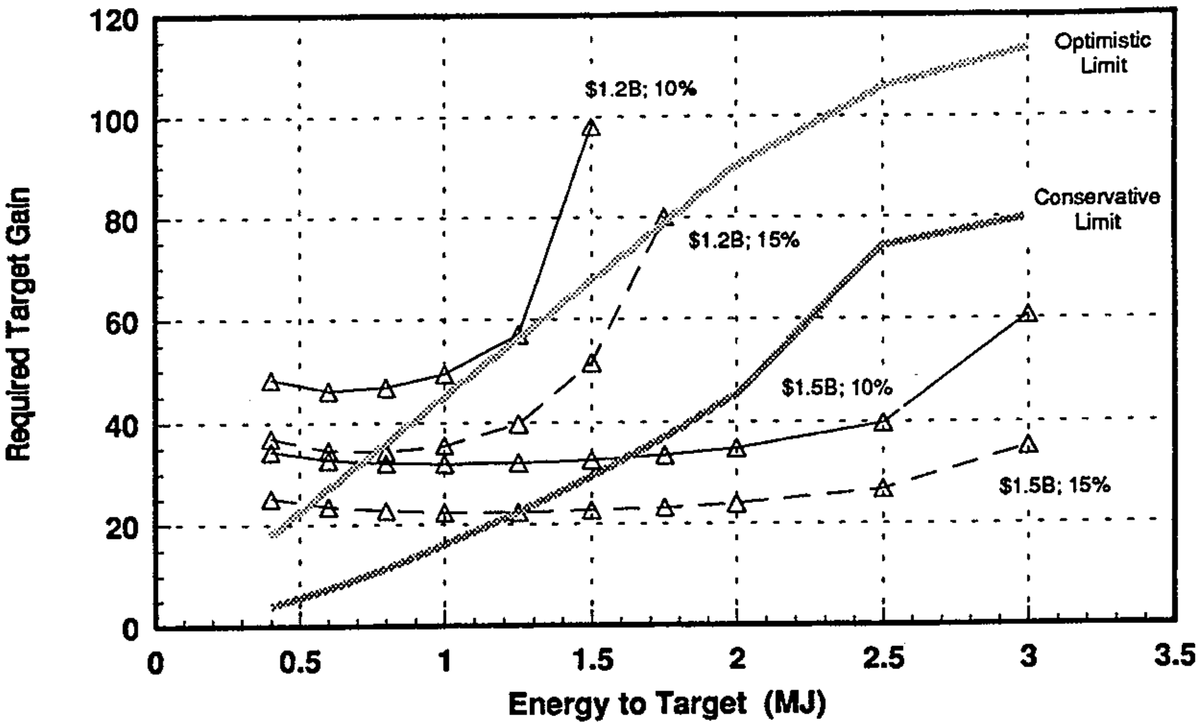

Figure 2.6-1. Projected 100 MWe Demonstration Power Plant Gain Space Windows for the Prometheus-L Driver Configuration. Values Indicated Only Include Direct Costs.

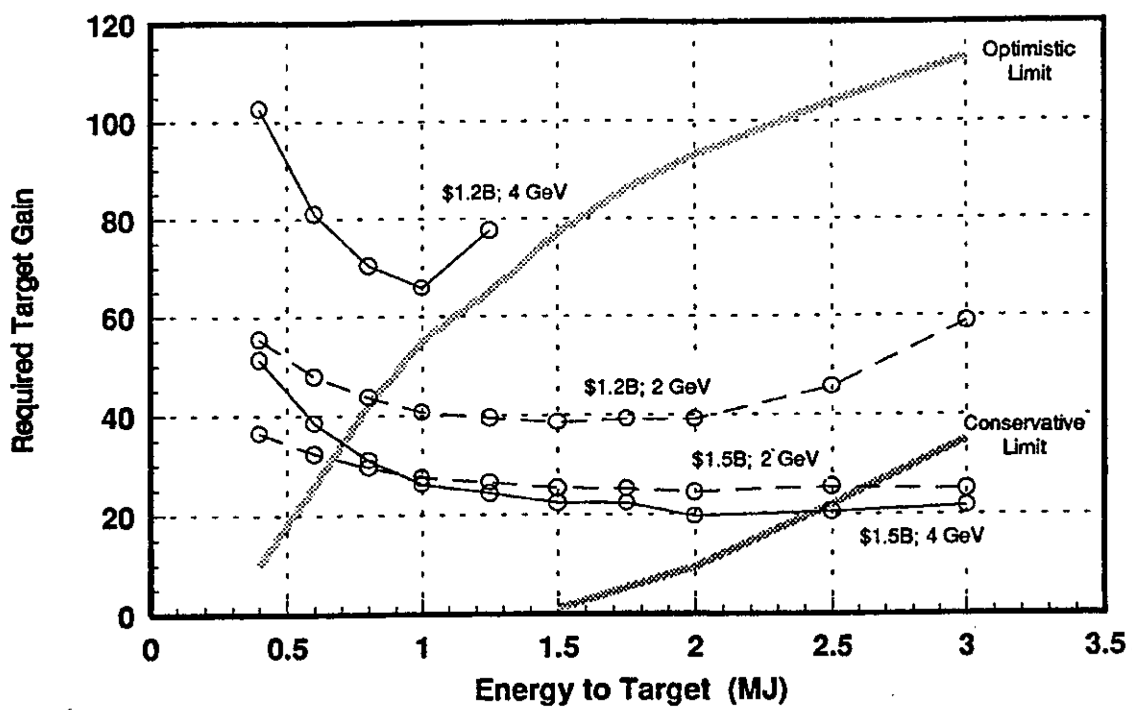

Figure 2.6-2. Projected 100 MWe Demonstration Power Plant Gain Space Windows for the Prometheus-H Driver Configuration. Values Indicated Only Include Direct Costs.

(2) Feasibility of Direct Drive Targets - There are strong incentives to consider direct-drive (DD) targets because of higher gains. However, the feasibility and performance characteristics of DD targets are presently uncertain. The fundamental Prometheus-L driver and cavity designs are strongly influenced by the direct-drive (DD) target illumination requirements given by the TWG. Unfortunately, the specified TWG requirements may contain some serious inconsistencies with published plasma physics requirements for efficient laser/target coupling. The laser driver spatial intensity profile in the target plane suggested by the TWG is not consistent with the Fresnel number of the beam at the location of the targets for the Prometheus-L design. In addition, the suggested long, 80 ns precursor pulse may produce significant deleterious effects, such as generation of non-linear scattering processes that may lead to target preheat, thereby preventing an efficient D/T implosion from occurring. TWG guidelines for DD targets appear to have been anchored on experiments conducted on miniature DD targets illuminated with only a few kJ of laser energy. Large reactor sized, multi-MJ DD targets will likely require different illumination scenarios. For reactor operation, the DD targets must also be accurately injected into the target chamber with an active tracking/alignment system capable of meeting the illumination uniformity requirements discussed in Chapter 5.

(3) Feasibility of Indirect Drive Targets for Heavy Ions - The feasibility of the indirect drive (ID) targets for the heavy ion (HI) driver is, in part, linked to the properties of the method used to transport the HI beam to the target, to the accuracy and reproducibility of the HI target launch system that repetitively propels the ID targets to the center of the target chamber, and to the ability of the high-Z hohlraum cavity to efficiently convert and smooth the radiation incident on the DT capsule. This study proposes innovative solutions to accomplish these tasks.

In the approach considered for the Prometheus-H IFE Reactor Design, seven heavy ion beamlets (six main and a prepulse) from two sides of the cavity are focused onto stripping gas jets at the back surface of the blanket. The beamlets are thereby highly stripped, yielding mega-ampere currents that trap the ions in a small diameter (5 mm) channel whose direction is (hopefully) accurately determined by the pre-pulse beam. This self-focused, small diameter beam subsequently strikes the energy converter regions at either end of the moving hohlraum target that has been accurately launched to arrive at the center of the reactor target chamber synchronously with the arrival of the HI beams.

Two types of ID heavy ion fusion targets were considered in this study:

(1) Lead and plastic targets designed for single-sided irradiation
(2) Similar targets designed for two-sided irradiation.

The feasibility of efficiently imploding both of these ID targets depends upon the successful resolution of a series of technical problems, including:

- Providing return paths for the MA beam currents incident on the target.
- Successful injection and self-pinching of the HI beams passing through the stripping jets into a self-focused, small diameter beam directed at the target.
- Accurate pointing of the transport channel(s) at the energy converter regions.
- Accurate launching of the targets to arrive at the center of the target chamber synchronously with the arrival of heavy ion beams.

(4) Feasibility of Indirect Drive Targets for Lasers - As was assumed in the indirect drive, heavy ion fusion target, the indirect drive laser fusion target considered in the Prometheus study is a similar lead, two-sided hohlraum. The feasibility of efficiently imploding this ID laser target involves concerns arising from three major sources:

- Closure of the two entrance apertures to the hohlraum by ablation plasma.
- Accurate target tracking and pointing of the required multiple laser beams to coincide with the two entrance apertures of the moving ID target.
- Accurate and reproducible launching of the indirect drive targets into the center of the target chamber.

Significant misalignment of the laser beams could damage the radiation casing of the target capsule and cause a target misfire.

(5) Cost Reduction Strategies for Heavy Ion Drivers - The attraction of the Heavy Ion (HI) approach to IFE has always been related to the fundamental technical feasibility of building a system with the required properties to drive a pellet to ignition. The basic accelerator technology is well developed, the beam physics is tractable, and existing accelerator systems have exhibited 25-year lifetimes with 95% availabilities. A system to provide the required average power could have been built ten years ago. The problem is cost. A 10 GeV linear accelerator built with today's technology would cost billions of dollars.

There are two key issues associated with the HI driver cost reduction strategies proposed by this study:

- Space charge limited transport of a bunched beam.
- High current storage rings for heavy ion beams.

Existing experiments and computer simulations indicate that transporting HI beams for several km at their space charge limit is feasible but this has not been demonstrated at the proposed beamlet current levels. More restrictive limits would increase the number of beamlets further complicating the LINAC design. The ILSE program will address many of these issues. The proposed use of high current storage rings results in significant cost savings for the LINAC but shifts technology risk to the storage rings. Issues of resonance losses and beam induced vacuum instability must be addressed.

(6) Demonstration of Higher Overall Laser Driver Efficiency - The excimer laser driver system has a number of components that can individually be optimized to improve efficiencies. The achievement of higher efficiency is now viewed as a crucial requirement for laser drivers to compete economically with heavy ion linacs for IFE. This, however, cannot be at the sacrifice of reliability. The laser driver consists of four major elements: (1) the excimer laser amplifiers, (2) the Raman accumulators, (3) the SBS pulse compressors, and (4) the computer controlled and self-aligning optical train which directs the laser beams through the various optical components and down into the target chamber.

The latter three elements require some additional development and testing before they can be judged adequate to be incorporated into a mature laser driver design. The major problem to be addressed here is the first element, the excimer laser amplifiers.

The key to an efficient, reliable Prometheus laser driver is the successful design, construction, and testing of modular excimer laser amplifiers.

During the past five years, relatively little work has been carried out in the U.S. with regard to improving the efficiency and the reliability of moderate-sized excimer laser amplifiers. Some analytical studies[1] have been carried out on both electron-beam excited excimer lasers (EBEELs) and electron-beam sustained electric discharge lasers (EBSEDLs) which offered (on paper) gross wall plug efficiencies as high as 17%. These efficiencies, however, are more likely to be reduced significantly if incorporated into a large laser system architecture. The main concern is that no experimental work in excimer amplifier development is either currently in progress or planned in the U.S. Work in the Soviet Union with sliding discharge cathodes in CO_2 discharge lasers has produced some promising results which may offer alternatives to the EBSEDLs.

(7) <u>Tritium Self Sufficiency in IFE Reactors</u> - Satisfying fuel self sufficiency conditions is necessary for a renewable energy source. A key condition is that the achievable tritium breeding ratio (TBR), Λ_a, must be equal to or exceed the required breeding ratio (Λ_r). Analysis shows considerable uncertainties in estimating Λ_a and Λ_r. The required TBR is a strong function of many reactor parameters as shown in Figure 2.6-3. Λ_r is particularly sensitive to the tritium fractional burnup in the target, the mean residence time of tritium in the target factory, the number of days of tritium reserve on site, and the reactor doubling time. For Prometheus, reference parameters Λ_r is ~1.05. However, Λ_r rises rapidly to ~1.2 or higher when significant changes are made in the reference parameter set, as shown in the figure.

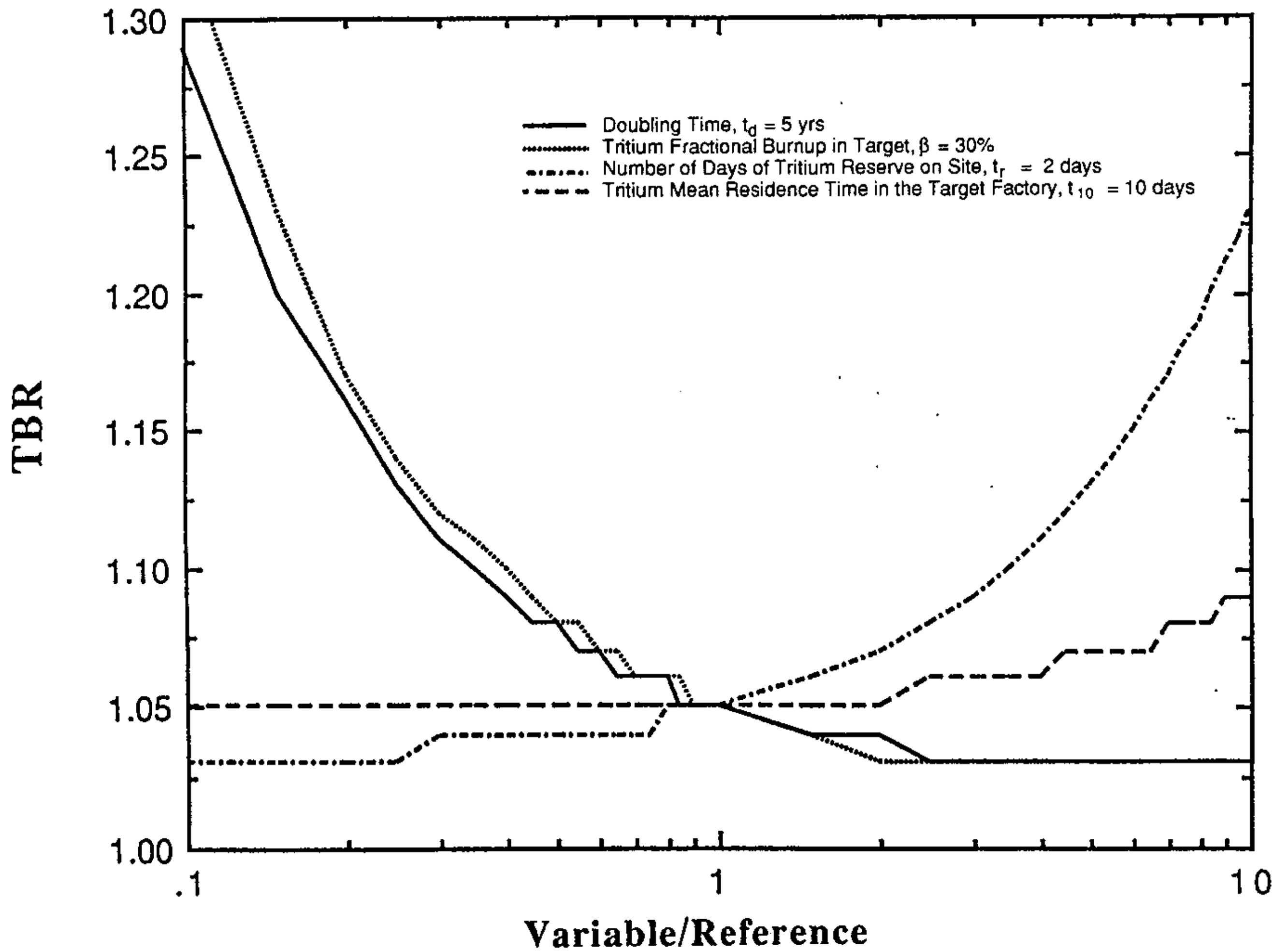

Figure 2.6-3. Variation of Required TBR with Reactor Parameters

The achievable TBR, Λ_a, is also a function of the reactor design with strong dependence on the first wall and blanket concepts. Accurate prediction of Λ_a suffers from uncertainties in the system definition and inaccuracies in prediction due to errors or approximations in basic nuclear data, calculational methods, and geometric representation.

For Prometheus, the reference Λ_a is ~1.2. Thus, the Prometheus design appears to satisfy the tritium self sufficiency conditions. However, in view of the large uncertainties in Λ_a and Λ_r, significant R&D is required. Furthermore, self sufficiency conditions impose clear requirements on the parameter space in which IFE reactors are allowed to operate. These are discussed in Chapter 5.

(8) Cavity Clearing at IFE Pulse Repetition Rates - IFE reactors must be pulsed several times per second. Following each pellet explosion, target debris and materials evaporated from the cavity surfaces must be removed before the next target is injected. The base pressure requirements are important for three reasons: (1) the time required to evacuate the chamber depends on the pressure, (2) the level of protection to the first wall (and final optics) afforded by the background gas depends strongly on pressure, and (3) propagation of targets and driver energy are strongly influenced by the base pressure. For the Prometheus designs, these issues are of greatest concern for the laser driver. However, heavy ion beam transport without transport channels involves comparable pressure requirements.

Calculations for Prometheus indicate the cavity pressure drops below 1 mtorr before the next shot, which is adequate for propagation of targets as well as laser and heavy ion beams. However, the actual physics of energy and mass transport and vapor recondensation is very complex under the extremely dynamic conditions following a target explosion. The cavity gas is partially ionized and subject to highly time-dependent processes such as hydrodynamic shock waves. Non-ideal effects such as liquid droplet formation and effects of penetration provide additional uncertainties.

(9) Performance, Reliability and Lifetime of Final Laser Optics - Previous IFE studies identified radiation protection of final optics as a serious issue in laser-driven reactors because of severe effects of radiation on the performance, reliability, and lifetime of the final optics. In this study, workable conceptual focal mirror designs were introduced. These designs involved both the dielectric turning mirror and the final optical component, the Grazing Incidence Metal Mirror (GIMM). Analyses indicate that, with proper selection of materials

and mechanical configuration, the GIMM lifetime may be very long—on the order of the plant lifetime. This approach, coupled with clever shielding designs and materials selection for the dielectric elements, will likely lead to great improvements in the overall laser reactor concept. All previous studies of laser fusion have concluded that the final mirror will need to be located in excess of 30-40 m away from the cavity center and that the lifetime and reliability will be small. An in-depth study of the performance, reliability, and lifetime of the final dielectric components for the GIMM geometry is necessary. Advances in this area will undoubtedly lead to significant improvements of the entire concept and will likely benefit other technological areas which rely on the reliable performance of large laser mirror systems.

(10) Viability of Liquid Metal Film for First Wall Protection - In the Prometheus designs, a thin liquid metal film wets the first wall in order to prevent the solid structures from rapidly degrading due to the extremely high instantaneous heat and particle loads. To prevent liquid from entering the cavity, the thickness of the film is maintained as small as possible. For this scheme to be successful, all structures exposed to the blast must be covered. Analysis of dry spots suggests that operation of the SiC wall can be operated at full power for 10 to 15 minutes without irreparable damage to the first wall.

While a great deal of research has been carried out on film flows, the materials, configuration, and environmental conditions for fusion are unique, and little effort has been expended in the IFE community to determine how films will behave under these conditions in a real engineering system. The major uncertainties include: film feeding and thickness control, blast effects, flow around geometric perturbations (such as beam penetrations), and protection of inverted surfaces.

The film thickness must be relatively uniform in Prometheus because the surface power conducts through the film. The local film thickness determines the local surface temperature, which strongly influences the condensation rate. Even for very thin films, the flow becomes turbulent and instabilities are likely to develop. Therefore, a better understanding of the nature of instabilities and possible remedies is critical. Good wetting between the solid surface and liquid film is very important.

Explosive effects resulting from the blast may lead to further problems. The problem of wall protection with films near inverted surfaces is particularly difficult.

(11) Fabricability, Reliability, and Lifetime of SiC Composite Structures - The viability of using SiC structures in the first wall and blanket is a 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. Without this knowledge, system reliability, maintenance, and economics would be seriously challenged. In order to perform this task, several investigations need to 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 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. A detailed assessment 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 both economics and design.

(12) Validation of Radiation Shielding Requirements, Design Tools, and Nuclear Data - Radiation shielding must protect both personnel and sensitive reactor components. Components with the most stringent protection requirements include the final optics in a laser-driven fusion reactor. Other components with important radiation protection requirements include magnets in the heavy ion driver and instrumentation and control. Two important requirements must be imposed on the radiation shield in order to enhance attractive environmental and safety features of IFE reactors. First, the bulk shield (immediately surrounding the blanket) must be designed so that the long-term activation in reactor components outside the cavity and inside the reactor building is minimum. Second, the IFE shield should be designed to permit some personnel access to the reactor building outside the bulk shield within days after shutdown.

These critical requirements on the shield combined with the fact that the shield is one of the largest (in volume and weight) and more expensive components in an IFE reactor necessitate careful shield design. Sophisticated capabilities for predicting the radiation field and associated radiation response in materials are required. Although advanced capabilities exist, uncertainties in accuracy remain due to modeling complexities, nuclear data uncertainties, limitations of calculational methods in void regions and deep radiation penetration problems, and time dependent behavior of materials and components. Improvements in methods, data, and experimental verification of prediction capabilities are needed.

Establishing accurate radiation protection requirements is also necessary, particularly for components whose shielding is either physically difficult (e.g., final optics in laser driver) or results in substantial economic penalty.

(13) Reliability and Lifetime of Laser and Heavy Ion Drivers - The reliabilities and lifetimes of excimer laser and heavy ion driver systems profoundly affect the operating characteristics of an IFE reactor. The critical problems associated with the two drivers are discussed in Chapter 5. IFE can likely benefit from the decoupling of the driver from the cavity nuclear environment, but the drivers are complex, high technology pieces of equipment that require careful development to realize their potential.

(14) Demonstration of Large-Scale Non-Linear Optical Laser Driver Architecture - The fundament of the Non-Linear Optical subsystems proposed for the Prometheus-L driver is based upon a very strong experimental and theoretical basis of non-linear optics. Since both proposed subsystems are simply large optical cells filled with H_2 and SF_6 respectively, there are very few components present which can fail. The primary question is how well the system will function on the first pulse. If the electro-optical subsystems can be tailored to achieve first time operation, the overall architecture should prove to be as reliable as other state-of-the-art, high speed, high voltage electronics. A balance must be struck between the extremely high gains and concomitant high conversion efficiencies of which these systems are capable. Thus, the reliabilities and lifetimes of the two types of non-linear optical subsystems proposed for the Prometheus-L IFE reactor design hinge primarily on the support optical equipment that is associated with the non-linear optical (NLO) devices. The two NLO devices are: (1) the Raman accumulators, and (2) the SBS pulse compressors.

Numerous key non-linear optical (NLO) subscale experiments and analyses have been performed in the last 20 years that demonstrate the capabilities of these two types of NLO devices. In order to properly implement them, however, each needs to be supplied an appropriate Stokes seed beam, and therein lies most of the questions regarding successful implementation.

Subscale experiments have demonstrated efficiencies comparable to those proposed here for both Raman and Stimulated Brillouin conversion, but full aperture cells require technology development. This is also true for the large aperture Pockels cells proposed for converting the depleted SBS pump beams into a target prepulse. The SBS pulse compressor and attendant Pockels cell E/O switchyard represent the highest risk elements in the Prometheus-L design.

(15) Demonstration of Cost-Effective KrF Amplifiers - One of the key elements associated with developing a cost-effective KrF laser driver for the Prometheus study is the design of the output KrF laser amplifier module. These KrF amplifier modules represent the fundamental building blocks of the KrF driver, generate the output energy pulses for the KrF laser driver, and the nature of their design represents a major fundament of the laser driver reliability.

Previous Department of Energy (DOE) and Department of Defense (DOD) excimer laser research and development programs have identified two general excimer laser amplifier design configurations:

(1) Direct electron beam excitation of relatively large (V > 1000 liters) excimer laser amplifier volumes.
(2) Electric discharge excimer laser amplifiers with the excitation of the KrF excimer achieved along the neutral channel for geometries involving moderate volumes (<200 liters).

The first excimer laser amplifier design configuration, electron beam excited excimer lasers (EBEL), has received extensive development from both the DOE and the DOD with KrF amplifier modules as large as 2000 liters being constructed. The second configuration, electric discharge excimer lasers (EDEL), has been much less thoroughly investigated; some preliminary theoretical work was funded by DOE[1] several years ago, but little experimental verification of the predicted high EDEL efficiency was made.

The EBEL has received priority development over the EDEL because the EBEL scales to larger volumes (and hence larger output energies) much more readily than does the EDEL. For single-shot DOE applications and for some DOD applications, this scalability advantage of the EBEL has been important. For an IFE reactor application in which reliability for 10^9 cycles over long periods of time at repetition rates of 3-10 Hz is crucial, the potentially higher reliability of the EDEL enhances its attractiveness. Development issues confronting both approaches are summarized in Table 2.6-2.

Table 2.6-2 Summary of EBEL and EDEL Development Issues

No.	Description of Problem Area	Possible Solution
EBEL		
1	Foil Rupture	Homogenize E-Beam Current Density
2	Parasitic Oscillations	Lower Amplifier Reflectivities
3	Amplified Superfluorescence	Reduce Amplifier Solid Angle
4	High Cost of Large Windows	Segmented Optics
5	Radiation Damage from E-Beams	Lower Anode Voltage
6	Reduced Beam Quality	Phase Conjugation
7	Optics Damage	Reduce Radiation Fluence
8	Catastrophic Failure Mode	Redesign Foil Support Structure
EDEL		
1	Stabilization of Discharge	Discharge Uniformity; Control F_2 Burn
2	Uniformity of Discharge Excitation	Elimination of Cathode Fall Region
3	Reduced Excimer Beam Quality	Beam Combination in Raman Cell
4	Achieve 10^9 Shot Lifetime	Engineer Pulsed Power/Electrodes
5	Optics Damage	Reduce Radiation Fluence
6	Verify Excitation Efficiency	Conduct Full-Scale Experiments

(16) Demonstration of Low Cost, High Volume Target Production Techniques - Target production for IFE reactors will require technologies that are presently either non-existent or insufficiently developed for such an application. It is, therefore, very difficult to accurately estimate the production costs of such targets. These difficulties are further aggravated by the potential need for sabots to deliver the targets to the reactor chamber and, as in the indirect drive target, for an outer case which must meet stringent engineering requirements. Target cost is clearly a critical issue in light of the fact that IFE reactors will consume huge numbers of targets (on the order of 10^8 per year) and will be uneconomical and, therefore, impractical if these targets are too expensive.

Reference for 2.6

1. "New Techniques for KrF Laser Fusion Systems," Interim Report for Los Alamos National Laboratory, Mark Kuschner, et al., Spectra Technology, Inc,. Seattle, WA (1986).