2.7 Comparison of IFE Designs

There are several design and technology options for IFE reactors, e.g., laser and heavy-ion drivers, direct and indirect drive targets, and dry and wetted first wall. Comparison among options is necessary in order to select, or at least reduce, the number of options that are worthy of further R&D. This study developed a clear Evaluation Methodology that permits quantitative analysis and comparison of options. The insight gained from the process of applying the methodology is by itself as valuable as the quantitative results. The methodology was applied to compare the two Prometheus reactor designs developed in this study, one with laser and one with heavy ion-driver.

Design options for power plants that can be constructed today can generally be compared based on economics and safety and environmental attractiveness. However, fusion is in a relatively early stage of research and development. The data base is incomplete and success in developing particular design options for subsystems cannot be assured. Designers have to extrapolate present knowledge to predict performance in fusion power reactors, with the degree of extrapolation varying greatly from one design option to another. Furthermore, there are substantial differences among proposed design options in the probability of success and in the time and cost required to develop these options. Therefore, a prudent evaluation methodology for comparing fusion reactor conceptual designs must account for these differences.

Five major areas of evaluation were established. These are:

(1) Physics Feasibility
(2) Engineering Feasibility
(3) Economics
(4) Safety and Environment
(5) Research and Development Requirements

Each of the above areas is quantified through a system described in Chapter 5. In this system, a number of detailed criteria are developed for each area. For each criterion there is an attribute (index) that can be quantified. A weighting scale is devised for the attributes. The weighted sum of the attribute for each evaluation area represents a SCORE for this area.

The result of the evaluation process for a given reactor design concept is a numerical score for each of the five evaluation areas. No mixing of the scores for the five evaluation areas was attempted; i.e., the numerical scores for the five areas were not combined to derive one final composite score. Instead, the overall comparison is based on a qualitative judgment of the relative scores for the five areas. This process is highlighted in Figure 2.7-1. Ideally, a panel of knowledgeable experts would interpret the resulting scores in each of the five evaluation areas and collectively agree

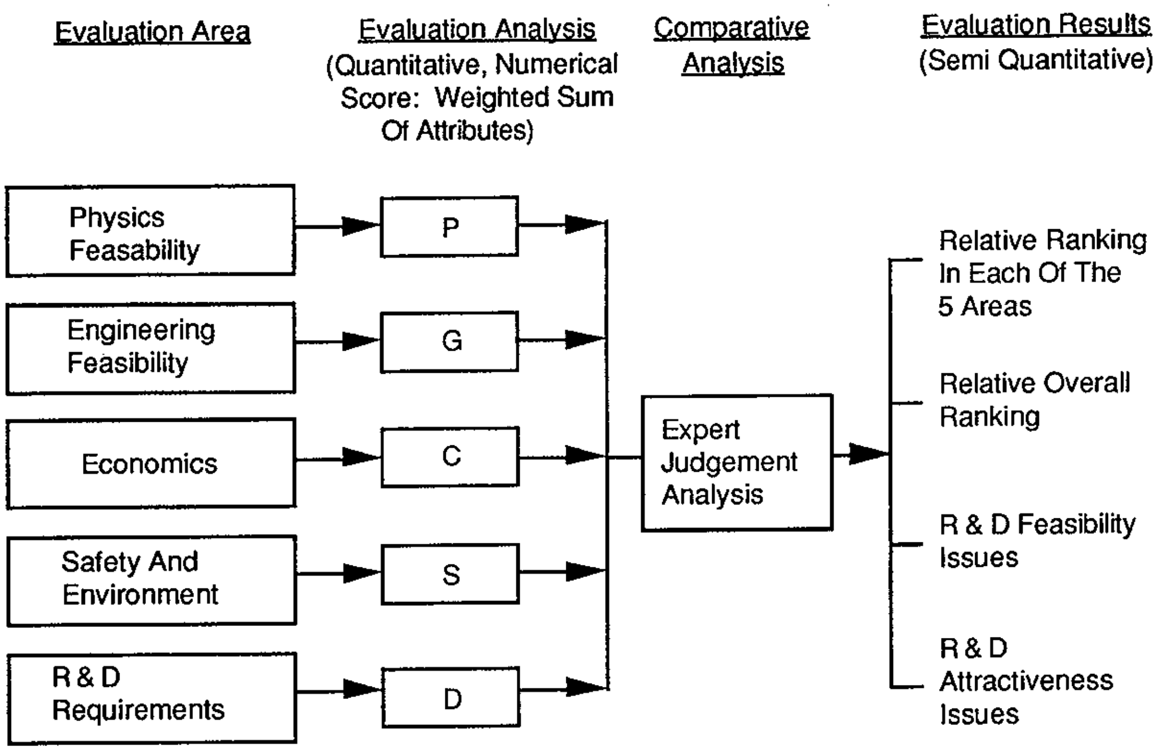

Figure 2.7-1. Evaluation Methodology Approach

on the relative merits/issues for both approaches. Time did not permit this part of the comparison to be completed.

This methodology was used to compare the laser- and heavy ion-driven reactor concepts developed in Prometheus. The details of the results for the five evaluation areas are given in Chapter 7. A summary of the final figures of merit for the five evaluation areas is given in Table 2.7-1. The scores were normalized so that higher numbers correspond to a more favorable assessment. Two key conclusions can be made based on the overall evaluation analysis and the scores in Table 2.7-1:

(1) Heavy ion-driven reactors appear to have an overall advantage over laser-driven reactors based on existing R&D data and performance projections.

(2) However, the differences in scores are not large and, given technology uncertainties, results of future R&D could change the overall ranking of the two IFE concepts.

Table 2.7-1. Summary of Scores for the Five Evaluation Areas

	Score*	
Evaluation Area	Laser-Driven	Heavy Ion-Driven
Physics Feasibility (P)	50	57
Engineering Feasibility (G)	85	93
Economics (C)	68	78
Safety and Environment (S)	95	93
R&D Requirements (D)	52	56

*Scores normalized so that higher numbers reflect better scores.

2.8 Study Conclusions

This study has contributed greatly to the advancement of the state-of-the-art for IFE conceptual reactor designs. The results show that self consistent designs can be developed for IFE commercial power plants that have excellent potential to be economically competitive with very attractive safety and environmental features while maintaining a high degree of technical credibility. The study has developed a number of innovative concepts that, if proven out, would resolve known problems and enhance the attractiveness of IFE power plants. Key issues have been identified and characterized and the R&D required to resolve them has been described and documented.

Targets - Both direct drive and indirect drive targets have been examined for use with the laser driver. From the data provided by the TWG, it is concluded that the direct drive target is more attractive for a commercial laser-driven power plant. The principal reasons are higher gain at the same driver energy and lower cost per target. However, significant uncertainties exist in the capability to realize this suggested performance advantage. For the heavy ion concept, the indirect drive target is chosen. The beam geometry for direct drive presents a very difficult engineering problem because of the stiffness of the high energy beams. Indirect drive targets mitigate these concerns because they are only illuminated from two sides. In addition, no gain data was provided for direct drive heavy ion targets.

The functions and processes necessary for a target factory have been identified and tested. It is concluded that both direct and indirect drive targets can be produced at 20 cents or less per target (fuel and O&M) assuming reactor-size shells can be mass produced using droplet generators combined with microencapsulation. Large, thick shells meeting the high requirements on surface finish and shell geometry required of reactor grade targets have not yet been produced using these methods. However, it is argued that no great technological leap of faith is necessary to assume they will be available. Few attempts have been made to create large, thick shells because there has been no demand for them. Available drivers require much smaller targets. If significant research and development resources are made available, it is considered very likely that the necessary technology will be developed. It is also concluded that the diffusion filling with beta layering techniques will make it possible to fill reactor targets with DT fuel and then deposit the fuel into a uniform ice layer as called for in the TWG guidelines. These techniques will make it possible to cheaply mass produce targets without surface holes or cracks and to dispense with fabrication steps such as joining and fitting shell hemispheres with fill plugs.

Two target injection systems have been developed—a pneumatic system for the heavy ion indirect target and an electromagnetic system with a sabot for the laser direct-drive target. It is concluded that systems meeting the reliability and accuracy requirements of IFE reactors can be produced using presently available technology. Few conclusions can be drawn regarding the design and physical performance of IFE reactor targets in an unclassified report.

Laser Driver - During the course of this study, it has been demonstrated that the application of current excimer laser and non-linear optical technology will permit the construction of a laser driver capable of meeting the demanding performance requirements while maximizing safety and reliability. For direct-drive (DD) targets, the optimum Prometheus-L laser driver pulse was found to consist of a total energy of 4 MJ delivered in two temporal formats: a ramped precursor pulse containing 30% of the energy (or 1.2 MJ) and a main laser pulse with the remaining 70% (or 2.8 MJ). The 4 MJ is equally distributed among 60 beamlines (for DD targets) and delivered at a 5.65 pps repetition rate. Similar results were obtained for indirect-drive (ID) targets using a different beam configuration.

The Prometheus-L laser driver design achieves high levels of safety and reliability. This improved safety and reliability is accomplished through the use of numerous (~1,020) small, fail-safe electric discharge excimer lasers (EDELs), Raman accumulators, and SBS pulse compressors. Furthermore, it was found that gas pressures inside the excimer lasers, Raman accumulators, and stimulated Brillouin scattering (SBS) pulse compressors could be selected to lie near 1 amagat densities, thereby permitting the use of thinner windows and reducing gas overpressures. On the basis of currently available technology (together with projected future reliability development), an ultimate goal for mean firings between failure of ~10^9 amplifier pulses was projected. Past work suggests that moderate-sized electric discharge excimer lasers (EDELs) provide the most promising development pathway to this goal.

By reducing the required EDEL output energy to a moderate range lying between 4 and 6 kJ, it was found that the Prometheus-L laser design permits EDEL failures during normal operation to occur without forcing a corresponding shutdown of the IFE reactor. Since approximately 1,020 6-kJ EDELs are required in the 60-beam Prometheus-L laser driver, the failure of one amplifier would reduce the energy in a single beam by only 6%, an amount that could readily be overcome literally on the next firing of the laser driver by increasing the output energy of each remaining amplifier by 6%, a feat which could be automatically accomplished by the Prometheus-L computer control system.

It was found that the development of a comprehensive laser driver control system was a key element in meeting projected driver reliability requirements. In many cases, the analyses showed that the laser driver control system would be able to compensate for the loss of a particular driver component by employing redundant elements or by increasing the output for similar elements working in parallel. These analyses indicated that it was feasible for each of the 60 Prometheus-L beamlines to deliver approximately 67 kJ to the target (for DD irradiation) following pulse compression.

It was also found that, by using the Prometheus-L driver design, the "depleted pump" pulse from the SBS pulse compressors could be used to generate the target precursor ramp pulse (required to contain ~30% of the laser energy). Because the short (SBS Stokes output) main pulse precedes the longer duration depleted pump pulse out of the SBS pulse compressor, an electro-optic switchyard is provided to invert temporarily the order of the pulses. In the Prometheus-L design, this is accomplished with a large aperture Pockels cell, a Brewster-angle polarizer, two mirrors, and several large aperture quarter-wave plates arranged in an optical delay line.

In this manner, the required complex, high power pulse shapes required for both DD and ID target irradiation can be generated at relatively high efficiency (~75% from the output of the discharge lasers to the target) and high reliability (10^9 firings) by the NLO beam combination and pulse compression subsystems of the Prometheus-L driver. Furthermore, a collimating mirror in each beamline, which focuses each of the 60 beams down through a radiation-limiting field stop located in the shielding, significantly reduces the amount of radiation escaping from the Prometheus-L target chamber.

Lastly, it was found that, by allowing the focusing mirror to image the field stop focus onto a plane located a few centimeters behind the DD target, it is feasible to apodize the laser beams. Thus, the incoming beams can be nested on the spherical surface of the target at relatively small angles of incidence ($\lambda_{max} < 23°$). Calculations indicate that this beam arrangement enhances inverse Bremsstrahlung target coupling compared to the conventional tangential focusing geometry. Supporting analyses suggest that the precise sensing of the target location required for such advanced illumination schemes can be accomplished holographically using laser beams reflected from a "shine shield" on either DD or ID targets.

Heavy Ion Driver - Performance optimization studies for the Prometheus-H design led to a HI driver energy of 7.8 MJ. This energy is provided in the form of 18 beamlets of 4 GeV lead ions at a pulse repetition rate of 3.54 pps. Six of these 18 beamlets (three per side) are used to form a single, larger prepulse for each side of the target. The remaining 12 beamlets (six per side) form the main target compression pulse.

For the indirect drive HI target, the optimized pulse consists of a ramped precursor of approximately 30 ns duration containing ~30% of the energy and a main driver pulse of 7.3 ns duration having the remainder of the driver energy. The six main beamlet focusing magnets are bundled around the single precursor magnet on an 8.5° cone.

In the Prometheus-H focal geometry, the precursor beams enter the target chamber on axis of a self-pinching transport channel.

During the study, it was concluded that a single-beam LINAC consisting of a ramp-gradient and constant-gradient section operated in a 30-kHz burst mode could generate the 18 HI beamlets serially at significantly lower cost than was projected to accelerate the beamlets in parallel. Since the energy must be delivered to the HI target simultaneously, the LINAC output is transferred into 14 superconducting storage rings to hold the beamlets until the total energy is generated (<1 ms). The Prometheus-H control system then initiates appropriate switching magnets that eject the 12 main pulse beamlets into one multiple beam buncher accelerator (designed to create 7.3 ns pulses) and eject the remaining two precursor beamlets into a second buncher accelerator (designed to create 30 ns pulses).

It was observed that the application of current superconducting accelerator and particle beam technology permitted the construction of a HI driver capable of meeting the derived HI driver performance requirements. An important element in the Prometheus-H control system was the capability to sense driver component failure modes before failure occurs.

A key feature of the Prometheus-H driver beam transport is a pair of pre-formed channels combined with self-pinched beam propagation to the target through two small (2-cm diameter) openings in the target chamber blanket (for two-sided ID targets). Although review of previous work has shown that this HI beam self-pinched channelling approach requires additional technological development, the resulting focusing geometry has significant shielding advantages over conventional ballistic focusing, which would require focusing through 14 relatively large openings in the HI target chamber blanket.

Lastly, it was determined that the six superconducting main pulse beamlet focusing magnets can be configured with an allowance for radiation shielding on a cone subtending a small angle (8.5°). By passing the beams through a lead vapor neutralizing cell, the beams form small waists (<6-mm diameter) at the rear surface of the blanket that intersect at a common point. Further calculations showed that a lead vapor jet at each HI focus could then serve to strip the 4 GeV lead beams to a high charge state thereby boosting the beam current above 1 MA. The resulting high solenoidal magnetic field of the combined stripped beams is capable of collapsing all six main HI beamlets on each side of the target chamber to self-pinch within the channel and re-image the 6-mm diameter focal spot on the target.

Reactor Cavity - Design work on the reactor cavity shows that the cylindrical configuration is more favorable than other geometries. It is consistent with conventional plant layout and, at the same time, allows for better control over the flow of the thin liquid film on the surface of the first wall.

The unique physical separation of first wall and blanket functions resulted in a number of important consequences. First, the lifetime of the FW system, which is shown to be governed mainly by radiation-induced swelling, will be shorter than that of blanket modules. Thus FW modules can be separately changed on a more frequent basis. The overall reliability of the cavity is thus enhanced and the downtime minimized. The first wall system handles over 40% of the total power in a relatively small volume. In fact, the average power density in the FW system is about a factor of 20 higher than that of the blanket/reflector system. We conclude that the separation between the functions of the first wall and the blanket adds a desirable flexibility to IFE reactor designs.

The wetted wall concept adopted in our study offers several advantages over other wall protection schemes. The concept allows for good accommodation of beam lines, low liquid metal inventory with the associated safety benefits, and shorter time between successive pulses.

With a ^{6}Li enrichment of 25%, a tritium breeding ratio of 1.2 is achieved in the cavity design. The current nuclear design of the blanket results in a power multiplication factor of 1.14. The thermal-hydraulic design approach uses low-pressure helium coolant with an inlet pressure of 1.5 MPa to enhance the system safety and component reliability.

Structural materials are selected to achieve the following design goals:

(1) High-temperature operation or improved thermodynamic cycle efficiency.
(2) Low-activation for shallow land burial waste disposal.
(3) Low afterheat for mitigation of operational accidents.

An optimum choice, which satisfies all these conditions, was concluded to be the SiC/SiC composite material.

For the laser optical system, a unique design was achieved for the last optical component: the Grazing Incidence Metal Mirror (GIMM). It was concluded that a long lifetime for the GIMM can be achieved if the optical function of the surface is separated from the structural function. This is realized by depositing a thin layer of aluminum on top of a rigidly clamped structural composite. When the thickness of the aluminum layer is graded, such that the leading edge of the mirror is thinner than the trailing edge, plant lifetime can possibly be achieved for this sensitive component.

A high degree of safety and environmental attractiveness was achieved in this design. The choice of materials leads to low long-term radioactivity, and short-term radioactivity is so low that decay heat can be accommodated through entirely passive means. The reactor building was designed to allow personnel access after only one day following shut down. The design has a high degree of tolerance to failures. None of the accident scenarios that were considered could lead to public exposure.

Balance-of-Plant and Safety - The fuel processing system necessary to support the IFE reactor power plant is available with the state-of-the-art technology. Current development in tritium processing and handling technology will further improve the safety and environmental performance of the tritium systems.

The balance-of-plant system appears to be a mature technology. Further developments to improve the thermal conversion efficiency and BOP availability can provide significant improvement in the economic competitiveness of IFE power plants.

The Prometheus configuration and engineering features were carefully selected to maximize reliability and enhance maintainability. Fully remote maintenance operations are provided for. High overall availability for the power plant, approximately 80%, is estimated.

The Prometheus study has identified applicable safety and environmental regulations that must be factored into the design of a commercially viable IFE power plant and demonstrated before they can be met. The ESECOM level of safety assurance methodology[1] was applied to Prometheus in assessing off-site doses due to releases of key radionuclides present in the plant. With the exception of W^{185} and Pb^{203}, the Prometheus Inventories allow the plant to be classified as totally passively safe (LSA=1). The tungsten isotope was also identified in the ESECOM study,[1] but not seen as a problem due to its immobility. The lead isotope, however, is unique to Prometheus with its lead coolant, and design features to remove lead afterheat in the event of loss of cooling have been incorporated to address this issue. The careful selection of materials in Prometheus, particularly the structural material (SiC) has minimized the long-term activation. Practically all materials in Prometheus meet Class C or better for waste disposal.

Critical Issues - Although the Prometheus reactor power plants look attractive, many technical issues must be resolved and a substantial program of R&D must be undertaken on the path to commercialization. Detailed technical issues were identified and characterized. The critical issues are:

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 Design Tools and Nuclear Data
13. Reliability and Lifetime of Laser and Heavy Ion Drivers
14. Demonstration of Large-Scale Non-Linear Optics Laser Driver Architecture
15. Demonstration of Cost Effective KrF Amplifiers
16. Demonstration of Low Cost, High Volume Target Production Techniques

The R&D program required to develop the data base for the design and construction of an IFE Experimental Power Reactor (IEPR) is roughly $2B for either the laser-driven or heavy-ion-driven reactors. The most extensive and relatively expensive parts of the R&D program relate to the driver-target development and coupling.

The study has demonstrated that quantitative evaluation methodology can be developed and applied successfully in comparing design and technology options. The evaluation methodology developed in this study includes five areas: physics, feasibility, engineering feasibility, economics, safety and environment, and R&D requirements. The methodology can be applied in the future for other applications. Comparative evaluation of Prometheus-L and H leads to two conclusions:

(1) The heavy-ion driven reactors appear to have an overall advantage over laser-driven reactors based on existing R&D data and performance projections.
(2) The differences in scores are not large and future R&D results could change the overall ranking of the two IFE concepts.

Reference for 2.8

1. J. P. Holdren et al., "Report of the Senior Committee on Environmental, Safety, and Economic Aspects of Magnetic Fusion Energy," LLNL Report URL-53766, 25 September 1989.