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CHAPTER 7
COMPARISON OF IFE DESIGNS

7.1 Introduction

There are several design and technology options for inertial confinement fusion reactors, e.g. laser or heavy ion drivers, direct or indirect drive targets, and dry or wetted first walls. Comparison among options is sought by decision-makers in order to select or identify options for further research and development (R&D).

A quantitative methodology is a useful tool in comparing and selecting among options. In some cases, the basic information required to perform this quantitative comparison is not available. Therefore, decisions to narrow design and technology options for further R&D must be made based on "expert judgment." Quite often, the experts disagree on their preferred choices, further confusing the decision process. The Prometheus study developed a comparative methodology. In this methodology, some data were not available or did not exist and a "best guess" by technical experts is substituted for such data. Results of the comparative evaluation were analyzed and discussed with experts who attempted to formulate conclusions. One advantage of using this quantitative and comparative methodology was that differences among experts and methods for resolution became clear. Another process advantage is that experts gain insight into important areas of differences among design and technology options. Such insights foster more informed decisions even if the results of the comparative analysis are not clear-cut conclusions.

Section 7.2 presents the highlights of the Evaluation Methodology developed in the Prometheus design study. The methodology has utilized previous work when available, e.g. References 1, 2, and 3. Section 7.3 summarizes the results of applying this methodology to comparisons of Prometheus Laser-Driven and Heavy-Ion Driven reactor designs. An attempt was made to keep the methodology framework general enough to allow future comparisons of other options, e.g. comparing inertial and magnetic fusion reactors.

7.2 Evaluation Methodology

Design options for power plants constructed today can be compared on economics, safety, and environmental attractiveness. However, fusion is in an early stage of research and development. Data bases are incomplete and success in developing particular design options for subsystems cannot be assured. Designers extrapolate present knowledge to predict fusion performance with varying results. Further, there are substantial differences among proposed design options: probability of success, time, and developmental costs required. Therefore, a prudent evaluation methodology for comparing fusion reactor conceptual designs must account for these differences.

Five major areas were evaluated:

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

Each major area was quantified using a detailed criteria developed for each area. For each criterion, there is an attribute (index) that can be applied and weighting scale devised. Weighted sums of each attribute were evaluated according to a score.

Evaluation results of each reactor design concept gave a numerical score in each of the five evaluation areas. No mixing of the scores for the five evaluation areas was allowed; i.e., the numerical scores are not combined to derive one final composite score. Instead, the comparison among reactor design concepts involved comparative analysis of the scores for the five areas. A panel of knowledgeable experts then interpreted the results in each of the five evaluation areas. The evaluation approach is highlighted in Figure 7-1.

Evaluation results are impacted by the many choices available to designers. For this study, it is very important to distinguish scoring impact between generic and non-generic design choices. For example, selection of low activation structural material is not a necessity, but a designer's choice. Therefore, a reactor concept with low activation materials cannot be compared to a reactor design with high activation structural materials (or vice versa). Evaluations are dictated by different design requirements. A description of the evaluation system for each of the five evaluation areas follows.

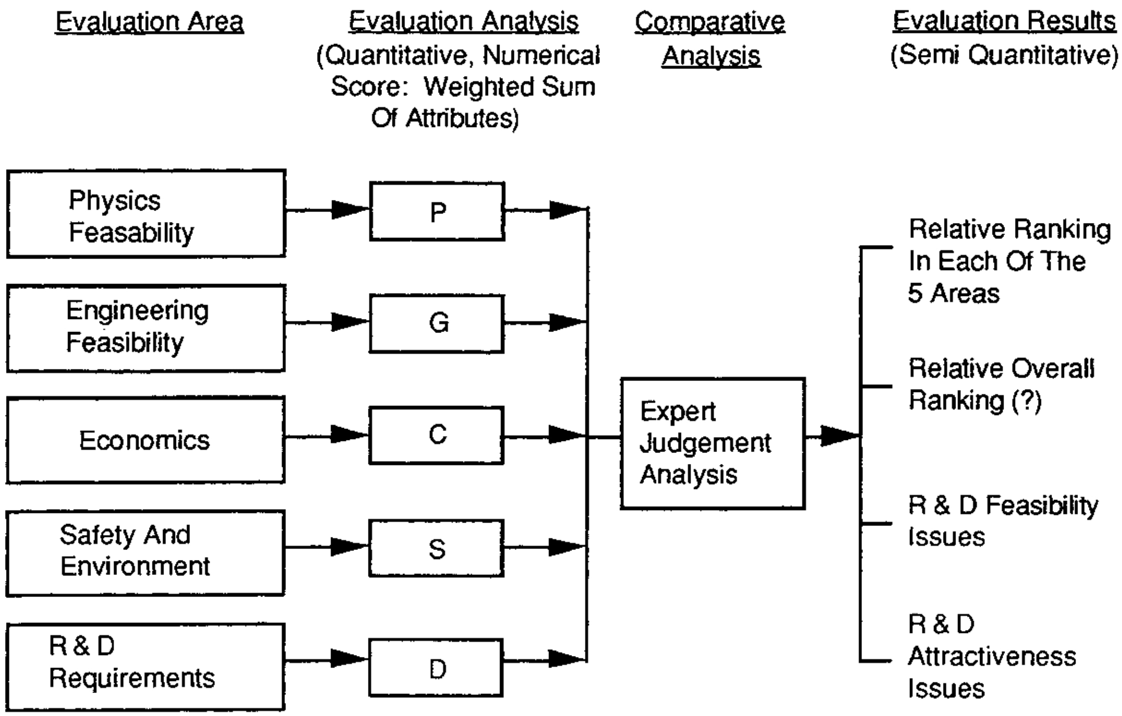

Figure 7-1. Evaluation Methodology Approach

Physics Feasibility - Physics feasibility is clearly a requirement for acceptance of any reactor design concept. However, the required and achievable physics performance goals vary from one reactor concept to another, such as the fusion yield of direct or indirect-driven targets in laser or heavy ion reactors and ß (ratio of plasma-kinetic to magnetic pressure) in magnetic fusion reactors. In IFE reactors, feasibility extends beyond the implosion to cover other physics areas associated with the driver and driver-target coupling.

The study did not attempt to develop a general methodology for comparative evaluation of physics feasibility for all options. Rather, a specific methodology was developed to compare laser and heavy ion-driven reactor physics feasibility. This methodology is presented in Section 7.3.2, together with the application to compare Prometheus-L and H.

Engineering Feasibility - Present conceptual designs are based on extrapolations from present engineering knowledge and experience. Hence, there are uncertainties in the ability to develop conceptual designs that meet study goals. These uncertainties vary between designs, depending on extrapolation and performance optimism. Various design options may be rewarded indirectly through "economics" and "safety and environment" categories of the evaluation criteria. A key purpose of the "engineering feasibility" is to scrutinize, assess, and calibrate each extrapolation and provide a figure of merit. This attempts to balance "questionable rewards" made in other categories of the comparative evaluation. Another key purpose of engineering feasibility is to assure certain goals must be met (e.g. tritium self-sufficiency) in order for the reactor design concept to be acceptable.

The Engineering Feasibility category has two subcategories:

(1) Ability to achieve design goals
(2) Ultimate potential.

Subcategory (1) provides a measure to account for uncertainties in achieving the design goals. Subcategory (2) provides a measure for comparing the practicality of various designs in ultimately reaching very desirable goals such as inherent safety; low, long term activation; and enhanced energy conversion efficiency.

Figures of merit for Engineering Feasibility, G, are obtained as follows:

$$G = W_a I_a + W_p I_p$$

where

W_a = weighting factor for the "ability to achieve design goals" subcategory
I_a = score for "ability to achieve design goals" subcategory
W_p = weighting factor for the "ultimate potential" subcategory
I_p = score for the "ultimate potential" subcategory

W_a is assigned 60% while W_p is assigned 40% to reflect the notion that the ability to achieve design goals has somewhat higher priority than capabilities to ultimately reach desirable goals.

Each subcategory is further divided into a number of attributes (indices), each has a weight and score. The score for each subcategory is obtained as the weighted sum of the scores for the attributes.

Table 7-1 shows the various indices and assigned weights. A scoring system has been devised so that the maximum score for any given index is 3. Since the sum of the weights for all indices is 1.0, the maximum score for Engineering Feasibility is 3. Table 7-2 shows the scoring system for engineering feasibility.

Economics - A single figure of merit, cost of electricity, was adopted. Use of the cost of electricity as a figure of merit integrates the weighted effects of capital, operating costs, replacement time and frequency, fusion power, thermal power conversion efficiency, and recirculating power requirements.

Table 7-1 Engineering Feasibility Evaluation

Ability to Meet Design Goals	Weight (0.60) ×		
1. Component Fabricability	0.1		
First Wall		× 0.35	
Blanket		× 0.20	
Driver		× 0.15	
Beam Transport		× 0.15	
Final Optics		× 0.15	
2. Subsystem Performance Goals	0.3		
Cavity		× 0.4	
First Wall Protection			× 0.5
Blanket			× 0.5
Fusion Reaction Support Systems		× 0.6	
Driver			× 0.2
Beam Transport			× 0.2
Final Optics			× 0.2
Target Fabrication			× 0.2
Target Injection			× 0.2
3. Tritium Fuel Self-Sufficiency	0.2		
4. Reliability Goals	0.1		
First Wall		× 0.35	
Blanket		× 0.20	
Driver		× 0.15	
Beam Transport		× 0.15	
Final Optics		× 0.15	
5. Maintainability	0.1		
First Wall		× 0.35	
Blanket		× 0.20	
Driver		× 0.15	
Beam Transport		× 0.15	
Final Optics		× 0.15	
6. Lifetime Goals	0.1		
First Wall		× 0.35	
Blanket		× 0.20	
Driver		× 0.15	
Beam Transport		× 0.15	
Final Optics		× 0.15	
7. Cost Projections	0.1		
Cavity		× 0.25	
Driver		× 0.25	
Target Manufacture		× 0.25	
BOP		× 0.25	
Ultimate Potential	**(0.4)** ×		
8. Potential for Inherent Safety	0.25		
9. Potential for Low, Long-Term Activation	0.25		
10. Engineering Simplicity	0.3		
Individual System Complexity		× 0.5	
Interdependence of Systems/Functions		× 0.5	
11. Operating Requirements	0.10		
12. Potential for Enhanced Energy Conversion Efficiency	0.10		

Table 7-2 Scoring System for Engineering Feasibility

	Score
Component fabricability	
Existing technology	3
Direct extrapolation of existing technology	2
New technology	1
Subsystem performance goals	
Demonstrated performance in existing facilities	3
Uncertain, but judged to be resolvable with R&D	2
Highly uncertain – may be impossible	1
Ability to achieve tritium fuel self-sufficiency (margin = $\lambda_a - \lambda_r$)	
$\lambda_a - \lambda_r > 0.2$	3
$\lambda_a - \lambda_r > 0.1$	2
$\lambda_a - \lambda_r < 0.1$	1
$\lambda_a - \lambda_r < 0.0$	0
Reliability goals	
Goals based on extrapolation of relevant data	3
Little data, but confidence in estimates	2
Little confidence in estimates	1
Maintainability	
Maintenance achieved by demonstrated methods	3
Some novel or complex maintenance procedures	2
System availability depends on novel or complex procedures	1
Lifetime goals	
Credible data exists to support lifetime estimate	3
Existing data can be extrapolated to support goal	2
Little or no data to support lifetime estimate	1
Cost projections	
Credible data exists to support cost estimate	3
Existing data can be extrapolated to support estimate	2
Little or no data to support cost estimate	1
Potential for inherent safety (IS)	
No reason inherent safety couldn't be achieved	3
Some sources/pathways may prevent IS	2
Some features of design probably prevents IS	1
Potential for low long-term activation (LTA)	
No sources of LTA	3
Sources of LTA could be eliminated with R&D	2
Sources of LTA inherent to design	1
Engineering simplicity	
Simple design and/or operation	3
Some complex aspects of design and/or operation	2
Highly complex aspects of design and/or operation	1
Operating (e.g., startup-shutdown) requirements	
Response times <hours	3
Response times >hours	2
Off-normal operation puts plant or personnel at risk	1
Potential for enhanced energy conversion efficiency	
Well-defined options exist	3
Some speculative options exist	2
No credible means known to significantly Improve efficiency	1

The "first year" cost of electricity in then-year dollars is defined by the following equation.

$$COE = \frac{\text{Annualized Capital Cost + Yearly Operating Cost}}{\text{Net Power x Plant Availability x Time}}$$

$$COE = \frac{(DC+SPR+CTGY+ID+INT+ESCL)\ FCR + (O\&M+SCR+Fuel)(1+ESC\ Rate)^{Yrs}}{(\text{Thermal Power x Gross Efficiency-Recirculating Power})(\text{Availability})(\text{Hrs/y})}$$

where

COE	=	Cost of Electricity
C	=	Figure-of-Merit for the Economics Evaluation Area
DC	=	Direct Capital Costs
SPR	=	Spare Parts Allowance
CTGY	=	Contingency Allowance
ID	=	Indirect Costs (Constr. Services and Engineering)
INT	=	Interest During Construction
ESCL	=	Escalation During Construction
FCR	=	Fixed Charge Rate
O&M	=	Operations and Maintenance Cost
SCR	=	Scheduled Component Replacement Cost
FUEL	=	Annual Fuel Cost
ESC RATE	=	Annual Escalation Rate
YRS	=	Construction Period

Cost of electricity is the total busbar energy cost for the first year of operation. Total capital investment is equally divided and charged to the annual operating periods through the use of a fixed charge rate. Annual operating costs are also included with appropriate escalation from the year of the estimate (start of construction) to the initial operation date. See Figure 3.5-1 for specific economic guidelines and bases used in this study.

Safety and Environment - The most important incentives for fusion energy development is its potential safety and environmental attractiveness. Therefore, enhancing safety and environment features impact the ultimate acceptance of fusion. The Safety and Environment evaluation area measures the relative safety and environmental attractiveness of each design concepts.

Limited study resources and knowledge preclude performing a complete probabilistic risk assessment to obtain a total risk to the public single figure-of-merit. Therefore, a simpler approach was adopted based on a method developed earlier in BCSS.[3] Three subcategories define the Safety and Environmental area as shown in Figure 7-2 and listed below.

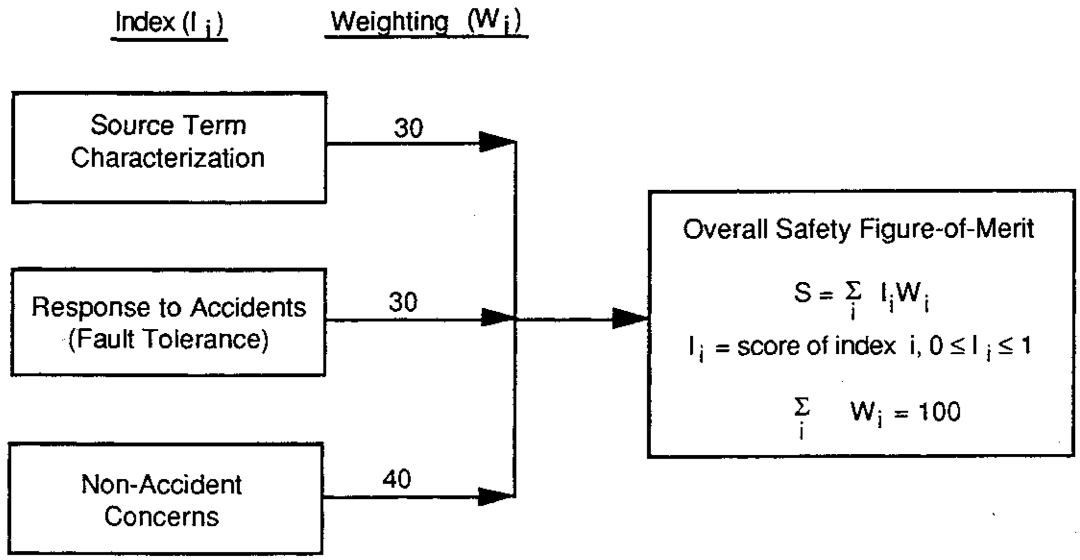

Figure 7-2. Safety and Environment Evaluation Approach

(1) Source Term Characterization (I_1)
(2) Response to Accidents (Fault Tolerance) (I_2)
(3) Non-Accident Concerns (I_3)

The attribute for each subcategory, I_i, is measured on a scale from 0.0 to 1.0 and has a weighting value, W_i. The overall figure of merit (S) for the safety and environmental area for a given reactor design concept is defined as

$$S = \sum_{i=1}^{3} I_i W_i \quad (7\text{-}1)$$

with

$$\sum_i W_i = 100 \quad (7\text{-}2)$$

The weights given to each of the three subcategories are shown in Figure 7-2.

Subcategory (1) is a measure of the component of accident risk from the radioactive and chemical source term common to accident initiators. The value of the attribute, I_i, for this subcategory is obtained from the scores of subindices, f_j, for key components of the reactor as:

$$I = \sum_j f_j \omega_j \quad (7\text{-}3)$$

where $0.0 \le fj \le 1.0$ and $\sum_j \omega_j = 1.0$.

The weights assigned to various reactor components are given in Table 7-3.

Table 7-3: Safety and Environmental Evaluation Indices and Weights

	ω_j
Source Term Characterization (Score = I_S, W_S = 30%)	
Source Term in Target Factory	0.2
Source Term in the Chamber First Wall	0.2
Source Term in the Breeding Blanket and Shield	0.2
Source Term in the Driver	0.2
Non-radiological Sources (e.g. Fluorine)	0.2
Sum of Weighted Score for Source Term $I_S = \Sigma f_j \omega_j$	—
Response to Accidents (Fault Tolerance) (Score = I_R, W_R = 30%)	
Response to LOCA and LOFA in the Chamber First Wall	0.12
Response to LOCA and LOFA in the Breeding Blanket and Shield	0.12
Response to Beam Pellet Misfire Accident in the Chamber Wall	0.12
Response to Loss of Coolant in the Final Optics or Focusing Magnet Vacuum Pumping System	0.12
Response to LOCA in the Driver System	0.12
Fault Tolerance to Loss of T_2 and D_2 Containers	0.10
Fault Tolerance to Containment Integrity	0.10
Fault Tolerance to Target Factory Integrity	0.10
Fault Tolerance to Driver System	0.10
Sum of Weighted Score for Response to Accidents (Score = $IR = \Sigma \omega_j f_j$)	—
Non-Accident Concern (Score = I_N, W_N = 40%)	
Occupational Exposure (Regular, Maintenance)	0.25
Routine Radioactive Emission Rate	0.25
Waste Disposal (Radiological, Hazardous, Mixed)	0.20
Non-radiological Hazards (Fluorine, Lead)	0.15
Heat Dissipation	0.10
Construction Impacts	0.05
Sum of Weighted Score for Non-Accident Concerns $I_N = \Sigma f_j \omega_j$	—
Overall Safety Figure of Merit = $W_S I_S + W_R I_R + W_N I_N$	—

Subcategory (2) relates to the likelihood and response to accidents. Again, the value of the attribute is obtained as the weighted sum of several indices related to the initiators of specific accidents. The indices, f_j, and weights, ω_j, for this subcategory are shown in Table 7-3. Subcategory (3), Non-Accident Concerns, has indices related to occupational exposure, radioactive emission rate waste disposal, non-radiological hazards, heat dissipation, and construction impact. Each has an assigned weight as shown in Table 7-3.

Research and Development Requirements - An important figure of merit in comparing options is the R&D required of future technology. Developing a complete R&D plan is not within the scope of this study; however, R&D data base requirements for design and construction of a Prometheus experimental power reactor were evaluated and discussed in Chapter 5.

Three important subcategories comprise the figure of merit for the R&D requirements:

(1) Cost
    (a) Average annual operating cost
    (b) Capital cost of required facilities (new or upgrades)
(2) Time: Total time to complete the R&D
(3) Risk

The relative risk in not resolving key issues is weighted by the potential consequences of negative results.

The overall figure of merit (D) for R&D is written as

$$D = W_c R_c + W_t + R_t + W_r R_r$$

where R_c, R_t, and R_r are the scores for cost, time, and risk, respectively, and W_c, W_t, and W_r are the corresponding weighting factors.

Subcategory (1) – Cost (R_c)

R_c = 0.5 (A + F)
A = Score for average annual operating cost
F = Score for capital cost of required facilities

Average Annual Operating Cost	Score A	Capital Cost of Required Facilities*	Score F
> $ 100 M	1	> $500 M	1
$50 - 100 M	2	$200 - 500 M	2
< $50 M	3	< $200 M	3

* Summation for all key issues
* Specific dollar numbers for categories may change depending on the issues included and the purpose of comparison

Subcategory (2) – Time (R_t) - Time is the longest time required to resolve the issues. It is either cumulative time for sequential tasks or the longest time for parallel tasks. The score is according to the following table.

Time Scale	Score R_t
> 30 yr	1
15-30 yr	2
<15 yr	3

Subcategory (3) – Risk (R_r) - The figure of merit, R_r, accounts for the probability of not resolving the key issues and the consequence of negative results. It is written as:

$$R_r = \frac{1}{3n} \sum_{i=1}^{n} P_i C_i$$

where n = number of key issues. Dividing by the Factor 3n ensures the maximum score for R_r is 3. P_i is the probability of not resolving the issue (negative result) and is assigned as follows:

Relative Probability	P_i
Unlikely	3
Even (50/50)	2
Likely	1

C_i is the consequence of not resolving the issue (i.e., of negative results)

Relative Consequence	C_i
Severe Impact	1
Moderate Impact	2
Low impact	3

7.3 Comparative Evaluation Results

7.3.1 Introduction - Evaluation methodologies developed in the previous section compared the two inertial fusion reactor designs: Prometheus-L and Prometheus-H. Comparisons covered the five evaluation areas: physics feasibility, engineering feasibility, economics, safety and environment, and R&D requirements.

Evaluation efforts relied on the quantitative data available from the conceptual design study and other sources wherever possible. However, time and resource limitations precluded complete quantitative analysis. Whenever data was not readily available, "expert judgment" was substituted. Results of the comparative evaluation in each of the five evaluation categories are presented in the following subsections. Subsection 7.3.7 discusses the overall evaluation results.

7.3.2. Physics Feasibilities of KrF and Heavy Ion Inertial Confinement Fusion - The physics feasibilities of both the KrF and the Heavy Ion drivers are described briefly below.

7.3.2.1 <u>KrF Laser IFE Physics Feasibility</u> - Physics feasibility of the KrF Laser Driver has two parts:

(1) Feasibility of efficient laser interaction with the direct drive DT target and its subsequent implosion (which may be beset with a variety of laser-plasma interactions driving Rayleigh Taylor instabilities). Also, efficient conversion of laser light into soft x-rays and the subsequent desired implosion of an indirect-drive DT target.

(2) Feasibility of meeting DT target specifications of photon energies, phase distributions, intensity fluctuations, pulse duration, etc.

Much has been written about Subcategory (1), target interactions and design; however, the Prometheus study has concentrated on Subcategory (2), delivering appropriate laser pulses. Subcategory (2) also includes target fabrication, handling, and delivery methods.

A Prometheus KrF laser driver system is extremely complex with many elements required to perform at specified operating levels for extended periods of time. Laser driver elements are designed and engineered in such a manner as to attain performance levels at or below limits defined by the fundamental physics of the element. To assess the physics feasibility of the laser driver design, it is necessary to analyze the fundamental operating principles behind the crucial elements. Prometheus KrF laser driver physics feasibility criteria is based upon answering the following questions:

(1) Does the intended operational mode violate fundamental physics relationships?
(2) Can a self-consistent theory be developed which simulates the operation in the ranges of interest?
(3) If a self-consistent theory is developed, are there highly unstable regions in operational phase-space which could produce significant fluctuations or undesired interactions with other systems?
(4) If the device is to be integrated into a subsystem containing several similar or different devices, can an overall self-consistent theory be developed which describes the combined operation of the subsystem?
(5) Using the physics simulations described above, is it possible to define clear operational regimes of acceptable performance to define the functional phase space for the selected devices and subsystems?

Question (1) aside, affirmative answers signify that the fundamental physics are sufficiently understood and advanced simulations are capable of predicting operational behavior. Systems engineering assessments and simulations then evaluate the predicted performance of the overall laser driver system.

7.3.2.2 **Heavy Ion Driver IFE Feasibility** - As described for the KrF Laser Driver, there are two parts to the physics feasibility of the Heavy Ion Driver:

(1) The physics feasibility of the interaction of the heavy ion beams with the converter plugs to convert the energy efficiently into soft x-rays, together with the physics feasibility of the subsequent uniform implosion of the DT target within the hohlraum.
(2) Feasibility of generating the specified indirect-drive target irradiation conditions of particle energies, beam intensity profiles, directionality, focused beam diameters, pulse durations, etc.

The Prometheus study has concentrated on generating and delivering 4-6 MJ of heavy ion beam energy in 6 ns pulses in <6 mm-diameter focused beams at a 5 Hz rate. Category (2) addresses indirect-drive DT target fabrication and delivery.

Prometheus Heavy Ion Driver design is a complex system composed of bright Pb^{+2} source, ramp gradient accelerator, constant gradient accelerator, storage rings, bunching accelerator, focusing magnets, self-pinched channel generator, and target injection system. Each system element must perform at specified operating levels for a known length of time. Engineering feasibility is described in Section 7.3.3 for the heavy ion driver. To assess the Prometheus Heavy Ion Driver design physics feasibility, it is necessary to analyze fundamental operating principles supporting crucial elements. Typical Prometheus Heavy Ion driver physics feasibility criteria are based upon answering the following questions:

(1) Does the intended operational mode violate fundamental physics relationships?
(2) Can a self-consistent theory be developed which simulates operation in the ranges of interest?
(3) Do the simulations show that the device can actually operate in the region of phase space of interest?
(4) If a self-consistent theory is developed, are there highly unstable regions in operational phase-space which could produce significant fluctuations or undesired interactions with other systems?
(5) If the device is to be integrated into a subsystem containing several similar or different devices, can an overall self-consistent theory be developed which describes the combined operation of the subsystem?
(6) Using the physics simulations described above, is it possible to define clear operational regimes of acceptable performance to define the functional phase space for the selected devices and subsystems?

Question (1) is a sanity check of the fundamental idea behind the device. Question (2) eliminates novel ideas which are not sufficiently mature to be developed into a device at the present time. Question (3) assesses whether or not the range of phase space occupied by the device in operation adequately overlaps the desired performance levels. In general, affirmative answers to Questions (2) through (6) signify that the fundamental physics bases of the devices in question are sufficiently well understood and advanced simulations are capable of predicting operational behavior. Simulations are extremely important since heavy ion drivers must typically be investigated experimentally at full scale, a fact which can make development of heavy ion drivers very expensive. Providing a fundamental physics model for the heavy ion beam propagation, bunching, neutralization, and self-pinched channel formation is well understood. Subsequent systems engineering assessments and corresponding end-to-end system simulations permit evaluation of the predicted performance.

7.3.2.3 Summary of KrF Laser and Heavy Ion Driver Physics Feasibilities – Detailed physics analyses and evaluations of the fundamental elements of both the KrF Laser and Heavy Ion Drivers have revealed that both designs are consistent with known physics (affirmative answer to Question (1) in Sections 7.3.2.1 and 7.3.2.2). There are, however, uncertainties in whether we will be able to operate in the assumed parameter ranges when operating the actual devices. These uncertainties preclude us from guaranteeing that all parts of each driver will work together as a whole to the degree required to meet driver requirements. These uncertainties, in our estimation, can only be resolved by a series of experiments to be performed at a variety of levels. Samples of needed experiments are described elsewhere as Research and Development Experiments related to identified Critical Issues. The bottom line is that there appear to be no show stoppers for either the KrF Laser Driver or the Heavy Ion Driver, but some of the required work-arounds could raise the costs of both the laser drivers.

The physics feasibilities of both the KrF Laser and the Heavy Ion Drivers are summarized below in Table 7.3.2-1. The rating system assumes the following ranking:

7-9 = Demonstrated or easily extrapolated from existing systems
4-6 = Physics feasibility highly probable but needs verification
1-3 = Low physics feasibility except in limited parameter range

Table 7.3.2-1. Physics Feasibilities of Laser and Heavy Ion Drivers

No.	Category	Laser	Heavy Ion
1	**Overall Driver**	**5.8**	**6.6**
1a1	Excimer Amplifiers	4	
1a2	Raman Accumulators	7	
1a3	SBS Pulse Compressors	6	
1a4	E/O Pulse Shaping	5	
1a5	Final Focusing	7	
1b1	Injector		7
1b2	Main Accelerator		8
1b3	Storage Rings		5
1b4	Buncher		7
1b5	Beam Transport		6
2	**Beam Transport**	**7.3**	**4.7**
2a1	Excimer Laser Beam Quality Correction	8	
2a2	Image Relaying	8	
2a3	Beam Conditioning	7	
2b1	Transport to Final Focus		7
2b2	Autoneutralized Final Focus		4
2b3	Channel Transport		3
3	**Target/Beam Alignment**	**3.5**	**4.5**
3a1	Laser Beam Alignment/Overlap	4	
3a2	Target Positioning/Sensing	3	
3b1	Positioning on Target		6
3b2	Channel Motion		3
4	**Target/Driver Coupling**	**3.5**	**7**
4a1	Avoiding Rayleigh-Taylor Instabilities	3	
4a2	Efficient Inverse Bremsstrahlung Absorption	4	
4b1	Efficient Conversion in Hohlraum plugs		8
4b2	Generating & Focusing Soft X-rays		6
5	**Target Gain**	**Equal**	**Equal**
Total		**5.025**	**5.7**

Based upon our assessments, the heavy ion driver irradiating indirect-drive DT targets has a somewhat higher estimated physics feasibility than does the KrF laser driver irradiating direct-drive DT targets. As can be seen in Table 7.3.2-1, the laser driver physics feasibilities associated with Target/Beam Alignment and Target/Driver Coupling suffers considerably compared with the corresponding feasibilities associated with the Heavy Ion Driver. This major difference in target/beam physics feasibilities is due in part to the considerable technical difficulties in illuminating a moving direct-drive target with a 1% uniformity in the middle of a 5-m radius target chamber.

There is a fundamental connection between the "Research and Development Experiments" identified in the Prometheus study and estimates of low driver physics feasibilities. By dealing with the high risk physics issues promptly, the goals of inertial confinement fusion research can be met during the first half of the 21st Century.

7.3.3 Engineering Feasibility - An engineering feasibility evaluation was performed by several experts within the Prometheus team. Each subcategory was scored by the participants, and an arithmetic average was computed. The subcategory scores were then weighted and summed to obtain total scores. The results are shown in Table 7.3.3-1.

As discussed in Section 7.2, engineering feasibility is broken into two categories: ability to meet design goals and ultimate potential. The heavy ion reactor scored higher in both categories. The total scores were 1.87 and 2.04 for the laser and heavy ion reactor, respectively. Below, some of the reasons for the differences are highlighted.

In general, the heavy ion driver was judged to be easier to build and more reliable. Most of the technology is currently available for the accelerator. One of the largest differences shows up in the engineering simplicity attribute, where the heavy ion reactor scores much higher. For the same reasons, cost projections were felt to be more credible for the heavy ion reactor.

Several components of the laser reactor provide uncertainty in fabrication and performance. The final optics appears much more problematic. The large size, vulnerability to the blast effects, and difficulty with shielding lead to lower scores.

Shared cavity design concepts of the two reactors tended to reduce the differences. However, the large number of beamline penetrations for the laser reactor make it considerably less attractive. The smaller size of the heavy ion reactor makes fabrication easier, but uncertainties due to the higher power density offsets this advantage.

Table 7.3.3-1 Engineering Feasibility Evaluation

	Weight	Net Weight	Laser Score	Weighted Laser Score	Heavy Ion Score	Weighted Heavy Ion Score
Ability to Meet Design Goals	**(0.60)x**					
1. Component Fabricability	0.1					
First Wall	x 0.35	.021	1.375	.029	1.375	.029
Blanket	x 0.20	.012	1.625	.020	1.625	.020
Driver	x 0.15	.009	1.833	.017	2.5	.023
Beam Transport	x 0.15	.009	2.0	.018	2.75	.025
Final Optics	x 0.15	.009	2.333	.021	2.5	.023
2. Subsystem Performance Goals	0.3					
Cavity	x 0.4					
First Wall Protection	x 0.5	.036	1.375	.050	1.5	.054
Blanket	x 0.5	.036	2.375	.086	2.375	.086
Fusion Reaction Support Systems	x 0.6					
Driver	x 0.2	.0216	1.75	.038	2.333	.050
Beam Transport	x 0.2	.0216	2.0	.043	2.167	.047
Final Optics	x 0.2	.0216	1.5	.032	2.167	.047
Target Fabrication	x 0.2	.0216	2.0	.043	1.833	.040
Target Injection	x 0.2	.0216	2.0	.043	1.667	.036
3. Tritium Fuel Self-Sufficiency	0.2	.12	1.5	.18	1.5	.18
4. Reliability Goals	0.1					
First Wall	x 0.35	.021	1.5	.032	1.5	.032
Blanket	x 0.20	.012	1.75	.021	1.75	.021
Driver	x 0.15	.009	1.833	.017	2.5	.023
Beam Transport	x 0.15	.009	1.5	.014	2.5	.023
Final Optics	x 0.15	.009	1.375	.012	2.333	.021
5. Maintainability	0.1					
First Wall	x 0.35	.021	2.0	.042	2.125	.045
Blanket	x 0.20	.012	2.333	.028	2.5	.030
Driver	x 0.15	.009	2.667	.024	2.25	.020
Beam Transport	x 0.15	.009	2.0	.018	2.0	.018
Final Optics	x 0.15	.009	1.667	.015	1.667	.015
6. Lifetime Goals	0.10					
First Wall	x 0.35	.021	1.5	.032	1.5	.032
Blanket	x 0.20	.012	1.75	.021	1.75	.021
Driver	x 0.15	.009	1.5	.014	2.5	.023
Beam Transport	x 0.15	.009	1.5	.014	1.833	.016
Final Optics	x 0.15	.009	1.5	.014	1.5	.014
7. Cost Projections	0.1					
Cavity	x 0.25	.015	1.25	.019	1.25	.019
Driver	x 0.25	.015	1.75	.026	2.333	.035
Target Manufacture	x 0.25	.015	1.833	.028	1.833	.027
BOP	x 0.25	.015	2.375	.036	2.375	.036

Table 7.3.3-1 Engineering Feasibility Evaluation (Cont.)

	Weight		Net Weight	Laser Score	Weighted Laser Score	Heavy Ion Score	Weighted Heavy Ion Score
Ultimate Potential	**(0.4) x**						
8. Potential for Inherent Safety	0.25		.1	2.7	.270	2.75	.275
9. Potential for Low Long-Term Activation	0.25		.1	2	.200	1.917	.192
10. Engineering Simplicity	0.30						
Individual System Complexity		x 0.5	.06	1.75	.105	2.667	.160
Interdependence of Systems/Functions		x 0.5	.06	1.5	.090	2	.120
11. Operating Requirements	0.1		.04	2	.080	2	.080
12. Potential for Enhanced Energy Conversn Efficiency	0.1		.04	2	.080	2	.080
Totals							
Design Goals					**1.047**		**1.131**
Ultimate Potential					**0.825**		**0.907**
TOTAL					**1.872**		**2.038**

The use of direct vs. indirect drive targets did not lead to large differences in engineering feasibility. The impact of target choice is probably felt more strongly in the physics feasibility.

For both reactor designs, the Engineering Feasibility scoring for safety was very high. The scores for long-term activation were also relatively high, but somewhat lower than for safety. This is due to the presence of Pb and to uncertainties in predicting impurity levels and in the nuclear data.

7.3.4 Economic Comparison and Evaluation - Comparison and evaluation parameters judge the relative economic basis between the two reactor conceptual designs. Eventually this economic parameter will be the only meaningful measure to be used by utilities to judge the relative merit of opposing designs. As the experimental devices and the demonstration plants are developed and operated, the physics and engineering feasibility questions will have all been resolved in a positive or a negative manner. The R&D criteria is a measure to scope the money and effort required to realize the goal of commercial fusion. All other criteria and judgment factors such as safety will eventually be measured and compared in economic terms. A present example is that of an allowance for the decommissioning of the reactor. The plants with the lower environmental risk have a lesser cost factor for the decommissioning effort.

The criteria to be employed in this present Economic Comparison will be the cost of electricity (COE). This is a meaningful metric in that it combines many aspects of the plant into a single value. The component factors are weighted according to the cost structure employed in the U.S. utilities. The structure of the COE determination is as follows:

$$COE = \frac{[\text{Annualized Capital Cost} + \text{Yearly Operating Cost}]}{\text{Net Power x Plant Availability}}$$

$$COE = \frac{[\text{Annualized Capital Cost} + \text{Yearly Operating Cost}]}{[\text{Thermal Power x Efficiency - Auxiliary Power}] \text{ x } [\text{1-Sched Downtime-MTBFxMTTR}]}$$

This equation combines the effects of the capital costs of the entire plant facility as well as the time it takes to construct the plant. The capital cost emphasizes choice of materials, design optimization, and cost efficient processes. The yearly operating costs include the operating and maintenance staffs, fuel costs, and the maintenance and supply costs. These costs are offset by the production of energy sold to the distribution grid. To generate net power, thermal energy must be produced, thus emphasizing utilization of high quality energy conversion, high gain targets, high neutron and energy multiplication in the blankets, and efficient use of materials. Plant availability stresses minimizing the downtime, both the scheduled and the unscheduled. Reliability and maintainability of future systems is very difficult to predict.

Before the specific COE values are revealed, several comments should be discussed. Although one reactor design concept may show more favorable values of COE over the other concept, there are many competing and generally offsetting factors which should be recognized and considered.

Capital Costs Are Strong Drivers - Drivers, beamlines, power supplies, and reactor cavities are the most influential cost elements. Heavy ion drivers have the deserved reputation of being a very costly item. Our team took an innovative approach to minimize the cost of the heavy ion driver and succeeded in reducing the cost to that of the laser driver. The many laser beamlines required for symmetric illumination also strongly contributed to the cost of the laser plant. The quality of the laser driver power supplies implied a higher cost for the laser system than the heavy ion system. The lower system efficiency of the laser system caused a larger demand for recirculating power and, hence, more thermal power, more reactor plant equipment, more turbine plant equipment, more electric plant equipment, etc. Plant elements with a minor cost influence included the fuel cycle, the target factory, general-purpose buildings, and the shielding. Elements with slight influences were the reactor cavity and remote handling which did not significantly affect either candidate concept.

Operating Costs Did Not Have a Significant Impact - The level of definition in these studies did not offer any discernible differences in the operating costs between these two conceptual designs. The operating costs for the direct drive targets are nearly equal the indirect target costs. The targets are cheaper but more are required due to the higher repetition rate. An indirect target may be an option for the laser-driven plant but future target designs may significantly impact the performance of the targets which would outweigh the perceived cost differences.

Net Thermal Power Is a Split Decision - The higher gain of the direct drive target tends to favor the laser driver for the same energy level. However, the more efficient LINAC driver better utilizes the available target yields requiring less recirculating power be generated, thus delivering more net energy to the electric grid.

Overall Efficiency Is Credited to the Heavy Ion Driver - The higher system efficiency of the heavy ion LINAC makes better use of the driver energy, holds the size of the other plant equipment to a minimum, and maximizes the plant output for a given level of fusion and thermal plant output. Both reactor concepts have been designed with high temperature primary coolant in order to maximize the thermal efficiency conversion. To improve the efficiency of the KrF driver, the waste heat associated with the KrF gas flow loops was used as an additional source of energy.

Low Auxiliary Power Helps the Efficient Use of Energy - The LINAC has the advantage of requiring less auxiliary power delivered back into the LINAC. All other plant considerations are generally even.

Scheduled Downtimes Are Nearly Equal - It is believed that the Heat Transfer and Transport System, the Turbine Plant Equipment, and the Reactor Cavity are the systems which will require the majority of the scheduled downtime for the plant. The steam generator and the turbines will require routine preventative maintenance. The reactor cavity will have components with limited lifetimes which need periodic replacement. The laser mirrors and optics are designed for long lifetimes and only the final optics may need replacement a few times during the plant lifetime. The heavy ion driver components are designed for life of a plant.

The Unscheduled Downtime Is Determined by the MTBF and MTTR - The Mean Time Between Failures (MTBF) is again driven by the systems mentioned above which have large scheduled downtimes; namely, the Heat Transfer and Transport, Turbine Plant Equipment, and the Reactor Cavity. In addition, the Driver Plant Equipment will contribute to the unscheduled downtime. The laser amplifiers may have some failures, but these can be accommodated without causing a shutdown of the reactor. If a mirror or lens must be replaced, it can be done quickly with a low mean time to repair (MTTR). The LINAC components are more reliable but any failures of the main beamline elements would cause a shutdown of the entire reactor until the element is repaired. The net result of scheduled and unscheduled downtime is assessed in inherent availability which slightly favors the heavy ion design.

In summary, factors which contribute toward final economic evaluation are comprised of many issues which are not black and white. Both reactor and driver concepts have advantages and disadvantages as viewed with today's perspective. But technology marches ahead, making twists and turns, driven by market pressures, political maneuvers, and societal influences. Necessity, after all, is the mother of invention. So do not place too much faith in any of the absolute numbers given herein. We believe these studies have suggested some innovative and cost-effective solutions to existing problems, and we believe there are even better solutions yet to be uncovered!

Results of the Economic Evaluation - The Cost of Electricity for the two reactor concepts indicate that the heavy ion-driven reactor would be somewhat more attractive than the KrF laser-driven reactor as shown below:

Reactor Concept	Cost of Electricity
KrF Laser Driven	72.0 mill/kWh
Heavy Ion Driven	62.6 mill/kWh

7.3.5 Safety and Environment - Evaluation criteria falls into three general categories, with a weighting factor assigned to each, as follows: (1) Source Term Characterization (30%), (2) Response to Accident (Fault Tolerance) (30%), and (3) Non-Accident Concerns (40%). With these factors, accident conditions receive substantially more weight in the comparison (60%), than do normal operation factors (40%). Next, each of the three general categories was further divided into subcategories, as indicated on Table 7.3.5-1. As with the general categories, the subcategories were assigned weighting factors.

Each reactor design (laser or heavy ion) was then assigned a relative score for each subcategory. The design that has the least adverse impact for a subcategory is given a score of 1, while the score for the other design is based on how severe its impacts are relative to the least adverse design. For example, if the laser design is judged to have impacts which are twice as severe as the heavy ion design, then the heavy ion is assigned a score of 1, while the laser design is given a .5 score. If both designs are judged to be equal in their impacts of a subcategory, then both are given a score of 1.

Using this methodology, Table 7.3.5-1 presents the results of the safety and environment comparison. A brief rationale for the assignment of the scores is provided for each category. As shown, the laser design is slightly preferred over the heavy ion

Table 7.3.5-1. Safety and Environment Comparison

Category	WT	L	HI	Rationale
Source Term Characterization	30%			
Source Term in Target Factory	0.2	1.0	1.0	No difference at the level of this study
Source Term in the First Protection Chamber Wall	0.2	1.0	1.0	No difference at the level of this study
Source Term in the Breeding Blanket and Shield	0.2	1.0	1.0	No difference at the level of this study
Source Term in the Driver	0.2	1.0	.83	The heavy ion beam will activate the material in the beam funnel
Non-radiological Sources (Fluorine)	0.2	.75	1.0	The fluorine for the laser has no counterpart in the heavy ion
Total Source Term Characterization:		.95	.97	
Response to Accidents (Fault Tolerance)	30%			
Response to LOCA and LOFA in the First Protection Chamber Wall	12	1.0	1.0	No difference at the level of this study
Response to LOCA and LOFA in the Breeding Blanket and Shield	.12	1.0	1.0	No difference at the level of this study
Response to Beam/Pellet Misfire Accident in the Chamber Wall	.12	1.0	0.9	The loss of one of the two heavy ion beams will have greater effect than the loss of one of the laser's 60 beams
Response to Loss of Coolant in the Final Optics or Focusing Magnet or Vacuum Pumping Systems	.12	1.0	1.0	No difference at the level of this study
LOCA in Driver System	.12	1.0	.83	The loss of one of the two heavy ion beams will have greater effect that the loss of one of the laser's 60 beams
Fault Tolerance to Loss of T_2 and D_2 Containers	0.1	1.0	1.0	No difference at the level of this study
Fault Tolerance to Containment Integrity	0.1	1.0	1.0	No difference at the level of this study
Fault Tolerance to Target Factory Integrity	0.1	1.0	1.0	No difference at the level of this study
Fault Tolerance to Driver System	0.1	1.0	1.0	No difference at the level of this study
Total Response to Accidents:		1.0	.97	
Non-Accident Concerns	40%			
Occupational Exposure (Regular, Maintenance)	.25	1.0	.75	The heavy ion beam will activate the material in the beam tunnel
Routine Radioactive Emission Rate	.25	1.0	1.0	No difference at the level of this study
Waste Disposal (Radiological, Hazardous, Mixed)	.20	1.0	.75	The heavy ion will activate the material in the beam tunnel, causing more waste disposal
Non-Radiological Hazards (Fluorine, Lead)	.15	0.5	1.0	The fluorine for the laser has no counterpart in the heavy ion system
Heat Dissipation	.10	0.9	1.0	A greater amount of power is needed to drive the laser, with a corresponding greater amount of waste heat to be dissipated
Construction Impacts (Environmental)	.05	1.0	.75	The long heavy ion beam tunnel has no laser counterpart
Total Non-Accident Conditions		.92	.88	
Total Safety and Environment Comparison		.95	.93	

design. However, at the level of this study, the difference is not considered to be significant, and the two designs should be considered to be equal with regard to safety and environment.

7.3.6 R&D Requirements - An R&D assessment has been carried out for Prometheus-L and -H. Because of limitations on time and resources available for this study, the assessment has not attempted to develop comprehensive R&D plans. Rather, the effort was limited to identifying the R&D required to resolve the key technical issues identified for Prometheus. A specific development goal was selected as the ultimate objective of the R&D identified in this effort. This goal is to develop a physics and engineering data base sufficient to construct an IFE Experimental Power Reactor (IEPR). An IEPR is envisioned as a facility in which the basic physics and engineering performance, as well as system integration tests, are carried out. It will have prototypical components and will probably produce several hundred megawatts of fusion power and operate with about one pulse per second and overall availability of about 20-30%.

The R&D assessment focused primarily on critical components unique to IFE: target, driver, and cavity. Some modest R&D has also been identified for the tritium system and safety.

The evaluation methodology for the R&D category requires evaluation of costs (capital and operating), time, and risk. Since a comprehensive R&D assessment was not within the scope of this study, complete data was not available to rigorously follow the evaluation methodology.

The key items of the R&D costs are shown in Table 7.3.6-1. The costs for laser and heavy ion drivers are comparable with the heavy ion reactor concepts having a modest advantage in lower cost. The time it takes to perform the required R&D does not appear to be a significant discriminating factor for the R&D items evaluated in this study.

7.3.7 Overall Evaluation - A summary of the scores for the figures-of-merit of the five evaluation areas is given in Table 7.3.7-1 for the laser-driven and heavy ion-driven reactors. The scores were normalized so that higher numbers mean better scores. Two key conclusions can be made based on the overall evaluation analysis and the scores in Table 7.3.7-1:

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

Table 7.3.6-1. Summary of Key Items of Costs (Capital Plus Operating) of R&D for Laser and Heavy Ion Reactors

Areas Requiring R&D Effort	Laser	Heavy Ion
Cavity	(MS)	(MS)
First Wall Protection	175	175
Blanket	273	273
Shield	60	50
Target and Driver		
Driver	825	805
Target (for both)	235	235
Target (driver-target)	300	200
Tritium	30	30
Safety and Environment (specific items)	20	20
Total (for items shown)	**1918**	**1788**

Table 7.3.7-1 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

*Score normalized so that higher numbers mean better scores.

References for 7

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