TABLE OF CONTENTS – CHAPTER 5

TABLE OF CONTENTS – CHAPTER 5 (CONT.)

CHAPTER 5
KEY TECHNICAL ISSUES AND R&D REQUIREMENTS

This chapter presents the key technical issues and R&D requirements found during the conduct of the two IFE reactor design studies. The presentation of these issues and requirements will hopefully benefit the technical community and the decision makers to help them better formulate the program and technical plans toward the goal of commercial fusion energy.

5.1 Introduction

Purpose - Although significant progress has been made in inertial fusion energy research during the past decades, the field is still in its early stage of research and development and the present data base is severely 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.

This chapter contains a comprehensive list of key physics and engineering issues for the IFE conceptual reactor designs developed in this study. The chapter also includes an attempt to determine the additional research and development (R&D) needed to develop critical systems and reduce development risks for each of the two reactor design concepts.

The list of key technical issues, shown in Section 5.2, explicitly defines the uncertainties associated with the physics and engineering operation of IFE reactors and addresses the potential consequences resulting from each issue. It is believed that this list will be useful to engineering and physics researchers, reactor designers, experimentalists, and program planners in identifying the areas of greatest concern and their impact on the development and potential attractiveness of inertial fusion reactors.

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 issues impacts aspects of feasibility, safety, and/or economic potential of fusion reactors. Resolving these issues requires new knowledge through experiments, models, and theory. The issues identified here represent great details that are necessary to accurately prescribe the R&D necessary to resolve the issues. However, such details have made the list relatively long with each issue having a focus on a narrow technical area.

To provide a brief summary of the most important issues, a smaller number of issues, called critical issues, were identified in Section 5.3. A critical issue is broader in scope than a key issue; each critical issue may encompass several key issues.

In general, the issues identified here are for the two reactor design concepts developed in the Prometheus[1] study. However, many of the issues tend to be generic to IFE and are fairly independent of the specific selections made here. To maximize the usefulness of the list of issues, the degree of dependence of the issue on design specificity is explicitly identified. Many technical issues for IFE correspond to similar technical issues in MFE. The degree of similarity is also indicated to facilitate identifying areas of R&D that are of common interest to MFE and IFE.

There is an intentional bias towards testing issues–those likely to require testing (experiments) before a commercial reactor could confidently be built. However, it is not limited to testing alone, the entries in the list are described as "Issues/Technical Areas" to allow broader categories. The issues serve to identify the R&D needs which are listed later in the Section 5.5. Also, the quantification of the test requirements depends heavily on the issues.

The precise definition of an issue is difficult. One reason for this is the interrelated nature of the technical disciplines and the phenomena involved. For example, in the solid breeder blanket, thermal stresses may be a primary cause of structural failures. The thermal stresses are a function of temperature distributions, which depend on the allowable operating temperature window, which in turn is highly dependent on tritium transport and inventory, which in turn is a strong function of radiation effects on the solid breeding material. Structural failures are also affected by material property changes due to irradiation.

It is arbitrary to some extent how to break out pieces of the overall behavior of a reactor component and call them separate issues. Consider, for example, the blanket as a reactor component. The only real issue for the blanket is the demonstration of adequately meeting its functional requirements of tritium breeding and energy conversion at economical and safe conditions. To help alleviate this problem and still retain technical specificity in the issues, an attempt is made to illuminate the logical pathway to the ultimate consequences or failure modes. For the blanket, these relate to the basic functions of structural integrity, tritium breeding, heat transport, materials compatibility, etc.

Organization - The key issue list is arranged according to the major reactor components shown in the Table 5.1-1. A concise table (several pages) of the key issues appears in Section 5.2, together with table entries for potential impact, design specificity, level of concern, relevant operating environment conditions, and degree of relevance to MFE. Section 5.3 focuses on the critical issues. In Section 5.4, each issue identified in Section 5.2 is explained in detail, giving the rationale behind the table entries. For some of the issues, more detailed analysis of the issue is given. The numbering of the issues write-ups in Section 5.4 exactly corresponds to the numbering of the table in Section 5.2. The R&D requirements to resolve these issues are addressed in Section 5.5.

Table 5.1-1 Organization of Components and Technical Areas for which Technical Issues are Identified

A. Target
B. Driver
    - Laser
    - Heavy Ion
C. Vacuum System and Evacuation
D. Tritium Processing System
E. Cavity Design
    - Wall Protection
    - Blanket
    - Shield
F. Materials
G. Heat Transport and Secondary Energy Conversion
H. Maintenance and Configuration
I. Balance of Plant
J. Safety and Environment
K. Subsystem Interactions

Entries and Abbreviations - The entries for Table 5.2-1 and the rest of this chapter are explained below. The "Reactor Concept" entry simply indicates whether the issue is relevant to the Laser-Driven or the Heavy Ion-Driven reactor design, or both. The "Potential Impact" entry for each issue helps to determine the level of concern, or importance, of the issue. Seven possible impact categories have been defined in the FINESSE[2] study and are used here as defined in Table 5.1-2. The abbreviations used in Table 5.2-1 for "Potential Impact" are also defined in this table. These are divided into two classes of issues: feasibility issues and attractiveness issues. In general, a feasibility issue is more serious because it could rule out a component concept on scientific grounds without considering the cost, complexity, or safety implications relative to alternate energy sources. The most serious issues are those which can close the device operating window, or design window, thereby eliminating the design. The attractiveness issues may still be very serious, rendering a reactor design impractical on the basis of economics or safety.

Table 5.1-2 Definition of Potential Impact Abbreviations

Feasibility Issues:	DW	May Close the Design Window
	US	May Result in Unacceptable Safety Risk
	UL	May Result in Unacceptable Reliability, Availability, or Lifetime
Attractiveness Issues:	RP	Reduced System Performance
	RL	Reduced Component Lifetime
	IC	Increased System Cost
	RS	Less Desirable Safety or Environmental Implications

The Design Specificity entry indicates if the issue is generic to all the plant systems, components, or materials specific to an individual item. To reduce the table size, abbreviations are used to denote the specificity of components, specific design concepts, etc. These abbreviations are given in Table 5.1-3. Any feasibility issue that is generic to a class of component designs is considered to possess a critical level of concern. Other issues are regarded as high, medium or low levels of concern depending on a qualitative judgment on their overall severity.

Table 5.1-3 Definition of Design Specificity Abbreviations

System Abbreviation

B	Blanket
CBOP	Conventional Balance of Plant
DHI	Driver-Heavy Ion
DL	Driver-Laser
FW	First Wall
S	Shield
T	Tritium System
TF	Target Factory
V	Vacuum System
WP	Wall Protection

Other Abbreviations

CS	Ceramic Structure
DS	Draw Salt
LB	Liquid Breeder
LM	Liquid Metal
LS	Laser System
SB	Solid Breeder
SiC	Silicon Carbide
TC	Ternary Ceramic

The relevant environmental conditions in Table 5.2-1 indicate those particular parameters of the operating environment for the component that influence the issue severity. Those environmental conditions are particularly useful in defining the R & D required to resolve the issues and in identifying major facilities needs. Operating environment parameters such as temperature, stress, and surface heat flux are abbreviated as noted in Table 5.1-4. The influence of neutrons in the operating environment on a particular issue is important to clarify because of the large effect on the type of facilities required for the R&D. The effect of neutrons on the particular issue is indicated by three categories: bulk heating, material damage, and specific reactions. These are abbreviated in the Issue Tables as H, D, and R, respectively, with the abbreviations also given in Table 5.1-4.

Table 5.1-4 Key to Operating Environments

Neutron Effects

H	Bulk Heating
D	Materials Damage (Displacements, helium production, etc.)
R	Specific Reactions (Tritium breeding, helium production, hydrogen production, activation, sputtering, radiolytic decomposition, etc.)

General

F	Fluence	TWI	Target debris-Wall interactions
ϕ	Flux	G	Geometry
S	Spectrum	Q	Power Density
T	Temperature	t	Time
σ	Stress State	q	Surface Heat Flux
C	Chemical Environment	P	Pressure
I	Impurities	P_t	Tritium Pressure
H	Tritium	v	Velocity
A	Dimensions (Area)	N	Cyclic Operation
B	Magnetic Field Strength	s	Surface Condition
b	Transient Magnetic Field	γ	Gamma Radiation
L	Laser	HI	Heavy Ion
TG	Tritium Generation	IB	Beam Current
D	Debris	ρ	Pulse Shape
OF	Optical Energy Fluence	EI	Ion Energy
ρ_g	Background Gas Density	E	Beam Energy
n	Neutron Environment	V	Vacuum Environment

References for 5.1

1. Prometheus Study, This Report.

2. M. A. Abdou, et. al., FINESSE: A Study of the Issues, Experiments and Facilities for Fusion Nuclear Technology Research and Development, Interim Report, Volume 11, UCLA-EGG-84-30, p. 821, October 1984.

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5.2 Identification of Key Issues

This section contains the IFE Key Issues Summary, Table 5.2-1. For each issue, this table indentifies the applicable reactor concept, potential impact as to feasibility or attractiveness, specificity to the system design, level of concern, assessment of the neutron and general environment, and relevance to MFE. Each issue is discussed in detail in section 5.4.

Table 5.2-1 IFE Key Issues Summary

Issue/Technical Area	Reactor Concept	Potential Impact	Design Specificity	Level of Concern	Operating Environment: Neutron	Operating Environment: General	Relevance to MFE
A) Target							
A.a Target physics							
A.a.1 Direct Drive Target Coupling	L/HI	DW,UL, RP	Generic	Critical		H, L, TWI, G, N	None
A.a.2 Indirect Drive Target Coupling	L	DW, RP, IC, RS	Generic	Critical		L,TWI,G,Q, N,I,S,F,T, q,s,t	None
A.a.3 Survivability of Targets in Chamber Environment	L/HI	DW, RP	Generic	High		S, T, A, G, Q, t, q, P, v	Low
A.b Beam/Target Interaction							
A.b.1 Demonstration of Injection and Tracking of Targets Coupled with Beam Steering	L/HI	UL	Generic	Critical		A, TWI, P	Low
A.c Fabrication							
A.c.1 Manufactur-ability of High Quality, Low Cost DD and ID Targets	L/HI	UL, RP, IC, RS	Generic	High		H, TWI, N	Medium
B. Driver							
B.a Laser							
B.a.1 D/T Target Illumination	L	DW, UL, RP, IC	DL	High		L, t, G	None
B.a.2 Large Laser Bandwidth	L	RP, IC	DL	High		L, t, G	None
B.a.3 Final Optics Pointing System	L	DW, UL, RP, IC	DL, S	High	H, D, R	L, t, G	None

Table 5.2-1 IFE Key Issues Summary (Continued)

Issue/Technical Area		Reactor Concept	Potential Impact	Design Specificity	Level of Concern	Operating Environment		Relevance to MFE
						Neutron	General	
B.a.4	Grazing Incidence Mirror Damage	L	DW, UL, RP, IC	DL, S, V Mirror	High	H, D, R	L, F, TWI, Q, q, γ	None
B.a.5	SBS Pulse Compressor	L	IC	DL	High		L, t, G	None
B.b	Heavy Ion							
B.b.1	Timing of Heavy Ion Beam	HI	RP, IC	DHI	High		P,Q,I,B,G, N,T,E,EI,p, HI	Low
B.b.2	Channel Formation	HI	RP, IC	DHI	High		P,Q,I,B,G, N,T,E,EI,p, HI	Low
B.b.3	Channel Transport	HI	RP, IC, RS, RL	DHI	High		P,Q,I,B,G, N,T,E,EI,p, HI	Low
B.b.4	Stripping of HI Beam	HI	RP, IC	DHI	High		P,Q,I,B,G, N,T,E,EI,p, HI	Low
B.b.5	Alignment of Indirect HI Target		RP, IC	DHI	High	H, D, R	P,Q,I,B,G, N,T,E,EI,p, HI	Low
C.	Vacuum System and Evacuation							
C.1	Vacuum Seal Compound Survival in Nuclear Environment	L/HI		Generic	Low			High
C.2	Cryogenic Pump - Hydrogen Capacity	L/HI		Generic	High			High
C.3	Chemical Stability of the Reactor Exhaust	L/HI		Generic	Medium		C	None

Table 5.2-1 IFE Key Issues Summary (Continued)

Issue/Technical Area		Reactor Concept	Potential Impact	Design Specificity	Level of Concern	Operating Environment		Relevance to MFE
						Neutron	General	
D.	Tritium Processing System							
D.1	Tritium Inventory Mean Residence; Time of Tritium in the Subsystems; Tritium Losses from the Subsystems	L/HI	RS	B,T, TF	Medium			High
D.2	Tritium Permeation from the First Wall Coolant - Liquid Pb	L/HI						
E.	Cavity							
E.a	Wall Protection							
E.a.1	Cavity Vapor Hydrodynamics	L/HI	DW, UL	Generic	Critical		S,A,G,TWI, Q, t, q, P	None
E.a.2	Cavity Structure Mechanics Response to Blast	L/HI	UL, RP, IC	All	High		F,T,σ,A, TWI,G,Q, q,P,N,s	Low
E.a.3	Vapor Condensation Rate	L/HI	DW, RP, IC	WP	Critical		T,A,TWI,G, t, q, P	None
E.a.4	Radiation Heat Transport in Partially-Ionized Gas	L/HI	RP, RL	Generic	High		T,A,TWI,G, Q, t, q	Low
E.a.5	Film Flow Control: Injection, Uniform Thickness and Drainage	L/HI	DW	Generic Thin Film	Critical		A, G, v	Low
E.a.6	Film Flow Stability and Response to Impulsive Loading	L/HI	DW	Thin Film	High		A, G, v	Low

Table 5.2-1 IFE Key Issues Summary (Continued)

Issue/Technical Area	Reactor Concept	Potential Impact	Design Specificity	Level of Concern	Operating Environment		Relevance to MFE
					Neutron	General	
E.a.7 Pb/Sic Wet-ability	L/HI	RP, RL, IC	Specific	Medium		C, I, s	Low
E.a.8 Pb Compatibility with Steel	L/HI	RP, RL, RS	Specific	Medium		T, C, v	Medium
E.b Blanket							
E.b.1 Tritium Self-Sufficiency	L/HI	DW	Generic	Critical	H, D, R	F,ϕ,S,T,C, I,TG,A,G, Q,t,P_t,N,γ	High
E.b.2 Tritium Inventory, Recovery, and Containment	L/HI	DW, US, IC	SB	Critical	R, H	F,ϕS, T,C, I,A,G,Q	High
E.b.3 Breeder/Structure Mechanical Interactions	L/HI	RL, RP	SiC, SB	High	H, R	F,T,C,I,A,t, N,σ,P	High
E.b.4 Off-normal and Accident Conditions	L/HI	IC, RS	SiC	High	H	T,s,G,Q,t, P_t,V,P,N, TG	High
E.b.5 Structural Response and Failure Modes	L/HI	RS, UL	SiC	High	H, D, R	F,T,σ,C,I, A,G,Q,t,N, P	Medium
E.b.6 Corrosion and Mass Transfer	L/HI	DW	SB	High	H, R	F, T, C, I, t P_t, N	High
E.b.7 Tritium Permeation	L/HI	US, UL	Generic	High	R, D	F, N, T, P_t, I	High
E.b.8 Fabrication	L/HI	IC, UL	SB, SiC	High		A, G	Medium
E.b.9 Heat Generation and Power Production	L/HI	RP, RS	Generic	High	R, H	ϕ,S,G,Q,t, γ	High
E.c Shield							
E.c.1 Effective of Bulk Shield							
E.c.1.1 Biological Dose during Operation and Maintenance	L/HI	RS, UL	Generic	High	R, D	ϕ, F, S, G	High
E.c.1.2 Radiation Streaming	L/HI	RS, US	Generic	High	R, D	ϕ, F, S, G	High

Table 5.2-1 IFE Key Issues Summary (Continued)

Issue/Technical Area	Reactor Concept	Potential Impact	Design Specificity	Level of Concern	Operating Environment		Relevance to MFE
					Neutron	General	
E.c.1.3 Analytical Techniques and Data Base	L/HI	RS, UL	Generic	High	R, D	ϕ, S, G, F	High
E.c.2 Shield Compatibility with Cavity and Vacuum Boundary, Inclcing Assembly/ Disassembly	L/HI	RS, UL	Generic	High	R, D	ϕ, F, S, G	High
E.c.3 Activation of Reactor Building Components Outside the Cavity	L/HI	RS, UL	Generic	Low	R, D	ϕ, F,S, G	High
E.c.4 Shielding of Final Mirrors	L	UL, RP, RL, IC	Mirror	High	D, R, H	ϕ, F, S, G	None
E.c.5 Shielding of Quadrupole Magnets	HI	UL, RP, RL, IC	Magnets	High	D, R, H	ϕ, F, S, G	Medium
F. Materials							
F.a Viability of SiC Structure	L/HI	RP,RL,UL	FW, B	High	D, R	γ, T, σ	High
F.b Thermo-Mechanical and Materials	L	DW, RP	DL	High	D, R, H	γ, T, σ	Low
G. Heat Transport and Secondary Energy Conversion		No Key Issue Identified					
H. Maintenance and Configuration							
H.1 Computer Reliability	L/HI	UL	Generic	Low		t	High
H.2 Total Remote Maintenance	L/HI	DW, UL	Generic	Low		F,S,T,C,H, B	High

Table 5.2-1 IFE Key Issues Summary (Continued)

Issue/Technical Area		Reactor Concept	Potential Impact	Design Specificity	Level of Concern	Operating Environment		Relevance to MFE
						Neutron	General	
H.3	Material Joining	L/HI	DW, IC	Generic	High		F,S,T,C,H, B	High
H.4	Lead Flushing	L/HI	IC	Generic	Medium		F, T, H	Low
H.5	Seal life	L/HI	DW, IC	Generic	High		F,S,T,C,H, B	High
H.6	Embrittlement Temperature	L/HI	DW, IC	Generic	Medium		T	High
I.	Balance of Plant		No Key Issue Identified					
J.	Safety and Environment							
J.1	Overall plant tritium inventory	L/HI	IC, RS	T	Medium		H	Medium
J.2	Permeation of Tritium	L/HI	RP	T	Medium		H	Medium
J.3	Normal Operation Tritium Release	L/HI	IC	T	Medium		H	Medium
J.4	Neutronic Cross Sections/Data Library for Activation Analysis	L/HI	US	Generic	High	R	F,ϕ,S,Q,γ	High
J.5	Removing Decay Heat from Lead Coolant Under Accident Conditions	L/HI	US, IC, RS	FW	Medium	R	F,ϕ,s,Q,γ	Medium
J.6	Hydrogen Burn Due to Rupture of Diffusion Vessel	L/HI	RP, IC	TF	Medium		H, P_t	None
J.7	Detection of Local Dry Spots Prior to Failure	L/HI	US, IC	FW	High		F,ϕ,S,T,Q, σ	High

Table 5.2-1 IFE Key Issues Summary (Continued)

Issue/Technical Area		Reactor Concept	Potential Impact	Design Specificity	Level of Concern	Operating Environment		Relevance to MFE
						Neutron	General	
J.8	Detailed Accident Analysis	L/HI	IC, RS	All	High	-	All	Medium
J.9	Removal of Contaminants from the Liquid Lead	L/HI	RP, RS	WP	Medium	-	I	None
J.10	Impact of Large Quantities of Lead on Waste Disposal	L/HI	IC, RS	WP	Low	-	I	None
K.	Subsystem Interactions							
K.1	Laser System/ Cavity Interface and Final Mirror Protection	L	UL	DL	Critical		F,OF,S,C, T,n,γ,V,s, q	Low
K.2	SiC/Metal Piping Transition Interface	L/HI	IC	CS/ CBOP	Critical		C,T,H,A,P, Q,I,v	High
K.3	Heavy-Ion System/Cavity Interface and Beam Propaga-tion, Focusing and Optics	HI	DW	DH, WP	High	-	ρ_g,Q,IB,G, N,T,E,EI,p	Low

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5.3 Prometheus Reactor Design Study Critical Issues

This section presents the critical issues identified for the laser and heavy ion driver, reactor cavity and balance-of-plant systems considered for the Prometheus IFE power plant design study. Each critical issue is broad in scope and covers several of the most important key issues for a number of components and technical disciplines. The final list of critical issues is presented in Table 5.3-1. References are collected at the end of each issue discussion

Table 5.3-1. List of Critical Issues Identified by the Prometheus Design Study

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

5.3.1 Critical Issue No. 1: Demonstration of Moderate Gain at Low Driver Energy - The U.S. National Energy Strategy[1] envisions three major facilities for IFE/ICF applications development: a Laboratory Microfusion Facility (LMF) for high gain target performance characterization and advanced military applications development; an Engineering Test Facility (ETF) to provide high pulse rate capability supporting fusion energy technology development and testing; and a Demonstration Power Plant (DPP) to validate long term economic, reliability, availability and maintainability issues for IFE. The total development cost associated with this plan will be formidable because each facility will likely cost more than $1B. It therefore is worthwhile to consider development paths that might enable a single facility to address both LMF and ETF research and development needs. Hogan discusses the prospects for such a facility in a recent paper[2]. Target experiments could be carried out in a separate, single-shot cavity. Engineering development would be conducted in another cavity with the target design and driver pulse rate selected to produce relatively low yield and fusion power. This approach would dramatically lower the cost of IFE development potentially leading to a more near-term DPP.

Reactor design studies have typically focused on high-gain, multi-megajoule incident energy target concepts that are appropriate for economic power production. However, engineering development, is usually cost limited. It therefore is worthwhile to consider if target designs that provide moderate gain (20-50) at low drive energy (1-2 MJ) are justified. Such targets would lower the facility cost associated with IFE engineering testing and fusion power demonstration. Target design studies for the Nova Upgrade have identified conditions under which the ignition "cliff" is shifted to much lower drive energy with the penalty of lower gain. This is illustrated in Figure 5.3.1-1 which compares the projected gain for two different sets of implosion velocities and associated hohlraum temperatures to that projected for the LMF conditions. (The shaded region at the low energy end of the curves represents the uncertainty in the location of the ignition "cliff" due to uncertainty in the capsule surface finish.)

As indicated, the alternative target designs coupled with a driver comparable to the Nova upgrade (1-2 MJ) would be above the ignition cliff and repeatably produce the output distribution (neutron/debris/x-ray split) and energy spectra of higher gain targets. Reactor component development testing could thereby be conducted at low drive energy with a cavity radius scaled appropriately to duplicate the relevant reactor parameters. In principle, this should provide the capability to achieve most of the ETF goals at relatively low power levels with full thermonuclear effects in a moderate cost facility.

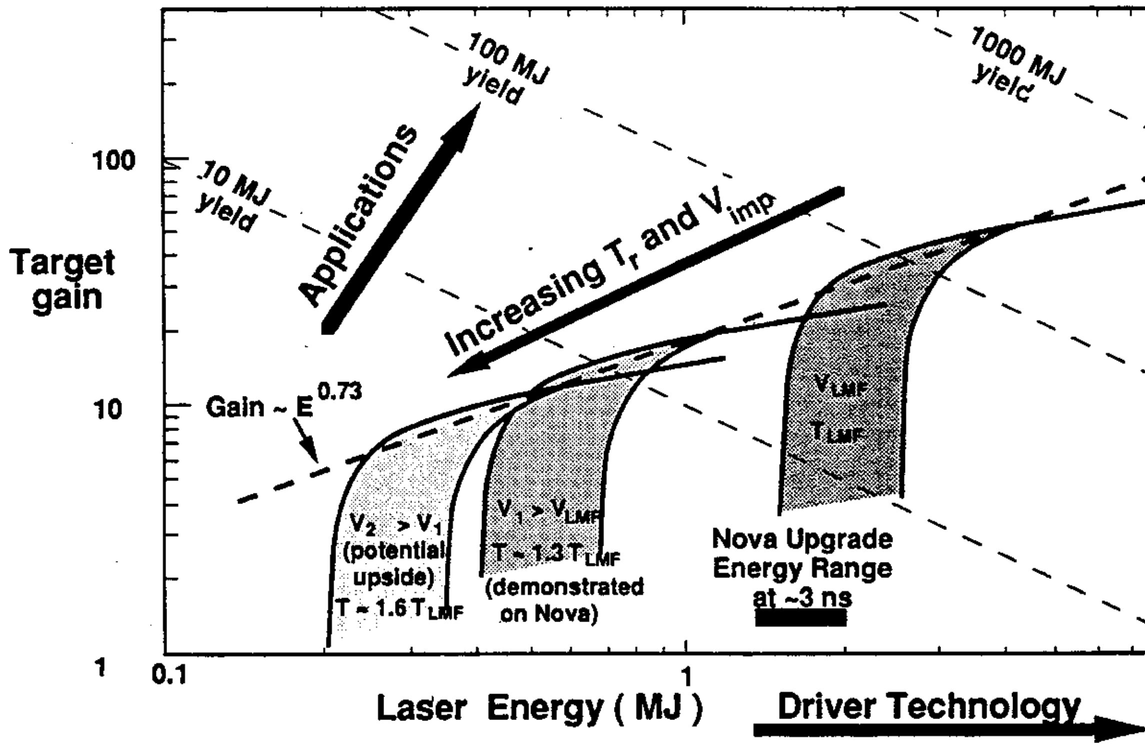

Figure 5.3.1-1. Gain Curve Scaling With Hohlraum Temperature Relative to Gain for the LMF Conditions. Nova Upgrade Will Characterize the 1-2 MJ Region of Gain Space and Reveal How Well the Location and Height of the Ignition Cliff Can Be Controlled. (Figure Courtesy LLNL).

Issue Resolution Strategy - To help identify the region of gain space that is attractive for reducing IFE development costs, the Prometheus driver, reactor and balance-of-plant design/cost scaling relations were used to project curves of target gain versus driver energy for a fixed capital cost facility. A 100 MWe demonstration power plant was chosen for illustration purposes. The costs are for a first-of-a-kind plant and include only direct construction costs. A summary of the cost elements included in the study and their scaling with yield (Y in MJ), pulse repetition rate (RR in pps), thermal power (P_{th} in MW), recirculating and gross powers (P_r and P_g in MWe) and driver energy (E_d in MJ) is presented in Table 5.3.1-1.

The resulting driver cost variation with output energy is shown in Figure 5.3.1-2 over the energy range of interest. This figure shows that projected laser costs are typically less than those for a multiple-beam LINAC but more than those for the 2 GeV single-beam system. The multiple-beam LINAC efficiency, however, is much higher than that for the other two driver options which offsets its higher cost.

Table 5.3.1-1. Summary of Demonstration Power Plant Direct Cost Scaling Used in Required Gain Curve Study

Cost Element	Cost Scaling Relationship (M$)
KrF Laser Driver (NLO)	$113 + 163\ E_d$
Single-Beam LINAC (4 GeV)	$288 + 76\ E_d$
Multiple-Beam LINAC (4 GeV)	$292 + 117\ E_d$
Single-Beam LINAC (2 GeV)	$218 + 35\ E_d$
Multiple-Beam LINAC (2 GeV)	$244 + 116\ E_d$
Land and Structures	$60 + 150(P_f/500)^{0.3}$
Reactor Plant	$50 + 480(P_{th}/3000)^{0.5} + 320(Y/500)^{0.5}$
Turbine Plant	$13 + 176(P_g/1000)^{0.8} + 20(P_{th}/2860) + 59((P_{th}-P_g)/1860)^{0.8}$
Electric Plant	$71.5 + 67(P_g/1000)$
Miscellaneous Plant	$57(P_n/1000)^{0.3}$
Target Factory	$50 + 100(RR/5.6)^{0.7}$

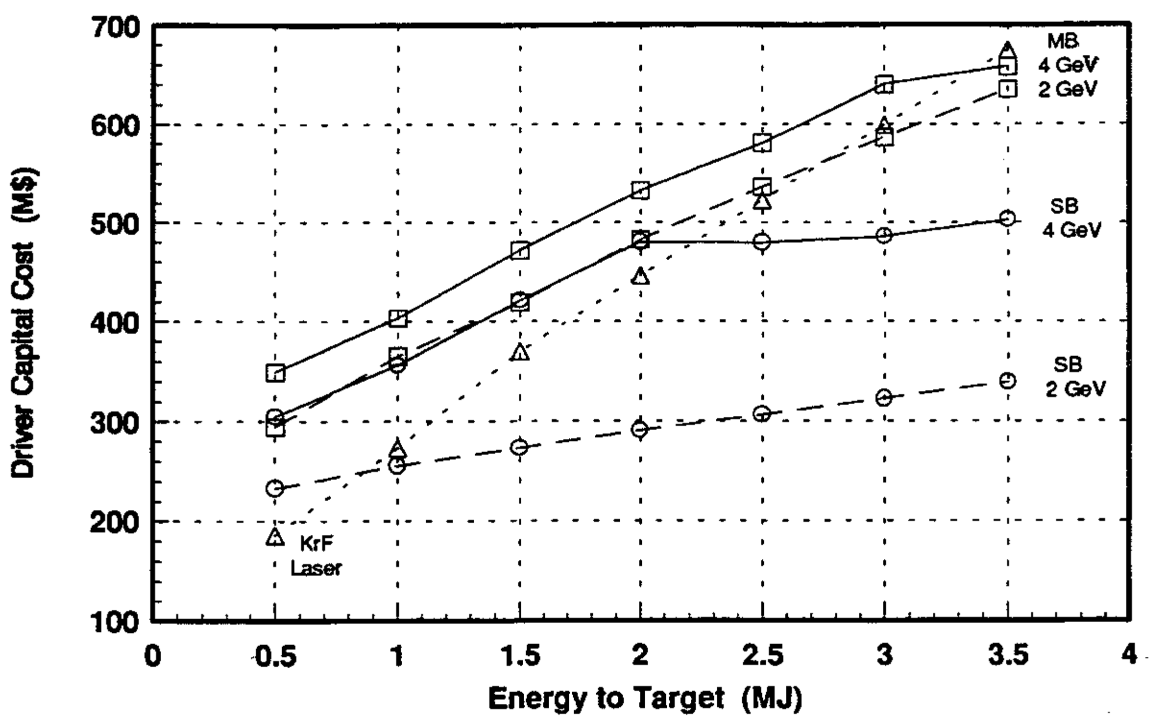

Figure 5.3.1-2. Projected Cost Scaling for Small-Size KrF Laser and Heavy-Ion LINAC Drivers

Efficiency plays a key role in minimizing the reactor and balance of plant costs for small plants where the net power is comparable to that required by the driver. This is because the recirculating power is equal to $P_{th} / (M \eta_d G)$ where M is the blanket energy multiplication (1.1-1.4). If the recirculating power exceeds the gross power ($\eta_{th} P_{th}$), no net power is generated. Conversely, if $M \eta_d G$ exceeds $1/\eta_{th}$ by more than a factor of two, the reactor and blance-of-plant costs are determined primarily by the net power requirement. As a result, in a cost-limited scenario, the gain (hence yield and associated plant cost) required to produce net power scales directly with driver efficiency. Figure 5.3.1-3 shows the projected efficiencies for the drivers considered in this study. The 10% Prometheus-L system efficiency may ultimately be increased to 15%, but both values are well below the 30% efficiency possible with a MB LINAC. This makes the MB LINAC an attractive option in spite of its higher capital cost.

It also is worthwhile to note that as driver energy increases, eventually there is no gain which will support both the recirculating and net output power requirements in a fixed-cost facility. The driver portion of the cost becomes too large. The required gain curves thus asymptote to infinity at some driver energy which is a function of the specified capital cost.

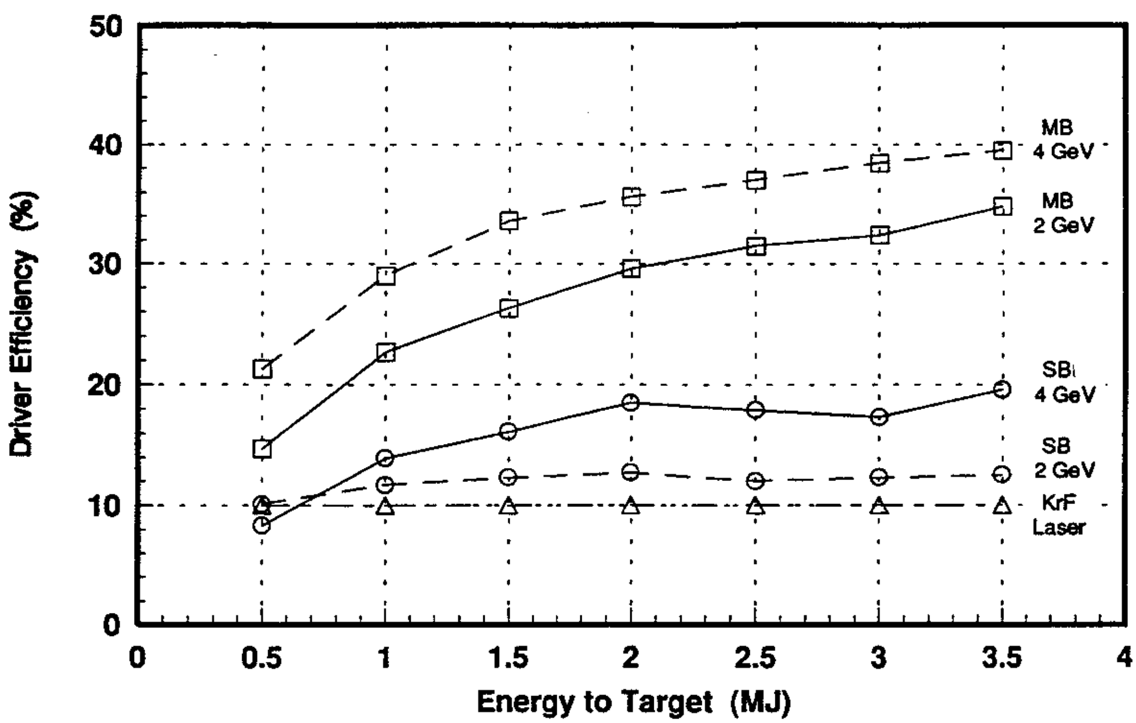

Figure 5.3.1-3. Projected Efficiency Scaling For Small-Sized KrF Laser And Heavy-Ion LINAC Drivers

These simple power balance and cost relations were used to define curves of required gain versus driver output energy for different fixed direct capital costs. Figure 5.3.1-4 shows the result for a 100 MWe power plant based on the Prometheus-L driver design at 10 and 15% efficiency. It should be noted that the target design windows for cost-limited development are the important consideration here not the projected capital costs. Absolute costs may change, but the parametric scaling should result in similar design windows. To assess whether the design windows are feasible, Figure 5.3.1-4 compares the gain requirement curves to possible optimistic and pessimistic physics limitations on target gain for indirect-drive targets suggested by Hogan[3].

The figure shows that target gains of 30-50 at a drive energy of 1-2 MJ provide a possible DPP design window for either 10 or 15% laser efficiency. Improved efficiency enlarges the design window (or conversely reduces the cost). But the gain required for a 10% efficient laser is less than conservative limits on possible target gain, with only $300M in additional funding beyond that needed to provide any design window. Therefore, there is significant motivation to develop target designs appropriate for this region of gain space. This is reinforced by the fact that such designs could likely be validated on Nova Upgrade.

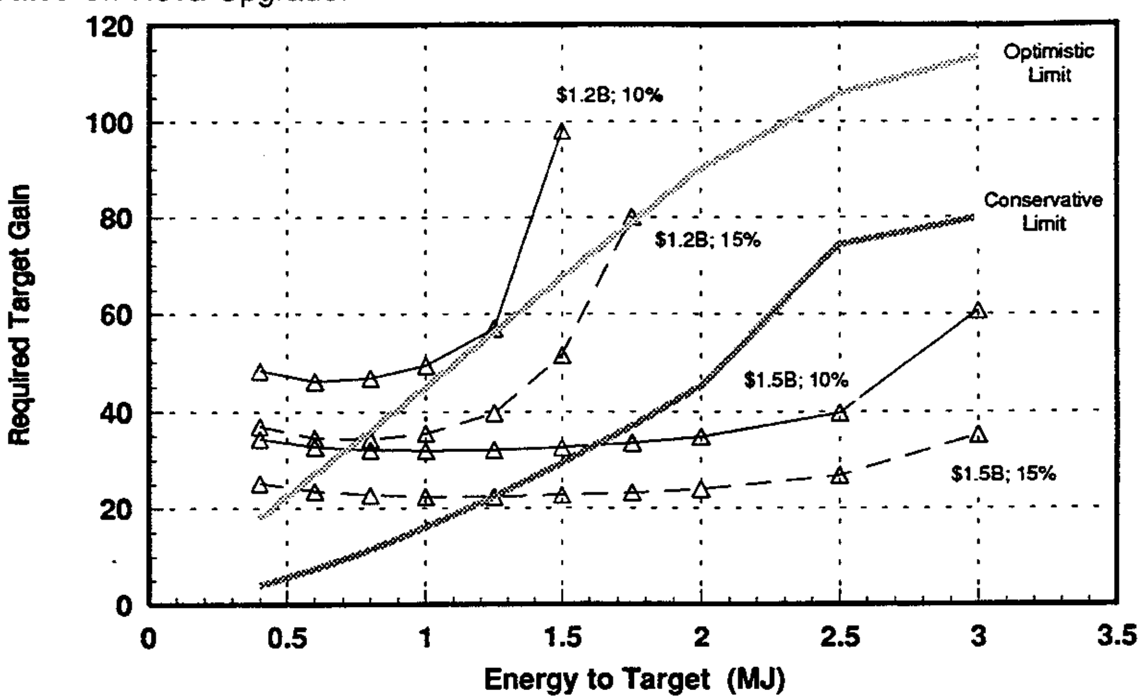

Figure 5.3.1-4. Projected 100 MWe Demonstration Power Plant Gain Space Windows for the Prometheus-L Driver Configuration. Values Indicated Only Include Direct Costs.

The simple power balance and cost relations were also used to evaluate the gain space appropriate for heavy-ion drivers. Figure 5.3.1-5 shows these results for a comparable 100 MWe power plant with a single-beam (SB) LINAC driver based on the Prometheus-H design configuration. To assess the feasibility of such designs, Figure 5.3.1-5 again includes possible optimistic and conservative limits on gain suggested by Hogan[3]. This figure shows that SB power plants only require gains of 20-30 at a drive energy of 1-2 MJ due to the higher driver efficiency. This is greater than the conservative limit on gain scaling would suggest, but it is well below the optimistic gain scaling limit. A driver with 2.5 MJ output is required to surpass possible conservative limits on gain.

It is also worthwhile to note that the 2 GeV option may provide an extremely attractive development path. As indicated in Figure 5.3.1-2, this driver costs ~60% of the 4 GeV system because it is half as long. At driver energies above 3 MJ, the number of beams becomes excessively large (greater than 40) for a 2 GeV system. However, if viable target designs are possible in the 1-2 MJ energy range, this option provides a very low-cost driver (<$300M) with a number of beams comparable to that proposed for the Prometheus-H plwer plant. Further characterization of heavy-ion target designs in this region of gain space thus is clearly justified.

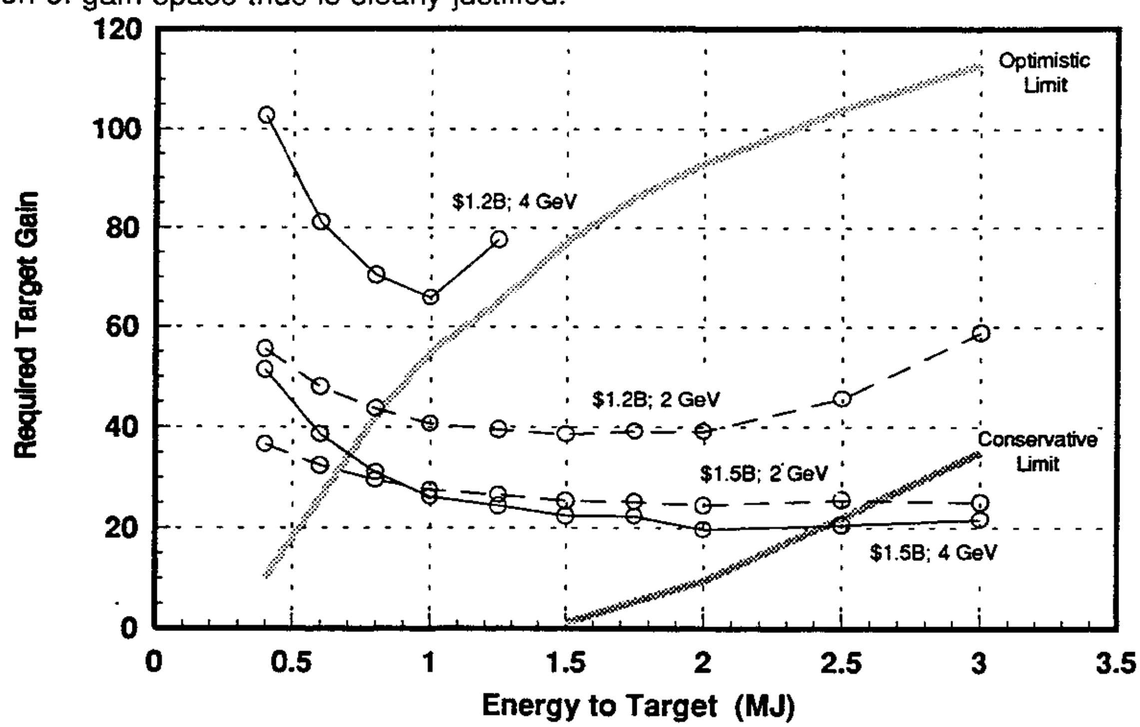

Figure 5.3.1-5. Projected 100 MWe Demonstration Power Plant Gain Space Windows for the Single Beam Prometheus-H Driver Configuration. Values Indicated Only Include Direct Costs.

Figure 5.3.1-6 shows these same gain space design windows for a 100 MWe power plant with a multiple-beam (MB) LINAC driver. This option eliminates the core recycling and storage rings required for the single beam design, which leads to efficiencies between 20 and 40% as indicated in Figure 5.3.1-3. This makes the MB LINAC an attractive option for a DPP in spite of its higher capital cost, as indicated in Figure 5.3.1-2, since recirculating power is significantly lower. This is highlighted in Figure 5.3.1-6, which shows that the required gain curves for an MB LINAC are actually lower than those for the SB LINAC once funding is large enough to get over the hump of its higher capital cost. Gains of 10-20 at driver energies between 1 and 2 MJ are all that is required to build a small DPP using an MB LINAC driver.

The figure also shows that the 2 GeV design may once again offer an attractive development pathway. The cost advantage of a 2 GeV system is reduced for the MBL driver, as indicated in Figure 5.3.1-2, but its efficiency is comparable to that at 4 GeV. Furthermore, target performance will likely be improved at this energy because of the shorter ion range. A 2 GeV MB LINAC may therefore prove to be the best option for a heavy ion DPP. The SBL capital cost is significantly lower, but this is offset by reduced BOP costs for the higher MB efficiency for a small DPP where there is little excess ηG.

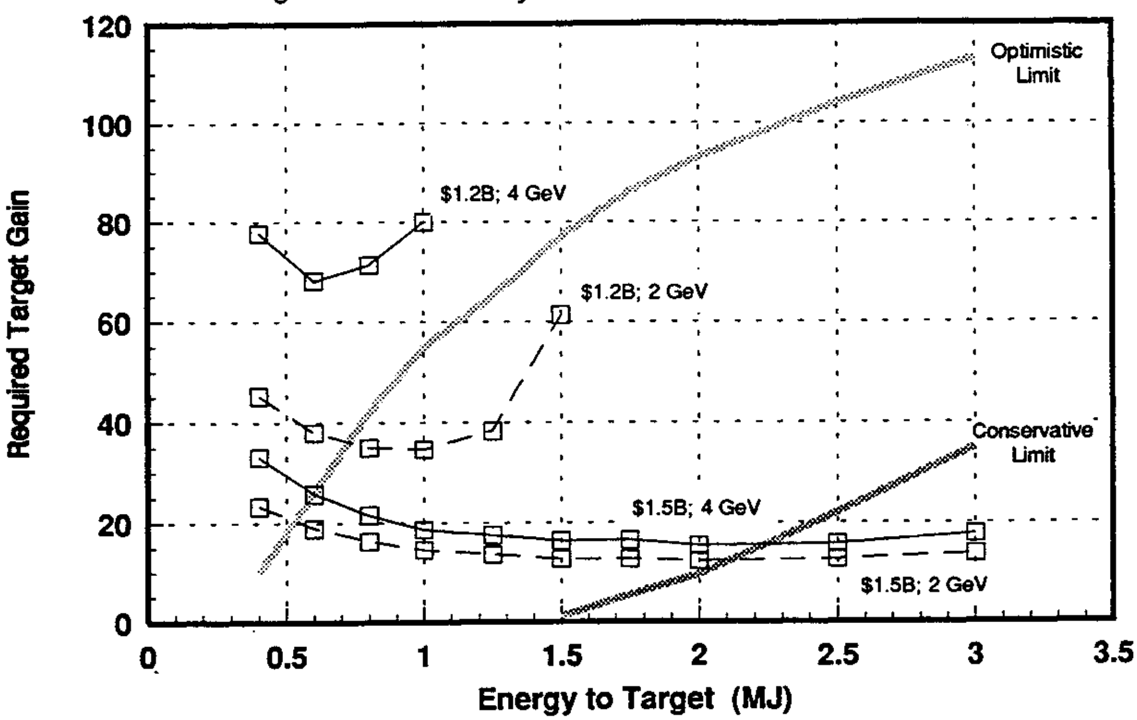

Figure 5.3.1-6. Projected 100 MWe Demonstration Power Plant Gain Space Windows for a Multiple Beam LINAC Driver. Values Indicated Only Include Direct Costs.

It, therefore, is critical that the Nova upgrade or a similar plant be implemented in a timely manner. Target experiments could then be conducted to characterize the location of the ignition cliff and the height of the gain curves for advanced target designs. This will establish a database for designing the ETF/LMF facility. An early ~2000 demonstration of low drive energy (1-2 MJ) target designs with repeatable gains comparable to those projected by this study would also provide strong justification for a lower-cost IFE development pathway utilizing such moderate-gain targets. This could provide the impetus to accelerate the engineering development and commercialization of IFE technology.

References for 5.3.1

1. National Energy Strategy, First Edition 1991/1992, U.S. Department of Energy, Washington, DC, February 1991.
2. W. J. Hogan, "Small Inertial Fusion Energy (IFE) Demonstration Reactors," to be published, Proceedings 14th IEEE/NPSS Symposium on Fusion Engineering, San Diego, CA, October 1991.
3. W. J. Hogan, private communication, 1992.

5.3.2 Critical Issue No. 2: Feasibility of Direct Drive Targets

Description of Problem - There are strong incentives to consider direct-drive (DD) laser targets because of higher gains. However, the feasibility and performance characteristics of DD targets are presently uncertain. These discussions are likely also applicable to heavy ion, direct drive targets, but the database is non-existent. The fundamental laser driver architecture of the Prometheus IFE Reactor Design is strongly influenced by the direct-drive (DD) target illumination requirements given by the Target Working Group (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 provided by the TWG is not consistent with the Fresnel number of the beam at the location of the target. In addition, there are concerns that the long, 80 ns precursor pulse may produce significant deleterious effects, such as generation of non-linear scattering processes which may lead to target preheat, thereby preventing an efficient DT implosion from occurring. Designs 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 apparently require entirely different illumination scenarios. For reactor operation, the DD targets must also be accurately injected into the target chamber with a tracking/alignment system capable of meeting the illumination uniformity requirements set forth below.

Review of Target Illumination Requirements Supplied by TWG - The TWG has provided the project with laser direct drive target illumination requirements which include the following elements:

(1) $\geq$ 60 beam illumination with $\pm$ 1% illumination homogeneity of a 6-mm diameter target
(2) 80 ns precursor pulse containing 30% of energy, followed by 6-ns main pulse (long prepulse generates underdense plasma atmosphere 3.2-cm deep prior to arrival of main pulse, thereby risking generations of SBS, SRS, hot electrons, and resonant absorption mechanisms)
(3) UV wavelength (<300 nm) with approximately 5 MJ of energy
(4) Tangential illumination (beam diameter at target = target diameter); no mention of focal zoom; beams are circular in cross-section, (very wasteful of laser light, excimer laser beams are square, may encourage resonant absorption in underdense plasmas)
(5) The spatial intensity distribution of the incident laser beams in the target plane is described by $I_{target}(x) = (\sin^2 x) / x^2$ (inappropriate apodization for homogeneous illumination and efficient excimer laser extraction)

There were no TWG specified requirements on beam polarization, bandwidth, or beam quality, all of which are important parameters in laser/target interactions. During the 6-ns main pulse duration, the direct drive (DD) target implodes from an initial 6 mm diameter down to 3 mm, which corresponds to an implosion speed of 2.5×10^7 cm/sec. Approximately 30% of the DT fuel is fused during the resulting implosion.

Physics of Target Implosion - Using the TWG criteria, the DD target is assumed to be a 6-mm CH spherical shell containing a layer of frozen DT. The initial laser photons incident on the CH shell blow off an underdense plasma from the CH shell to permit the main pulse to interact primarily with the plasma atmosphere. The intention is to drive a symmetrical implosion of the D/T fuel to at least 20 times liquid density. A diagram of a single beam (one of many) tangentially illuminating a spherical direct-drive target at the start of the laser pulse is shown below in Figure 5.3.2-1.

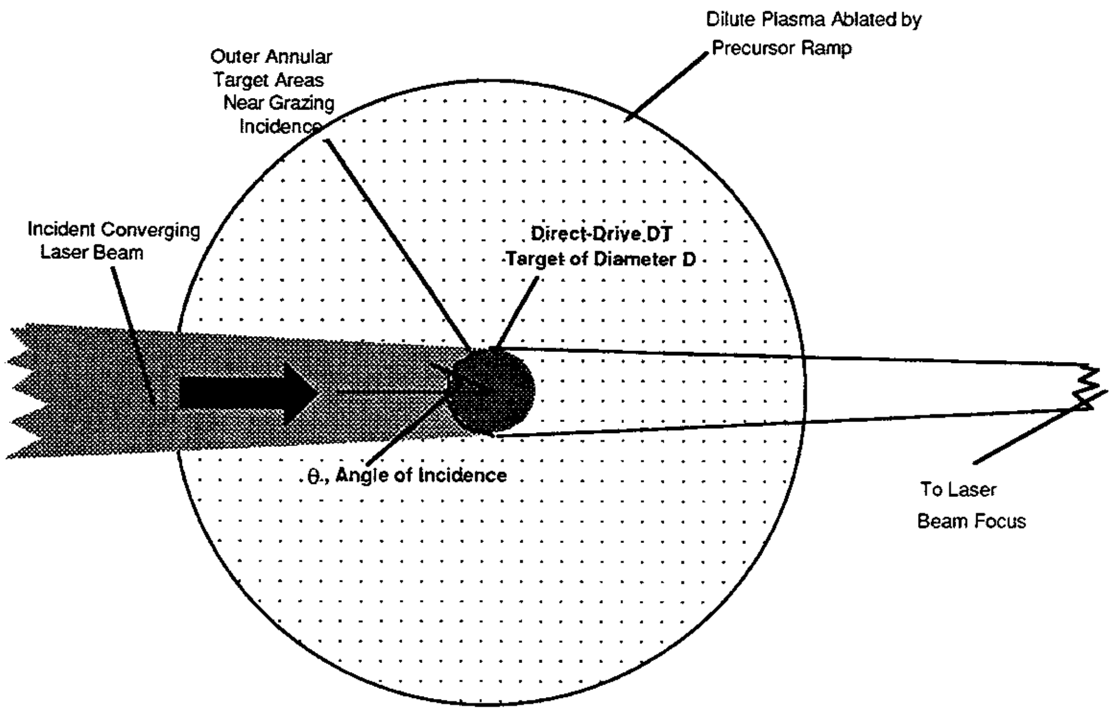

Figure 5.3.2-1. Diagram of Tangential Direct-Drive Target Illumination Geometry at Start of Main Pulse

A precursor pulse this long produces an underdense atmosphere 3.2 cm deep by the arrival of the main pulse, thereby providing a long gain length for non-linear processes which can cause target pre-heat. During the resulting implosion occurring at a speed of approximately 2.5×10^7 cm/sec., the target compresses to ~50% of its original diameter. Unless the laser beam focal spot sizes are also reduced by 50%, a significant amount of laser light would consequently miss the target. A diagram illustrating this problem is shown in Figure 5.3.2-2.

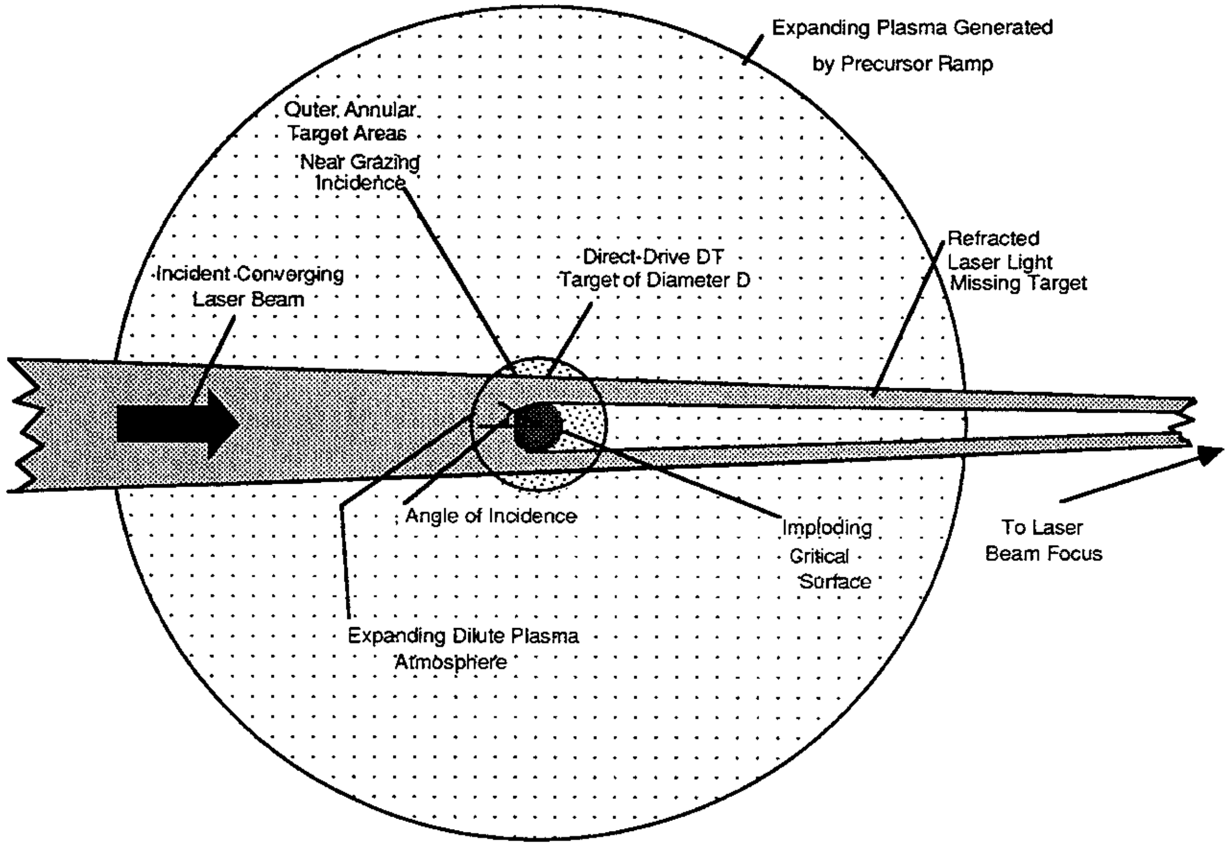

Figure 5.3.2-2. Diagram of Tangential Laser Illumination Geometry at end of 6 ns Laser Pulse

Recapitulation of Published Plasma Physics Target Coupling Requirements - Uniformity of target illumination for multiple beam geometries is essential for preventing the growth of Rayleigh-Taylor instabilities. However, it is also important that the angle of incidence, θ, between the incoming laser beams and the target be minimized in order to absorb the incident beam efficiently into the critically-dense plasma atmosphere blown off from the target. According to Kruer,[1] the fractional absorption, f_A, for a linear plasma density profile is given by the expression:

$$f_A = 1 - \exp\left(\frac{32\, v_{ei}\, L}{15c} \cos^5\theta \right) \qquad (5.3.2\text{-}1)$$

which, as indicated, depends upon $\cos^5 \theta$. Here, v_{ei} is the plasma collision frequency evaluated at the critical density, n_{crit}. In addition, since an obliquely incident optical wave reflects from the plasma at a lower density than the critical density, less collisional plasma is traversed by these waves, further decreasing the coupling fraction. Calculations were carried out using this absorption function using the geometry shown below in Figure 5.3.2-3.

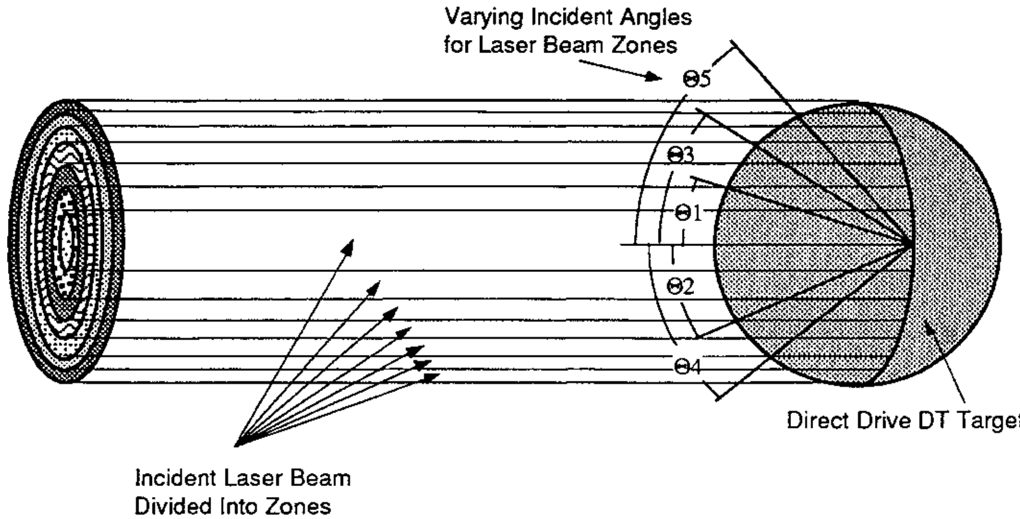

Figure 5.3.2-3. Geometry for Computing Angular-Dependent Light/Plasma Coupling Efficiencies

Using this geometry and Eq. 5.3.2-1, the target coupling efficiency was calculated assuming that $f_A = 1$ for $\theta = 0$ with a top hat apodization; the results are plotted below in Figure 5.3.2-4.

For a linear density profile averaged over the implosion time, these simulations estimate that only 15% of the laser light incident on the target will be absorbed. Since the actual beam shapes from the excimer lasers are square, a further reduction in target absorption efficiency of $\pi/4$ occurs. For an exponential electron density profile in the plasma ($n_c = n_{crit} \exp(-z/L)$, the fractional absorption, f_A, is given by the expression:

$$f_A = 1 - \exp\left(\frac{8\, v_{ei}\, L}{3c} \cos^3\theta\right) \qquad (5.3.2\text{-}2)$$

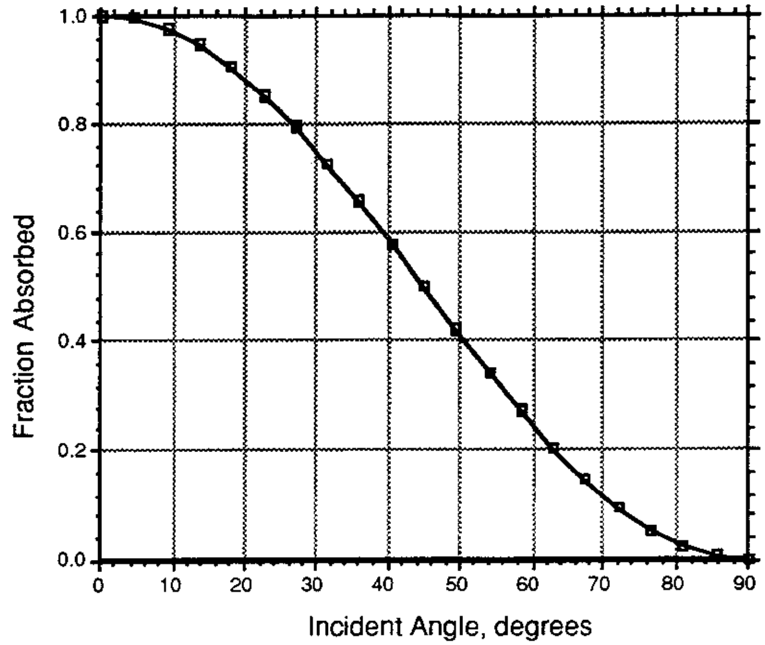

Figure 5.3.2-4. Fraction of Incident Laser Light Absorbed For Linear Plasma Density Profile

which, as indicated, depends upon $\cos^3 \theta$. Calculations were also carried out using this absorption function with a top hat apodization. In this case, 28% of the energy incident on the target would be absorbed.

Resonance Absorption Calculations - The energy absorbed by resonantly driven fields in the plasma is described by the expression:[2]

$$E_{abs} = \int \left(\frac{v\,(\langle E_r^* E_r \rangle)}{8\pi}\right) r^2\, dr \sin\theta\, d\theta\, d\phi \qquad (5.3.2\text{-}3)$$

where E_r is the radial electric field of the laser beam. Near the critical density, the expression for E_r is given by:

$$E_r = \frac{\ell\,(\ell+1)}{(i\varepsilon k^2 r^2)}\, a_\ell (1-\alpha_\ell^2)^{\frac{1}{4}} P_\ell^1(\cos\theta)\cos\phi\, \exp(i\delta)\, \frac{\Phi^2(\tau_\ell)}{2\pi\gamma\alpha_\ell^2} \qquad (5.3.2\text{-}4)$$

where α_l is given by the expression:

$$\alpha_\ell = \frac{\sqrt{\ell\,(\ell+1)}}{k\,R_c} \qquad (5.3.2\text{-}5)$$

(where R_c is the radius of the plasma critical density) and where $\Phi^2(\tau_l)$ is the absorption function for the lth mode. The fraction absorption of the lth mode, f_{RA}, is given by:

$$f_{RA} = \frac{\Phi^2(\tau_\ell)}{2\pi}\sqrt{1-\alpha_\ell^2} \qquad (5.3.2\text{-}6)$$

so that the total power absorbed from the laser beam as a consequence of resonance absorption is given by:

$$P_{RA} = \sum_\ell \frac{P_\ell}{2\pi}\,\Phi^2(\tau_\ell)\sqrt{1-\alpha_\ell^2} \qquad (5.3.2\text{-}7)$$

where P_l is the laser power in the lth mode. The net result of performing the integral in Eq. 5.3.2-3 is to show that resonance absorption generally depends upon $(\cos\theta_0)$;[2] the implication is that tangential target illumination proposed by the TWG would favor resonant absorption over inverse Bremsstrahlung for large angles of incidence. Perhaps a more serious result of these analyses[2] is that the spatial absorption distribution function is not uniform over the target sphere. The calculated RA distribution for a vertically polarized laser beam is shown in Figure 5.3.2-5.

As shown, resonance absorption is predicted to produce two symmetrical "hot spots" of absorption at mid-latitudes on the sphere when illuminated with linearly polarized light. This may constitute an absorption uniformity problem because this process occurs even when the sphere is uniformly illuminated. However, by using $\lambda = 248$ nm laser radiation, the effects of resonance absorption are not expected to be reduced relative to inverse Bremsstrahlung.

DD Target Injection, Tracking, and Alignment Problems - The 6-mm DD target is assumed to be injected into the target chamber with speeds of the order of 200 m/sec. Owing to the vagaries of mechanical and/or electromagnetic injection methods, tracking of the target and alignment of the 60 beamlines to the anticipated location of 'he target is mandatory. If tangential illumination is used, beams need to be aligned 'h an accuracy of $\pm 500\ \mu$ (corresponding to an angle $\Delta\alpha = 25\ \mu$rad as seen by the 'M) relative to the target. If pyramidal apodization is used, much more accurate

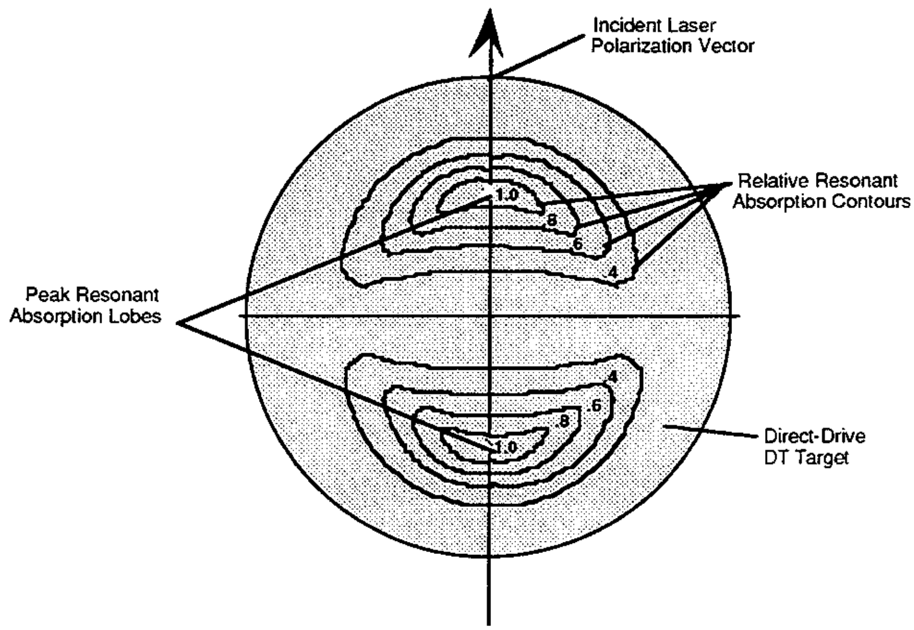

Figure 5.3.2-5. Resonant Absorption Contours on Spherical DD Target

target alignment is required (estimated to be ±5 μ [corresponding to an angle $\Delta\alpha = 0.25$ μrad as seen by the GIMM]). In order to achieve the requisite alignment accuracy in this case, a reflective "shine shield" on the direct drive target is strongly recommended. Although DD target injection, tracking, and alignment present technological challenges, it is believed that these problems can be solved using careful engineering, parallel dedicated computer processing, and advance metrology techniques.

<u>Summary</u> - Present specifications for the DD target illumination requirements such as those provided by the TWG, are based upon work performed at only a few kJ of laser energy. Elementary plasma physics and optics calculations suggest that the current TWG DD target illumination specifications are seriously flawed. It is essential that DD target results obtained at hundreds of kilojoules to megajoules be carried out as soon as possible to permit realistic DD target driver requirements to be generated. Such experiments could be performed using the Nova Upgrade laser proposed to be built at the Lawrence Livermore National Laboratory.[3,4] Using advances in laser technology together with SDIO tracking technology, we anticipate that high gain DD targets could be developed which require only a few MJ of laser energy to achieve optimum performance. These large reductions in the requirements for laser energy can lead to significant reductions in COE as well as an increase in reliability. More importantly, the development steps will have facilities of much smaller size and moderate costs.

References for 5.3.2

1. The Physics of Laser Plasma Interactions, William L. Kruer, Chapter 5, "Collisional Absorption of Electromagnetic Waves in Plasma," pp. 45-56.

2. "Laser Light Absorption in Spherical Plasmas," J. J. Thomson, C. E. Max, J. Erkkila, and J. E. Tull, Physical Review Letters 37, pp. 1052-1056 (1976).

3. "Nova Upgrade Facility for Ignition and Gain," LLNL ICF Program, UCRL-LR-106874, LLNL, Livermore, CA 94550, March 1991.

4. "Nova Upgrade–A Proposed ICF Facility to Demonstrate Ignition and Gain by the Year 2000," LLNL ICF Program, UCRL-LR-106736, LLNL, Livermore, CA 94550, March 1991.

5.3.3 Critical Issue No. 3: Feasibility of Indirect Drive Targets for Heavy Ions

Description of Problem - The feasibility of the indirect drive (ID) targets for the heavy (HI) ion driver is, in part, linked to: (1) the properties of the method used to transport and focus the HI beam to the target, (2) the accuracy and reproducibility of the repetitive HI target launch system which injects the ID targets to the center of the target chamber, and (3) the ability of the high-Z hohlraum cavity to efficiently convert and smooth the radiation incident on the DT capsule. This study is involved with finding innovative solutions only to the first and second tasks.

There are several methods of transport of the heavy ion beams across the cavity and focusing onto one or more locations on the target, either direct drive or indirect drive. Sections 4.3.2 and 6.5.2.6 discuss these options in some detail. Two methods are worthy of note, ballistic transport and channel transport. A concurrent IFE Reactor Design Study[1] was accomplished by a team lead by W.J. Schafer Associates. This team selected the ballistic approach while the MDA-led tema chose the channel transport. In the interest of brevity, the discussion of this issue will be limited to the channel transport option although may aspects of the issue are common and generic.

In the approach being investigated for the Prometheus-H IFE Reactor Design, a number of HI beams is focused onto a stripping foil or cell placed in front of a pre-ionized channel. The HI beam(s) are then completely stripped, yielding mega-ampere currents which overcome space charge repulsion to self-focus the beam(s), thereby trapping the ions in a small diameter (a few mm) channel whose direction is accurately determined by the pre-ionizing beam. This self-focused, small diameter beam is subsequently directed to the convertor regions of the moving hohlraum target capsule. The target has been injected to arrive at the center of the reactor target chamber synchronously with the arrival of the HI beam(s).

Two types of indirect drive, heavy ion fusion targets were considered:

(1) Single energy convertor ID hohlraum targets designed for single-sided target irradiation (SSTI), and
(2) Dual energy convertor ID hohlraum targets designed for dual-sided irradiation (DSTI).

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

(1) Providing return paths for the 13.3 x10^6 A current for the SSTI beam and for 6.7 x10^6 A for each beam for the DSTI case.
(2) Successful injection and self-pinching of the HI beams passing through the stripping foil(s) into a self-focused, small diameter beam directed at the SSTI or DSTI ID target.
(3) Accurate pointing of the pre-ionized channel(s) at the energy convertor(s) of the ID target.
(4) Precision launching of the HI ID targets to arrive repeatedly at the center of the target chamber and synchronized with the arrival of heavy ion beams.

Review of Target Irradiation Requirements Supplied by TWG - The Target Working Group (TWG) supplied the team with several unclassified documents[2,3] which were used to design a suitable HI driver design. The following general HI driver requirements were determined from the TWG recommendations:

(1) Tightly focused HI beams containing approximately 5 MJ of energy are to be delivered in a main beam pulse duration of 6 ns,
(2) The incident HI beam diameters need to be ≤6 mm at the $1/e^2$ points,
(3) The HI beams must intercept the convertor regions with an accuracy of ±0.5 mm.

Physics of Single-Sided HI ID Target Irradiation - Key to both the HI ID target irradiation of both single-sided and double-sided targets for the Prometheus IFE reactor is the collapse of all the separate HI beams into a single, pre-ionized channel of small dimensions. In the Prometheus IFE reactor design concept, this feat is accomplished by focusing the separate, bunched beams with large quadrupole magnets down to a common focus coinciding with a thin stripping foil. A schematic of this configuration is shown below in Figure 5.3.3-1. Background gas is present to permit autoneutralization of the focusing beams. Immediately prior to the arrival of the bunched beams, a non-bunched, precursor HI beam is precisely directed through the foil to the predicted location of the HI target. The target moves approximately 10 μm while the beams cross the cavity. Care must be taken to avoid damaging the HI ID target with the non-bunched beam. A dilute gas (Pb vapor) at a pressure of ~100 millitorr is present in the target chamber. The non-bunched precursor HI beam forms an ionized channel in the dilute lead vapor from the foil to the HI target.

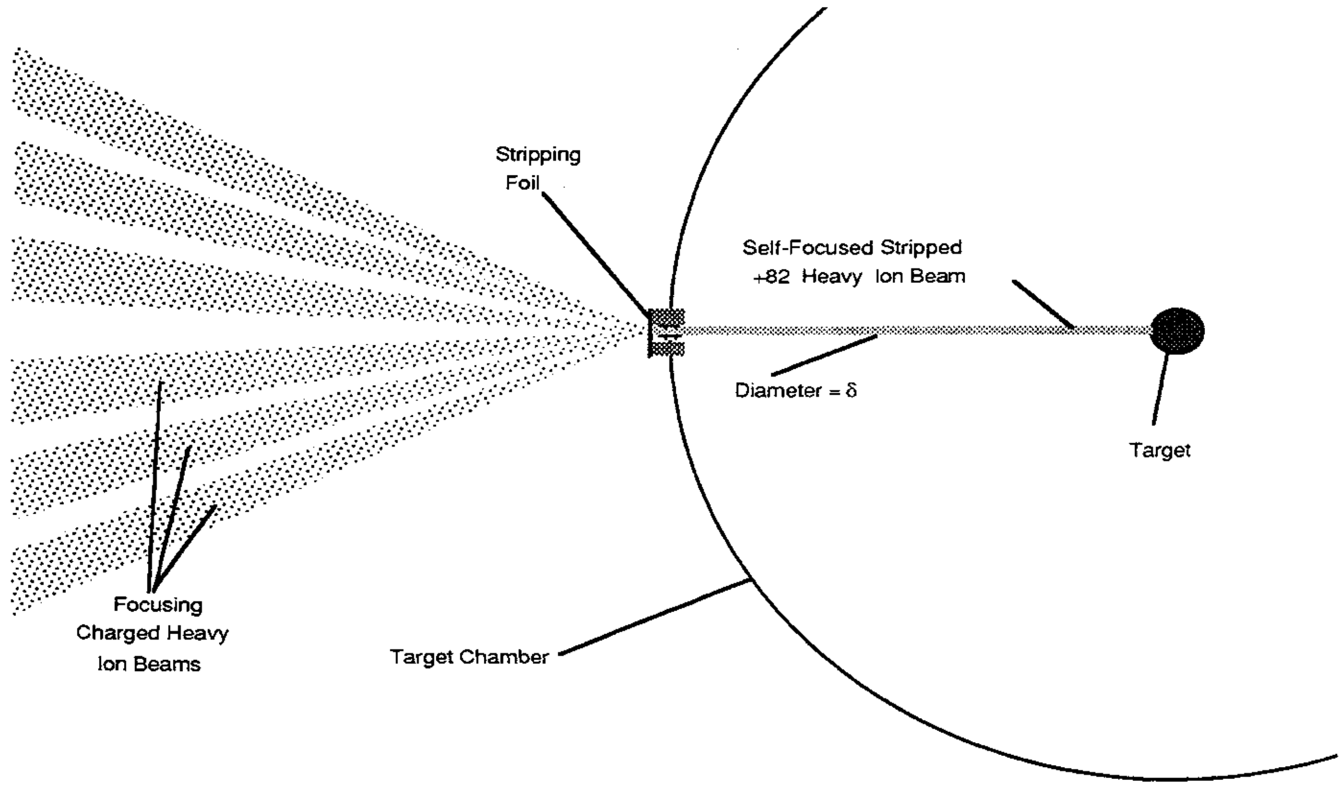

Figure 5.3.3-1. Schematic of Prometheus Approach for Heavy Ion Single Sided ID Target Irradiation

Following the arrival of the bunched HI beams, each +2 ion is stripped to an ~ +80 charge state, thereby increasing the current to a level of approximately 6 MA. This beam current is more than an order of magnitude larger than is necessary to self-pinch the combined beams, thereby leading to a trapped, self-focused HI beam precisely directed to the energy convertor of the single-sided HI target. The diameter, δ, of the self-pinched beam oscillates transverse to the beam direction with an amplitude determined by the original beam emittance and a period of approximately 20 cm.

<u>Physics of Double-Sided HI ID Target Irradiation</u> - The technical problems associated with double-sided HI ID target irradiation are similar to those described above for the single-sided HI ID target case. An additional constraint is that the two HI pulses must not only arrive near simultaneously at each of the target energy convertors, but they must also be accurately aligned spatially. A schematic of the double-sided HI ID target irradiation geometry is shown below in Figure 5.3.3-2.

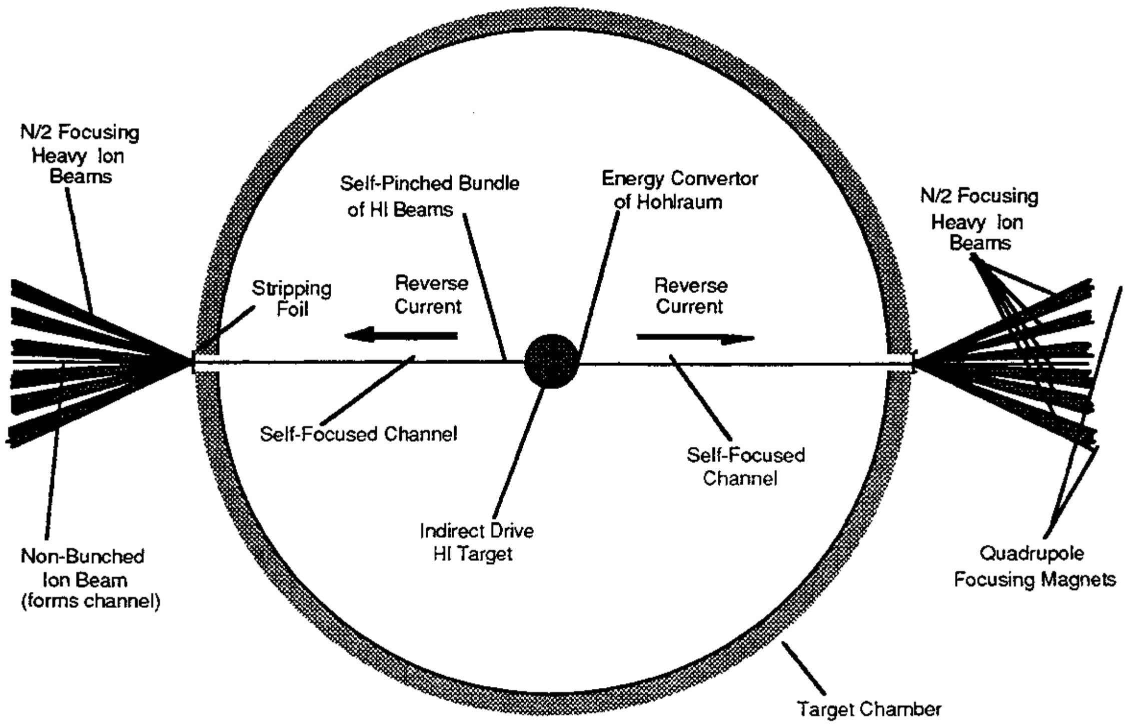

Figure 5.3.3-2. Schematic of Double-Sided Heavy Ion ID Target Irradiation Geometry

As noted above, key to the Prometheus HI ID double-sided target irradiation concept is the collapse of the two sets of separate HI beams into each of the two pre-ionized channels of ≤6 mm diameter. In this case, the non-bunched precursor HI beams create the ionized channels in the low pressure (100 millitorr or less) lead vapor prior to the arrival of the HI ID target.

In a manner similar to that described above for single-sided irradiation, following the arrival of the N/2 bunched HI beams, each +2 ion is stripped to a ~ +80 charge state, thereby increasing the current to a level of approximately 6 MA. This is sufficient to self-pinch the combined beams, thereby leading to a pair of colliding, self-focused HI beams precisely directed to the energy convertor of the double-sided HI target. Previous work performed with heavy-ion beams has shown that high degrees of precision can be achieved with regard to both timing of pulse arrival as well as intercepting a small aperture, providing the divergence associated with non-compensated space charge have been overcome.

ID HI Target Transport Problems - The problems asociated with transport of the indirect drive heavy ion beam target relates to two general categories:

(1) Protection of the cryogenic target from thermal radiation, primarily emanating from the cooling interior of the reactor chamber

(2) Accurate delivery of the indirect drive, heavy ion beam target to a location where the beams can successfully illuminate the target.

Indirect drive targets by their very nature are relatively fragile and difficult to accelerate rapidly. In general, accelerations greater than 100 m/sec^2 are to be avoided. Target velocities should be in the range of 200 m/s to minimize the transit time across to the center of the chamber. Since the cryogenic DT capsule is relatively well protected from the thermal radiation present in the target chamber, the HI ID target is predicted to be less prone to heating. Because of the 100 mtorr residual lead vapor pressure, the effect of viscous drag and turbulence on the motion of the target in the chamber must be determined.

As mentioned earlier, the target injector and the beams must work in conjunction with each other to provide the required illumination on every target. To date, the experimental targets have been stationary and the beams and/or target adjusted to achieve the desired illumination requirements. In demonstration power or commercial reactors, this degree of accuracy must be achieved every time, several times a second. This can be accomplished either with a highly precise target injector and the target can be tracked and the beams adjusted to the known or predicted location of the target.

The factors which effect the final position of the target include the velocity vector at release and the environment during the transit to the final position. The magnitude of the vector, if measurable, is not a serious problem as the timing of the beams can be adjusted to compensate. Alignment of the injector can easily be corrected. The alignment of the single-sided injector would be easiest because it would enter from the opposite side of the chamber and would be aligned coaxial with the beam. The alignment of the injector with dual-sided illumination is more difficult because coaxial injection is not permitted due to the on-axis precursor beams. The Prometheus recommendation was to locate the injector off axis by 10° to clear the beamline cone. This severely complicates the alignment because the lateral component of target motion relative to the nominal beam axis. Timing of the beam becomes more critical and/or beam adjustments are required.

One of the more serious difficulties is ensuring that during the release of the target from the injector no lateral forces are induced which would influence the target velocity vector. The precision of the injector can be analytically modeled and then tested experimentally to verify the required precision. The environmental influences within the chamber are more difficult, especially predicting how the environment will behave a few tenths of a second after the prior fusion reaction. Modeling and experimental evidence will be required to develop the necessary database.

Upon leaving the injector, the velocity and position of targets must be determined. The targets could be tracked (with difficulty) through the shield, blanket, and into the actual cavity. Depending upon the known characteristics and behavior of the cavity environment, the required degree of tracking is determined – the better the environment is known, the less tracking is required and vice versa. Sensors can be protected to some degree, but high levels of radiation hardening will be required inside the shield area.

Summary - In the Prometheus IFE reactor concept, the feasibility of indirect drive heavy ion targets is largely based upon the successful and efficient collapsing of a large number of low ionization state particles into one or two single, highly ionized, self-pinched ion beams that are accurately guided to the energy convertor(s) of a heavy ion indirect drive hohlraum. Since the TWG specifications for HI ID targets were vague, the Prometheus IFE reactor concept has necessarily incorporated a great deal of flexibility in the final focus and transport portions of the heavy ion driver design.

It is important to demonstrate the validity of the Prometheus heavy ion final focus and self-pinched propagation physics experimentally. Since these experiments must be performed at full scale, it will be necessary to construct a substantial heavy ion driver machine in order to demonstrate the concept. It is strongly recommend that this be accomplished within the next decade.

References for 5.3.3

1. W. R. Meier, et al., "OSIRIS and SOMBRERO Inertial Fusion Power Plant Designs," W.J. Schafer Associates Report, WJSA-923-01 (March 1992)

2. "Inertial Confinement Fusion Reactor Design Studies; Recommended Guidelines," Ronald C. Davidson, et al., prepared for the Department of Energy Office of Fusion Energy, September 1990.

3. "Revised Target Information for IFE Reactor Studies," received form Roger Bangerter, Lawrence Berkeley Laboratory, Bldg. 47, room 112, 28 February 1991.

5.3.4 Critical Issue No. 4: Feasibility of Indirect Drive Targets for Lasers

Description of Problem - As in the case of the indirect drive heavy ion fusion target, the indirect drive (ID) laser fusion target being considered by the Prometheus IFE Reactor Design is a symmetric, two-sided hohlraum design. The feasibility of efficiently imploding this ID laser target has difficulties arising from three major sources:

(1) Plasma closure of the two entrance apertures to the hohlraum,
(2) Accurate target tracking and pointing of the multiple laser beams to coincide with the two entrance apertures of the moving ID target, and
(3) Accurate and reproducible indirect drive target propagation from the pellet injector to 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.

Review of Target Irradiation Requirements Supplied by TWG - As in the case of the heavy ion indirect drive targets, the Target Working Group (TWG) has supplied the team with unclassified documents. In the original inertial confinement fusion driver guideline document[1] supplied us, all references to indirect drive laser targets had been removed. A second document,[2] obtained much later, has some information concerning indirect drive laser targets. After careful examining of the information in these documents[1,2] from the TWG, the following laser driver requirements were surmised:

(1) Using the Nova Upgrade laser plan of 288 independently pointed beams arranged in three or four rings of beams on each side of the target with the beams distributed in angles ranging from 30° to 60° from the target axis, the indirect laser target illumination requirement is achieved. It should be possible to reduce the total number of beams to approximately 50. This would require an energy balance between beams of 5%. (Achieving a 5% balance of power among the laser beams is significantly easier than the 1% illumination uniformity required for direct drive laser targets)

(2) Nearly diffraction-limited laser beams are required with essentially all of the ~2.5 MJ in each of the two beams being contained inside a 1.5-mm diameter spot. Pulse durations range from around 8 ns at a 5 MJ energy level to 10 ns at 10 MJ. of 6 ns. (This is readily achieved since the focal spot size from a 1-m aperture mirror located 20 meters from the target chamber can achieve a 15-µm spot size.)

(3) A laser wavelength is needed for which efficient inverse Bremsstrahlung can be achieved [UV Wavelength (<300 nm)].

(4) A precursor laser pulse containing 30% of the energy and having a duration of 40 to 50 ns is required.

In general, these requirements are easier to meet than those specified for the laser direct-drive target. There are, however, some additional problems associated with ID laser targets which may seriously affect performance.

ID Laser Target Transport Problems - As noted, indirect drive laser targets are relatively fragile and difficult to accelerate rapidly. In general, accelerations greater than 100 m/sec^2 are to be avoided. Since the cryogenic DT capsule is relatively well protected from the thermal radiation present in the target chamber, the laser ID target can survive for longer periods in the target chamber (i.e., the propagation speed of the laser ID target need not be as great as that required for the laser direct drive target owing to this protective feature). See Section 5.3.3 for a list discussion of similar problems.

Summary - The feasibility of indirect drive laser targets is largely based on overcoming a number of potential technical problems: (1) directing 50 nearly diffraction limited laser beams accurately to the entrance apertures of the target and (2) reliably transporting the indirect drive target to the center of the target chamber with great precision. A great deal of flexibility in the final laser beam focus and transport portions of the laser architecture was incorporated to accommodate the range of specified requirements. As in the case of the direct drive target, technical development of high speed tracking and laser pointing systems are required in order to assure that all laser beams would be properly positioned on the entrance apertures of the ID target.

References 5.3.4

1. "Inertial Confinement Fusion Reactor Design Studies; Recommended Guidelines," Ronald C. Davidson, et al., prepared for the Department of Energy Office of Fusion Energy, September 1990.

2. "Revised Target Information for ICF Reactor Studies," Received from Roger Bangerter, Lawrence Berkeley Laboratory, Bldg. 47, room 112, 28 February 1991.

5.3.5 Critical Issue No. 5: Cost Reduction Strategies for the Heavy Ion Driver

Description of Problem - 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 HI driver cost reduction:

(1) Space charge limited transport of a bunched beam, and
(2) High current storage rings for heavy ion beams.

Space Charge-Limited Transport of a Bunched Beam - Experiments and computer simulations have shown that transporting beams for several kilometers at their space charge limit should be possible, with little emittance growth. However, this HI beam transport has only been demonstrated with low energy, low power, unbunched beams.

If the HI beams have to be transported at currents lower than the space charge limit, then the accelerator will have to have a longer pulse (in the case of an induction LINAC) or more quadrupole transport channels within the same accelerator, thereby increasing the cost of the accelerator.

High Current Storage Rings for Heavy Ion Beams - One of the characteristic properties of linear accelerators is their ability to run at rather high average powers and relatively high repetition rates. Since the clearing time in the IFE reactor chamber precludes very high repetition rates for the DT pellet ignition, the LINAC is forced to operate at uneconomically slow repetition rates. This problem can be eliminated if the beams for the LINAC can be stored for a short period of time. By operating the induction LINAC in the burst mode, the induction cores are used over and over, and of course, each core is therefore smaller in diameter.

The issue here is one of demonstrating that a HI beam of the required intensity can be stored in a storage ring for the requisite time, typically on the order of 1 to 2 milliseconds. The issues are similar to those associated with bunched beam transport, but have the additional complications associated with closed orbit synchrotrons, such as betatron and synchrotron resonances, etc., which can give rise to emittance growth or beam loss. Furthermore, beam induced vacuum instability is another problem which must be overcome. All of these issues can only be resolved with an experimental storage ring with parameters reasonably close to what is required.

5.3.6 Critical Issue No. 6: Demonstration of High Overall Laser Driver Efficiency

Description of Problem - The excimer laser driver system has a number of components which can individually be optimized to yield high efficiencies. The achievement of high efficiency is viewed as a crucial requirement for the laser driver. In addition to the achievement of high efficiency is the corresponding goal of highly reliable components. The laser driver consists of the following four major elements:

(1) Excimer laser amplifiers
(2) Raman accumulators
(3) SBS pulse compressors
(4) 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 fundament of an efficient, reliable laser driver is the successful design, construction, and testing of excimer laser amplifier modules.

During the past five years, relatively little work has been carried out in the USA 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 by the Department of Energy (DOE).

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. The electric discharge lasers offer an inherently higher efficiency than the EBEELs since excitation of the excimer species occurs along the neutral channel, thereby avoiding the excitation of a large number of higher-lying states (which may contribute relatively little to the overall amplifier extraction efficiency). Moreover, by avoiding transmitting large beam currents through foils, hibachis, etc., the overall pumping efficiency may be significantly higher.

Required Future Work on Excimer Laser Amplifier Modules - There are several problems with the electric discharge excimer lasers which require further experimental work. These include:

(1) Characterization of the optimum pulse duration and gas mixture to achieve efficient operation with a matched, efficient, pulsed power system.
(2) Sensing and prevention of the formation of arcs in the discharges.
(3) Extension of the operating lifetimes of the amplifiers to reach levels of 10^9 to 10^{10} amplifier firings between failures.
(4) Control of color center formation and chemical attack of amplifier windows during the 10^9 to 10^{10} shot operational periods.

If these problems were analyzed theoretically and solutions found experimentally during a series of technological development programs granted by DOE to industry, the workhorse of the Prometheus excimer laser driver could be developed to the point that it could be incorporated into a credible IFE reactor system by the year 2030.

Summary - The major obstacle to the development of a reliable, highly efficient excimer laser driver for IFE reactors is the lack of work previously performed or currently planned on moderate-sized (2-4 kJ output) excimer laser amplifier modules. It is strongly recommended that DOE support an aggressive excimer laser amplifier program with the goal of producing a 2 to 4 kJ amplifier with a wall plug efficiency of 12% and a mean time between failures of between 10^9 and 10^{10} shots.

Amplifier modules this size can fail in operation without producing a deleterious effect on the overall operation of the IFE reactor. Additional work would be needed on the Raman accumulators, SBS pulse compressors, and beam conditioning systems as well in order to achieve the objective of an efficient, reliable, operational IFE laser driver by the year 2030.

Reference for 5.3.6

1. "New Techniques for KrF Laser Fusion Systems," Interim Report for Los Alamos National Laboratory, pp. 2-70 through 2-72, Los Alamos, New Mexico, written by Spectra Technology, Inc., Seattle, Washington.

5.3.7 Critical Issue No. 7: Tritium Self-Sufficiency in IFE Reactors

Introduction - Fuel self-sufficiency is a critical requirement for a renewable energy source. The first generation of fusion power reactors will operate on the DT cycle. Since tritium is not available in nature, tritium must be bred internally in fusion reactors using neutrons generated in the DT reactions. Therefore, careful analysis of the fuel cycle is necessary to evaluate the conditions that must be met in a fusion reactor design. These conditions must then be used as absolute criteria in selection among design concepts and in defining the range of acceptable performance parameters. Self-sufficiency requirements must be included in a prudent plan for fusion research and development.

Several characteristics of tritium and fusion reactors that make fuel cycle analysis complex are (1) tritium is a gas in the natural state, (2) tritium undergoes radioactive decay with a relatively short, 12-yr half life, (3) tritium must be fed nearly continuously into the reaction chamber, (4) the fractional burnup, i.e. the fraction of the tritium atoms fed into the reaction region that undergo fusion reaction before they are removed out of the reaction region, is relatively low, (5) removal and processing of the fuel exhaust from the reaction region involve many physical, chemical and thermal processes and, generally, require a significant amount of time, (6) tritium bred in the blanket surrounding the reaction region must be extracted and processed through several processes that take time and, (7) the amount of tritium that can be produced in the blanket per fusion reaction is sensitive to the choices of particular technologies of key reactor components (e.g. neutral beams vs. rf in MFE or laser vs. heavy ion beams in IFE) and to many of the specific design features and performance parameters for a given technology (e.g. penetrations associated with direct or indirect KrF laser driver).

In previous work,[1] fuel cycle analysis was performed and fuel self-sufficiency conditions were derived for magnetic fusion reactors. There are substantial differences in the fuel cycle and in the reactor characteristics, and hence in fuel self-sufficiency conditions and requirements between MFE and IFE reactors. The purposes of this work are (1) to develop a mathematical model for the fuel cycle in IFE reactors, and (2) to derive fuel self-sufficiency conditions and requirements. Future work should compare the requirements and potential for attaining self-sufficiency in future IFE and MFE reactors.

Self-sufficiency Condition - The tritium breeding ratio (TBR), Λ is defined[1] as:

$$\Lambda = \frac{\dot{N}^+}{\dot{N}^-} \qquad (5.3.7\text{-}1)$$

where $\dot{N}^+$ is the rate of tritium production in the system (primarily, the blanket) and $\dot{N}^-$ is the rate of burning tritium in the fusion reaction chamber (i.e., the fuel target in IFE or the plasma in MFE). Defining two specific breeding ratios, the required TBR, Λ_r, and the achievable TBR, Λ_a; the condition to attain tritium self-sufficiency in fusion reactors can then be written as:

$$\Lambda_a \geq \Lambda_r \qquad (5.3.7\text{-}2)$$

Since fusion is in a relatively early stage of R & D, accurate and clear definition of Λ_r and Λ_a must be general enough to account for uncertainties in reactor system description and in predicting its performance.

The required TBR (Λ_r) in a self-sustained fusion power economy must exceed unity by a margin, G, necessary to (a) compensate for losses and radioactive decay of tritium during the period between production and use, (b) supply a holdup inventory in various reactor components, and (c) provide inventory for startup of other fusion reactors.

The required Λ_r, as shown later, is a function of many reactor parameters as well as the doubling time, t_d, and the radioactive decay constant for tritium. Examples of these parameters are the fractional tritium burnup in the target, and the mean residence time and tritium inventory in various reactor components such as the target factory, blanket, and tritium processing systems. Many of these parameters vary from one design to another; and, for a given design, the prediction of some of these parameters is subject to uncertainties. We write:

$$\Lambda_r = 1 + G_o + \Delta_G \qquad (5.3.7\text{-}3)$$

where G_o is the breeding margin for a reference conceptual design based on a given estimate of its performance parameters, and where Δ_G is the uncertainty in estimating the required breeding ratio $(1 + G_o)$.

The achievable TBR, Λ_a, is also a function of the reactor design with particularly strong dependence on the first wall/blanket design concept. At present, accurate prediction of Λ_a suffers from two types of uncertainties:

(1) Uncertainties in system definition: Fusion reactor design concepts are evolving. The choices for many of the design features, materials, and technology options have not been made. The achievable TBR is strongly dependent on many of these choices.

(2) Inaccuracies in prediction: For a well-specified reactor system, the prediction of the achievable breeding ratio is subject to uncertainties. These are due to approximations or errors in the various elements of the calculations, e.g., in basic nuclear data, data representation, calculational methods, and geometric representation. We write the achievable TBR, Λ_a, as:

$$\Lambda_a = \Lambda_c - \Delta_a \qquad (5.3.7\text{-}4)$$

where Λ_c = TBR calculated for a specified blanket in a specified reactor system

Δ_a = uncertainty in calculating the achievable TBR

$$\Delta_a = \sqrt{\Delta_s^2 + \Delta_p^2} \qquad (5.3.7\text{-}5)$$

where

Δ_s = uncertainty associated with system definition; i.e., the changes in Λ_c due to probable changes in the system definition

Δ_p = uncertainty in predicting the breeding ratio (Λ_c) for the specified system due to nuclear data uncertainties, numerical approximations, geometrical modeling, etc.

In comparing the potential to achieve tritium self-sufficiency among various reactor concepts or among various blanket options for a given reactor design, it is useful to define a "figure of merit." One such figure of merit is

$$\varepsilon = \Lambda_a - \Lambda_c = (\Lambda_c - \Delta_a) - (1 + G_o + \Delta_G) \qquad (5.3.7\text{-}6)$$

<u>Required TBR</u> - The analytic model developed in Reference 1 was modified to describe the various elements of the tritium cycle in an IFE reactor. The model is shown schematically in Figure 5.3.7-1. A set of differential equations was written down to relate the tritium inventories in the various components of Figure 5.3.7-1 to their operating parameters. The equations were solved analytically to derive explicit expressions for the functional dependence of the tritium inventories. An exact expression for the required TBR as a function of the doubling time and the tritium cycle operating parameters was derived. A computer program was written, using these equations, to calculate the dependence of the required TBR on the key physics and technology parameters of an IFE reactor. Table 5.3.7-1 denotes the abbreviations used in Figure 5.3.7-1.

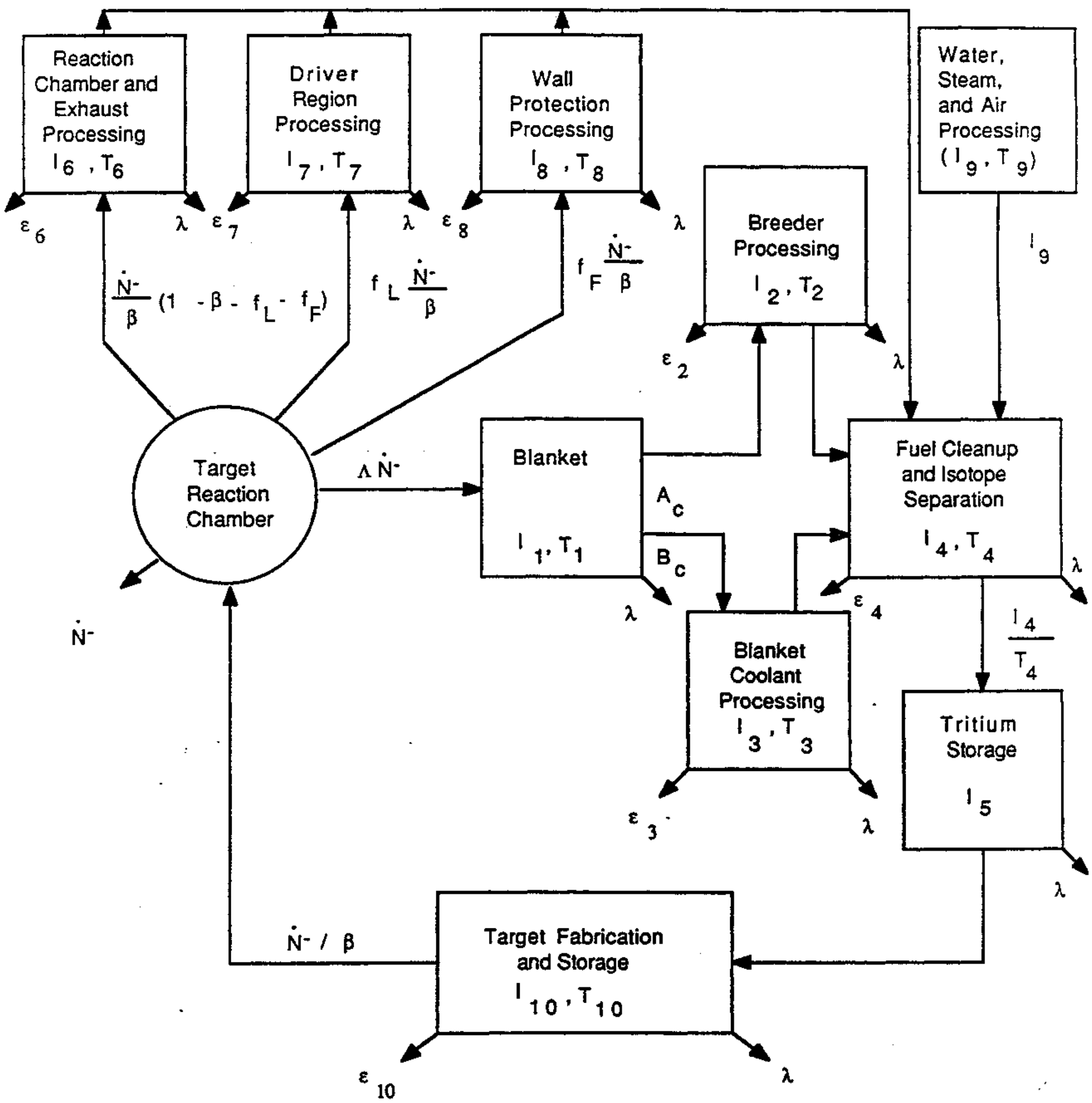

Figure 5.3.7-1. Schematic Model of the Fuel Cycle for IFE Reactor Operated on the DT Cycle

Table 5.3.7-1 Abbreviations Used in Figure 5.3.7-1

Λ	=	TBF
$\dot{N}^-$	=	tritium burn rate in the target
I_i	=	tritium inventory in compartment i
T_i	=	mean residence time of tritium in compartment i
ε_i	=	nonradioactive loss fraction of tritium in compartment i
λ	=	tritium decay constant
β	=	tritium fractional burnup in the target
f_i	=	tritium fractional leakage to compartment i
I_g	=	constant flow rate of tritium recovered from waste, steam, and air processing units
A_c	=	$\frac{I_1}{T_1}(1 - f_c)$
B_c	=	$\frac{I_1}{T_1} f_c$

A set of reference parameters was selected to represent the present best estimate. This reference parameter set is shown in Table 5.3.7-2. The calculated value of the required TBR with this reference parameter set is 1.05. A sensitivity study was then performed to determine the sensitivity of Λ_r to variations in various parameters. It was found that the required TBR is most sensitive to:

- β tritium fractional burnup in the target
- T_{10} the tritium mean residence time in the target factory
- t_r the number of days of tritium reserve on site
- t_d the doubling time

Figure 5.3.7-2 shows the variation of the required TBR with these most important parameters. It can be seen from this figure that the required TBR can increase to ~1.25. Figure 5.3.7-3 shows the variation of Λ_r with simultaneous change in the values of β and T_{10}. The required TBR increases dramatically, e.g. to ~1.5 if β drops to 5% and T_{10} becomes 20 days. Such high TBR can not be achieved in a fusion reactor.

Table 5.3.7-2. Reference Parameter Set for Tritium Self-Sufficiency Calculation

Tritium consumption (burn in plasma), $\dot{N}^{-}$ (kg/day)	0.3
Doubling time, t_d(yr)	5
Tritium fractional burnup in plasma, β(%)	30
Time reserved for independent tritium supply, t_r(day)	2
Non radioactive losses (chemical tie-up in radioactive waste, etc.) in	
Breeder processing, ε_2(%)	0.02
Blanket coolant processing, ε_3(%)	0.001
Fuel clean up and isotope separation units, ε_4(%)	0.0
Reactor chamber and exhaust processing, ε_6(%)	0.05
Driver region processing, ε_7(%)	0.1
Wall protection processing, ε_8(%)	0.1
Target fabrication processing, ε_{10}(%)	0.1
Tritium mean residence time in	
Blanket, T_1(day)	1
Breeder processing, T_2(day)	0.1
Blanket coolant processing, T_3(day)	100
Fuel cleanup and isotope separation units, T_4(day)	1
Reaction chamber and exhaust processing, T_6(day)	1
Driver region processing, T_7(day)	100
Wall protection coolant processing, T_8(day)	100
Target fabrication and target storage, T_{10}(day)	10
Tritium fractional leakage from	
Breeder to blanket coolant processing, f_C(%)	0.001
Plasma to limiter processing, f_L(%)	0.01
Plasma to wall protection processing, f_F(%)	0.01
Constant tritium flow returned from the waste, steam and air processing, 19(g/day)	0.01

The achievable TBR is generally in the range of 1.1 to 1.3 with about 20% uncertainty due to system definition and prediction capability. Two important conclusions arise from this analysis:

(1) R&D effort for IFE must aim at achieving certain range of parameters that have direct impact on tritium self-sufficiency. For example, the R & D goals should be to achieve $\beta > 20\%$ and $T_{10} < 10$ days.

(2) Tritium self-sufficiency is a critical issue in IFE, as it is in MFE. Demonstration of tritium self-sufficiency must be a goal for early integrated test facilities.

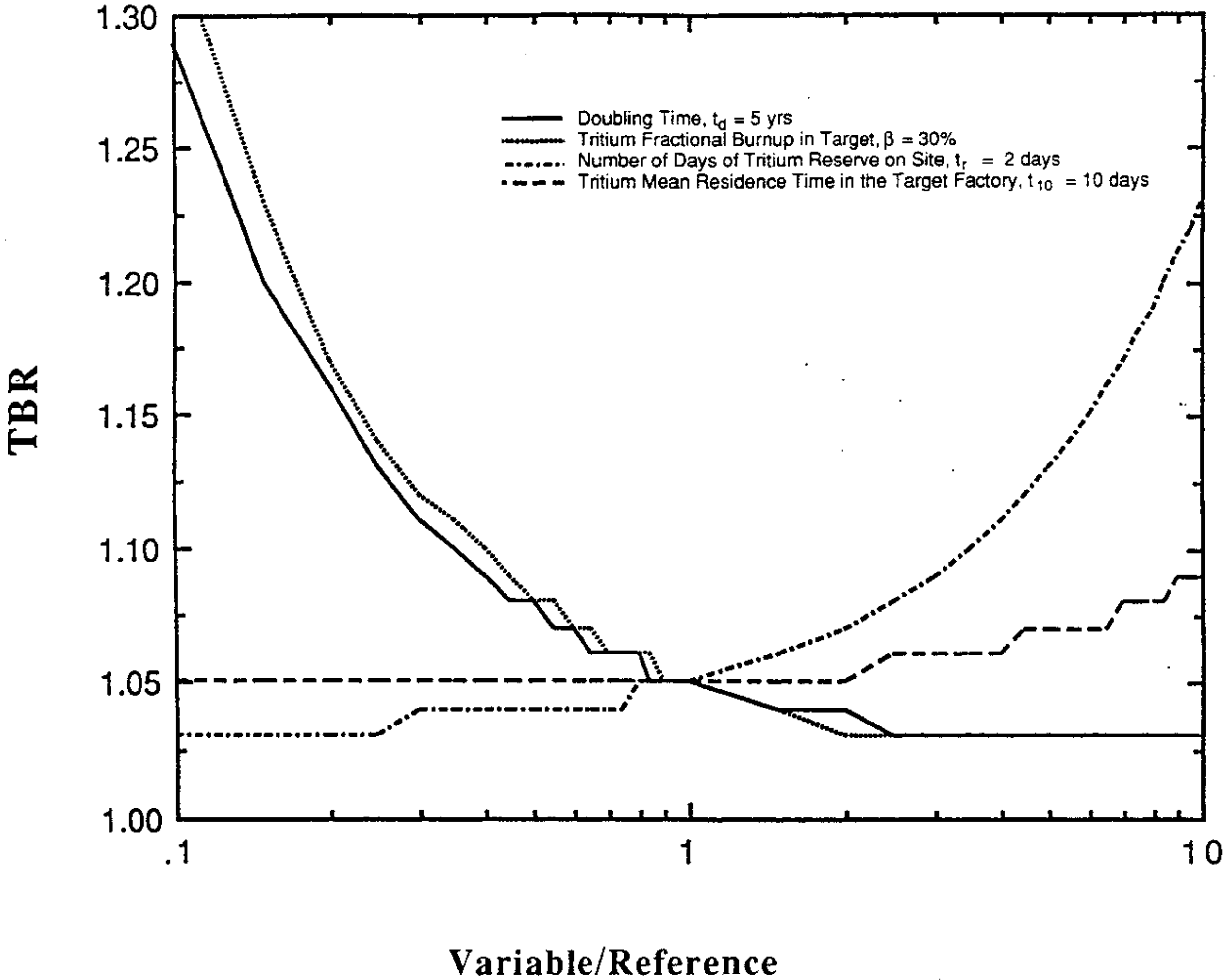

Figure 5.3.7-2. Variation of Required TBR with Reactor Parameters

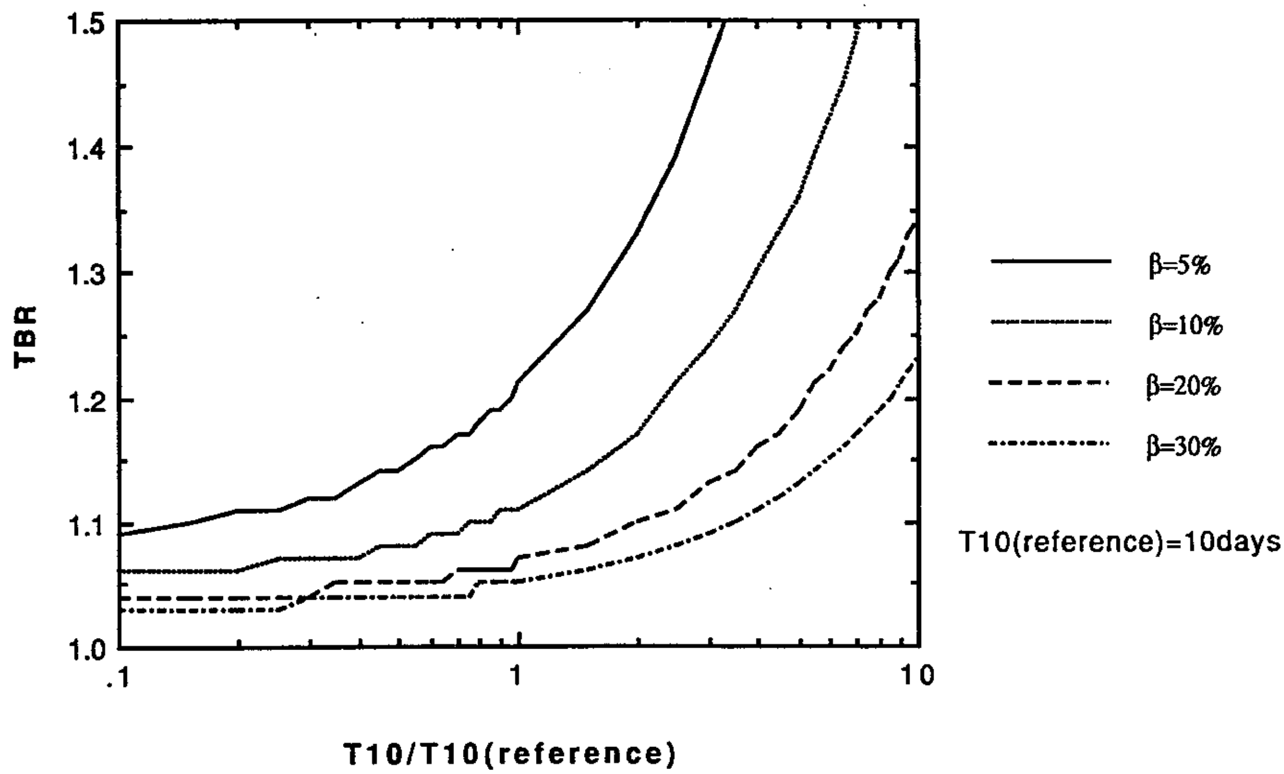

Figure 5.3.7-3. Variation of Required TBR as a Function of T_{10} (Residence Time in Target Factory) for Various Values of the Tritium Fractional Burnup (β).

References for 5.3.7

1. M. A. Abdou, et al, "Deuterium-Tritium Fuel Self-Sufficiency in Fusion Reactors," Fusion Technology, vol. 9, pages 250-284 (March, 1986).

5.3.8 Critical Issue No. 8: Cavity Clearing at IFE Pulse Repetition Rates

Description of the Problem - Following each pellet explosion, the cavity fills with target debris and material evaporated or otherwise ejected from the cavity surfaces. This material must be removed from the cavity before the next target is injected. In the Prometheus designs, the cavity is cleared by recondensing the condensable gases onto the surface of the first wall, and by pumping non-condensable gases out through large ducts.

Operation of a power reactor requires continuous operation at several (i.e., ~5-10) pulses per second. For a fixed reactor thermal power, lower repetition rates require higher yields, which in turn produce unacceptably high driver energy requirements and excessive loads on the surrounding components. In order to ensure that a feasible design window exists, the cavity pressure must be reduced to the level required for target and driver energy propagation.

Evacuation requirements are based on propagation limits for both targets and driver energy. Base pressure requirements are important for two reasons: (1) the time to evacuate the chamber depends on the pressure, and (2) the level of protection to the first wall (and final optics) afforded by the cavity background gas depends strongly on the pressure. If a sufficiently high background pressure could be allowed, the survivability of the solid surfaces might be substantially enhanced.

Analysis - Driver propagation requirements depend on the type of driver. For the Prometheus-L design, the Pb pressure limit for laser propagation was estimated as ~1 mtorr@0°C. Above this value, gas breakdown is expected to occur, in which case the laser beams would be degraded. Target gain would start to decline.

Due to the innovative, heavy-ion channel transport mechanism used in Prometheus-H, a much higher base pressure is considered acceptable. In this case, the 100 mtorr limit is determined also by target transport. Target propagation limits depend on the target design. Indirect drive targets are generally more robust than direct drive, and can propagate at higher base pressure with less degradation. In order to resolve this aspect of the issue, accurate estimates of maximum allowable base pressure need to be determined for each target and driver design to be pursued.

Under idealized conditions, achievable cavity clearing times can be estimated by analyzing mass and energy transport within the cavity. Figure 5.3.8-1 shows the results of such a calculation. Cavity vapor temperature and pressure histories are plotted for a Pb wetted-wall cavity design. In this case, approximately 3 kg of Pb are evaporated by direct energy deposition from the x-rays which reach the first wall. The initial average cavity vapor pressure and temperature are estimated as 49 kPa and 3 eV, respectively. A much larger amount of Pb is subsequently evaporated due to rapid radiation cooling of the cavity vapor. Before the recondensation phase begins, about 80 kg of Pb (10 μm) is evaporated.

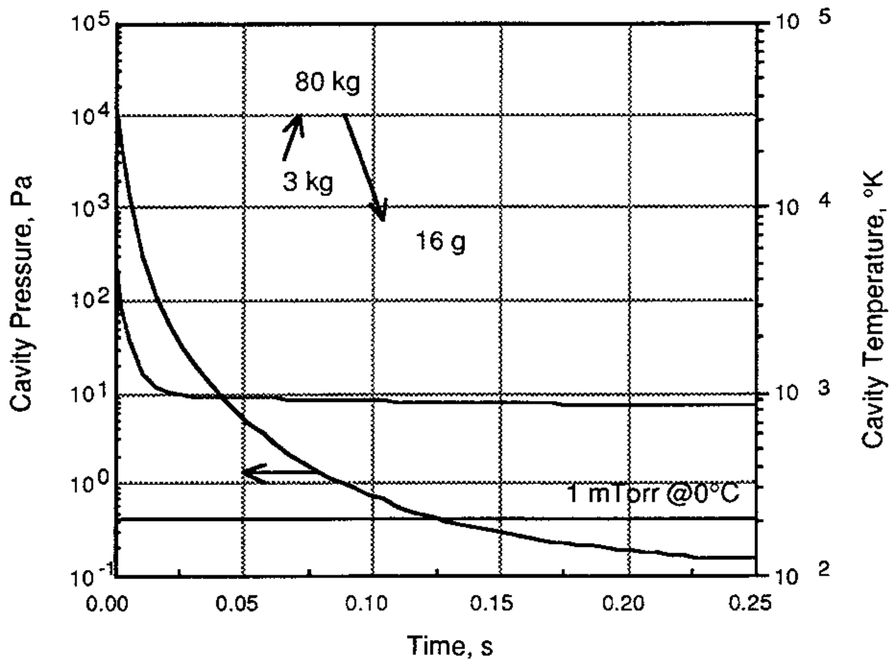

Figure 5.3.8-1. Cavity Vapor Pressure and Temperature Histories Following the Blast.

Based on this analysis, the cavity pressure drops below 1 mtorr before the next shot. However, the actual physics of energy and mass transport and vapor recondensation is very complex under the extreme 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 penetrations provide additional uncertainties.

While many uncertainties exist, there are also various design solutions which can be adopted to improve the cavity clearing rate. For example, condensing surfaces (or cold jets) could be added. Some design proposals use large slugs of cold liquid to evacuate the chamber. More research is needed to better understand clearing requirements, the recondensation process, and to develop design solutions to this critical issue.

5.3.9 Critical Issue No. 9: Performance, Reliability, and Lifetime of Final Laser Optics

Description - In this study, successful conceptual mirror designs were introduced. These designs involved both the dielectric turning and focussing mirror and the final optical component, the Grazing Incidence Metal Mirror (GIMM). Analysis of the proposed design indicated that, with proper selection of materials and mechanical configuration, the GIMM lifetime can be very long–on the order of the plant lifetime. Clever shielding designs and materials selection for the dielectric elements can likewise lead to great improvements in the overall laser reactor concept. In all previous studies of laser fusion so far, it has always been concluded that the final mirror will have to be at distances in excess of 30-40 m away from the cavity center and that the lifetime and reliability will be small. Preliminary analyses of the Prometheus design approach indicated the mirror could be a life-of-plant component and yet be located 20 meters from the cavity center. An in-depth study of the performance, reliability, and lifetime of the final optical components 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.

Analysis -

Turning Mirror - As far as the turning mirror is concerned, two categories of research will be pursued:

(1) Shielding design of a neutron dump, and pinhole for minimization of the damage caused by ionizing radiation (i.e. neutronic and photonic).
(2) Materials selection and data base analysis for the optimum choice of dielectrics with the minimum amount of damage. In this area, rate theory would be used to compute the accumulation rates of color centers and their impact on the optical properties of the dielectric. To our knowledge, this approach has not been attempted so far. A model with these capabilities can actually lead to the development of annealing strategies for the elimination or reduction of the effects of radiation on the optical properties of the dielectric materials.

Grazing Incidence Metal Mirror - The design of a reliable, long-life GIMM is critical to the success of the laser fusion concept. A detailed thermo-mechanical design involves the following features:

(1) De-coupling between the optical and structural functions of the mirror. A high strength aluminum alloy is deposited on top of a composite SiC stiffened

support structure. A very thin graphitic shear layer would be desirable, such that the larger thermal expansion of the aluminum surface does not lead to buckling patterns on the mirror's surface which would degrade the optical quality of the laser beam.

(2) A low activation, zero swelling composite structural support of the aluminum surface. Thermal deformations of the surface are corrected for by uniform end moments . These correcting moments can be induced by clamping the structural support to a rigid concrete shell, which would also give only one two degrees of freedom for thermal expansion. Design of mechanical sliding/bolting systems must be demonstrated in order that the deflections caused by the small temperature gradient across the mirror's surface can be completely eliminated.

(3) Detailed structural analysis of the aluminum optical layer, the supporting composite structure, and the graphitic shear layer.

(4) Determination and analysis of the possible modes of damage to the mirror. This would involve fatigue and creep damage assessments. It is to be borne in mind that fatigue analysis of the composite structural substrate does not follow the established rules for metal systems. On the other hand, fatigue of the surface aluminum layer (a few mm thick) can also be minimized, or perhaps eliminated, if more effort is directed toward stress redistribution in between the optical aluminum layer and the structural substrate.

(5) Investigation of the possibility of piezoelectric, or other error detection and correction mechanisms, for final mechanical control of the optical quality of the mirror's surface.

5.3.10 Critical Issue No. 10: Viability of Liquid Metal Film for First Wall Protection

Description of the Problem - 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 for periods of time greater than 10-15 minutes will cause 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 inertial 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)
- 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, better understanding of the nature of instabilities and possible remedies are critical. Good wetting between the solid surface and liquid film is very important.

Explosive effects resulting from the blast may lead to further problems. Several effects are present:

(1) A large impulse is imparted to the film following rapid evaporation at the surface
(2) Additional shock waves strike the wall as the cavity vapor responds to the blast. These shocks cause motion of the solid structures which could eject liquid into the chamber
(3) Rapid "isochoric" bulk heating of the liquid creates high pressures, which can cause fragmentation of the liquid film.

The problem of wall protection with films is particularly difficult near inverted surfaces (such as the upper hemisphere or tops of beamlines) or at penetrations and nonuniformities in the cavity interior. Dripping is likely to occur from inverted surfaces, so that the concept of slow porous flow may need to be supplemented with alternate methods, such as inertial jets or magnetic guiding.

Figures 5.3.10-1 and 5.3.10-2 show the jet velocity required, and the film thickness and minimum flow rate required for film attachment on the upper hemisphere. The velocity and thickness can be high, leading to large flow rates. The option of using MHD guiding has been shown to be capable of resolving this problem, but adds design complexity to the device.

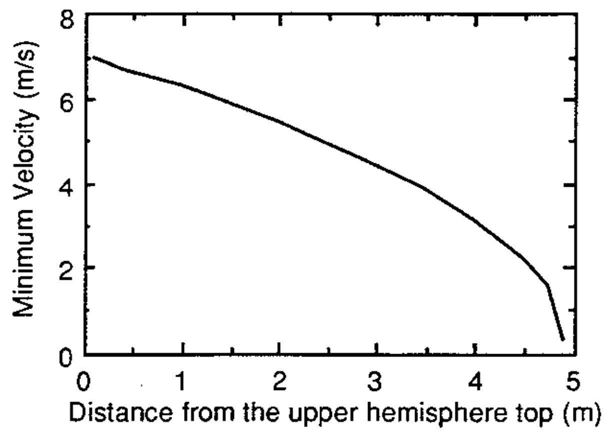

Figure 5.3.10-1. Minimum Velocity Required for Film Attachment on the Upper Hemisphere

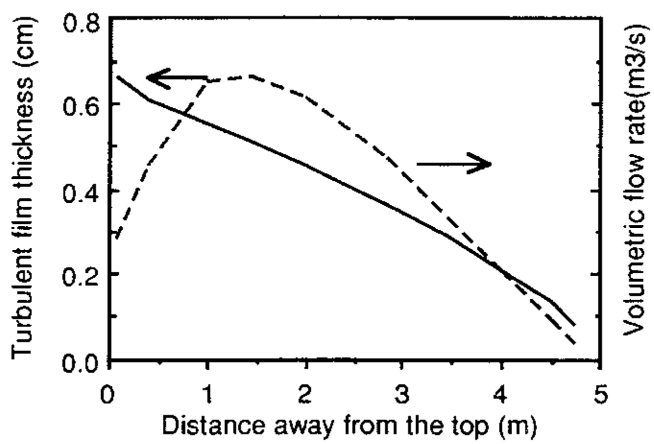

Figure 5.3.10-2. Turbulent Film Thickness and Minimum Flow Rate Required for Film Attachment on the Upper Hemisphere

5.3.11 Critical Issue No. 11: Fabricability, Reliability, and Lifetime of SiC Composite Structures

Description of the Problem - 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. Limited resources allocated to this area precluded a realistic assessment of the anticipated lifetimes. Without this knowledge, system reliability, maintenance and economics would be seriously challenged. In order to perform this task, several investigations need be considered. It is too simplistic, and perhaps misleading, to use the accumulated fluence, or displacements per atom, to make projections of lifetimes. The determination of such lifetimes would need knowledge of the various effects of radiation. The most prominent of those are neutron induced swelling, embrittlement, fiber shrinkage, and/or detachment from the matrix, creep crack propagation at high temperatures, and crack bridging mechanisms during irradiation.

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

Analysis

(1) Radiation Effects on the properties of SiC Composites: The relevant effect of irradiation to be investigated are: displacement damage production in various neutron spectra; swelling rate dependence on temperature, fluence and porosity; irradiation induced creep; irradiation embrittlement by amorphization; high temperature crack nucleation and propagation under static and dynamic conditions.

(2) Lifetime assessment of the FW: A realistic determination of FW lifetime would require analysis of a number of material and structural properties of the first wall. The data base accumulated under item (1) above would have to phenomenalogically modeled in the form of appropriate design equations. These equations will include crack growth under cyclic loading at high temperature, radiation creep rate, thermal creep rate, and swelling rate. These mechanical property equations will then be used in a structural analysis code

for determination of stress and strain fields under time-dependent loading conditions. The lifetime of the FW/B structure will be dictated by:

(a) fatigue crack growth.
(b) maximum allowable inelastic deformations.
(c) maximum stress/strain criteria under the complex multiaxial loading situation in the structure.

(3) Manufacturing and reliability: Existing manufacturing techniques involve CVD, CVI, and HIP technologies for the matrix. A wide range of fibers and architecture are also possible. The structural performance, lifetime and reliability are all dependent on the manufacturing method of the composite. In addition, cost is an important factor, which will be also determined by the manufacturing technique.

5.3.12 Critical Issue No. 12: Validation of Radiation Shielding Requirements, Design Tools, and Nuclear Data

Description of the Problem - 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, 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. Such components include the heat transport system, heat exchanger and/or steam generators, and a variety of auxiliary system and constitute a large material inventory that would tremendously increase the waste disposal problem if allowed to be highly radioactive. Second, the IFE shield should be designed to permit some personnel access to the reactor building outside the bulk shield within days after shutdown. Although full remote maintenance should be planned for, having personnel access capability after shutdown is deemed necessary in a number of foreseen cases and unforeseen events.

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. For example, it is likely that components will deform during operation, which may head to unpredictable streaming paths. Improvements in methods, data and experimental verification of prediction capabilities are needed.

Establishing accurate radiation protection requirements is necessary, particularly for components whose shielding is either physically difficult (e.g. final optics in laser driver) or results in substantial economic penalty. Thus, quantitative and reliable knowledge of the effect of radiation on materials and components is required.

5.3.13 Critical Issue No. 13: Reliability and Lifetime of Laser and Heavy Ion Drivers

Description of Problem - The reliabilities and lifetimes of excimer laser and heavy ion beam driver systems profoundly affect the operating characteristics of an inertial fusion energy (IFE) reactor. Although both the excimer laser and the heavy ion beam drivers are powered with somewhat similar pulsed power systems, the critical issues associated with these two drivers are sufficiently distinct that they should be considered separately. There are presently no known technical problems which could keep either of these driver types from performing reliably as IFE drivers.

Reliability and Lifetimes of Excimer Laser Drivers - Two general types of excimer laser amplifiers have been considered for IFE:

(1) Direct electron-beam pumping through a foil, and
(2) Electric-discharge pumping.

The first category can be constructed in larger sizes (and hence output energies) than the latter. Theoretical simulations suggest that the electric-discharge laser may be more reliable than the e-beam pumped laser. There are, in addition, a number of similarities which these two types of excimer lasers share. First of all, a key parameter for each of the lasers is the small signal optical gain, G_o given by the expression:

$$G_o = \exp(\sigma N L) \qquad (5.3.13\text{-}1)$$

where σ is the stimulated emission cross-section for the excimer laser transition, N is the inversion density of the excimer laser amplifier, and L is the length of the active excimer gain medium. Typically, G_o must be less than some fixed number (such as 20-30) in order to avoid unwanted parasitic oscillations in the amplifier volume. A somewhat higher limit is set by the superfluorescent limit which defines a relationship between the amplifier solid angle, Ω_a, and the small signal gain, G_o. A simplified expression[1] for the superfluorescent limit on amplifier gain is given by the inequality:

$$4\frac{\sqrt{\ln G_o^2}}{\sqrt{(G_o - 1)^3}} < \Omega_a \qquad (5.3.13\text{-}2)$$

where the amplifier solid angle is given approximately by d_a^2/L^2 for a rectangular amplifier (where d_a is the amplifier aperture). Since σ is nominally a fixed parameter, in order to keep G_o below the parasitic limit, L and/or N must be adjusted. The difficulty here is that the excimer inversion density, N, is related to the inversion energy, E_s, in the medium given by the expression:

$$E_s = NhvLd_a^2 \quad (5.3.13\text{-}3)$$

where, as before, d_a is the amplifier aperture, h is Planck's constant, and v is the laser frequency. An important parameter for laser amplifiers is the inversion energy per unit volume, $\rho_s = E_s/V = Nhv$. In optimizing amplifiers, frequently ρ_s is maximized in order to obtain the highest output energy/cm^3 form the excimer amplifier gain volume. A typical limit for ρ_s is 20 J/liter, or more typically 10 J/liter.[1] Thus, in order to keep G_o below either the parasitic limit or the superfluorescent limit, it is easiest to adjust L, the gain length. In carrying out these optimizations at constant σ and N, the results tend to reduce the size of the excimer laser amplifier to dimensions of the order of 50x50x200 cm with a volume of approximately 500 liters. Amplifiers this size tend to produce less than 5 kJ of output energy, an amount of energy which is only 0.1% of the total driver energy of 5 MJ; this is an important factor in performing the overall driver failure mode analyses. Designers of e-beam pumped lasers, however, have produced designs for much larger amplifiers, theoretically producing output energies of hundreds of kilojoules.

Each of these two types of excimer lasers is briefly described below:

<u>E-Beam Pumped Excimer Lasers</u> - Direct electron-beam pumping permits large volumetric excitation of the excimer gain media (typically a mixture of noble gasses plus a halogen). All of the pumping energy delivered to the gas is delivered by the e-beam. This excitation scheme has been attractive for the construction of large excimer lasers since it is readily scalable to large apertures (~100 cm), energies, and volumes (thousands of liters).

The e-beam is generated under hard vacuum conditions (10^{-7} torr or better), whereas the excimer gain medium is approximately 1 amagat (or 760 torr). A thin foil is used to separate the high vacuum e-beam from the corrosive halogen atmosphere inside the laser amplifier. Since the excitation area is given by the product d_aL, a relatively large foil area in a typical e-beam pumped excimer laser amplifier (such as the LAM[2] with a ~100x200 = 2x10^4 cm^2 area) is exposed to the vacuum interface. In order for the thin (several micron) foil mechanically to support the force exerted by 760 torr, a mechanical bridge-type structure (often referred to as a Hibachi) which may block a portion of the incident e-beam is installed to stiffen the foil structure. In operation, the high power e-beam is accelerated through potentials in excess of 10^6 V, and upon traversing the foil, some fraction (30-50%) of the electron beam energy is lost. The action of this large amount of energy is deposited into the small volumes of the foil and

Hibachi, thereby greatly stressing these elements, particularly the foil in cases in which the beam current density is not uniform. The problem increases significantly in repetitive operation since it necessitates water-cooled Hibachis. The repetitive operation of an e-beam pumped excimer laser has hitherto been unreliable because of periodic foil ruptures. In order to overcome this problem, e-beam pumped excimer laser have received a considerable amount of technological development.

Even with the greater energy capabilities of EBELs, a substantial number, n, of EBELs is required to generate the ~5 MJ of energy required for the Prometheus laser driver. (The required laser energy on target is 4 MJ but, owing to optical inefficiencies associated with beam combination, propagation, and pulse compression, the output energy from the EBELs needs to be at least 25% greater than the desired net energy.) Assuming that each of the n optimized e-beam pumped excimer amplifiers produces an output energy = 5 MJ/n (which is presumably more than 1% of the total driver output energy), the mean number of amplifier firings between failures must be at least n x 10^8 if the IFE reactor operation is not to be interrupted between maintenance periods.

Electric-Discharge Excimer Lasers - Much less experimental work has been carried out on electric discharge excimer lasers. In this case, excitation of the excimer gain medium occurs on the neutral channel with relatively low-lying species being produced. This can enhance the efficiency of the amplifier. Unlike the e-beam pumped excimer laser, the full pumping power does not flow through a foil/Hibachi structure, and predictions are that this design would be more reliable following an intensive development effort.

Owing to the nature of the electric discharge, the available pulse duration is shorter than that for the e-beam (200 ns compared with ~ 500 ns). Electric discharge lasers for which d_a > 30 cm appear to have serious discharge stability and efficiency problems. As a consequence, using the scaling relations outlines above, the electric discharge lasers tend to optimize at energies of a few kilojoules. For energies this small, the overall reliability of the IFE reactor would not be impaired if several electric discharge amplifiers failed. Assuming such amplifiers could readily be replaced by robotics, the impact of discharge amplifier failure on reactor operation is regarded as minimal. As a consequence, if failed electric discharge excimer lasers can be replaced more rapidly than they fail, then the mean time between failure characteristics the IFE reactor will be independent of the excimer amplifiers.

Reliability and Lifetimes of Heavy Ion Drivers - The fundament of an efficient, reliable Prometheus heavy ion driver is the successful design, construction, and testing of a full scale accelerator suitable for operation in a burst mode (~50 kHz) to fill storage rings with 18 beamlets at a rate of ~3.5 pulses/sec. Accelerators can be made to be very reliable if great care is taken with regard to the control of the magnets, particularly in the (recommended) case of superconducting dipoles, quadrupoles, and triplets. A large amount of data is available on the failure modes of linear accelerators (LINACs), and there are no serious technical problems which would render this design unreliable. The key element for long, reliable operation of the LINAC is a very fast, highly automated control system which can sense beam mispointing before superconducting magnets are either heated sufficiently to make them go "normal" or damaged by the beam. Under competent computer control, the heavy ion driver would only require attention during regular IFE reactor maintenance intervals (possibly every two years). A key element in this HI driver reliability assessment is the development of an adequate computer control system employing the latest developments in artificial intelligence, parallel processing, and expert systems (see Section 6.5.3.3).

Accurate simulations of the dynamics of the LINAC, the filling of the storage rings, the bunching, the rapid expansion to the triplet focusing magnets, the focusing down into the pre-formed channels, the complete stripping of the heavy ions, and the dynamics of self-focused heavy ion beams propagating down the channels to the target are too difficult to attempt presently, and the results, even if favorable, would require experimental verification to be trusted. Thus, the major emphasis on demonstrating the feasibility of heavy ion drivers should be experimental.

It is essential that a carefully planned heavy ion driver developmental program be designed to test each of the key elements of the proposed Prometheus-H IFE heavy ion driver in order to create a design data base sufficient to permit suitable modifications allowing the driver to reach its full reliability potential. In particular, experimental results on beamlet accumulation (without emittance growth) for ms time scales in storage rings, self-focused beam stabilities, locking the focused beams into a pre-formed channel, etc., are crucial for developing this promising driver concept.

References for 5.3.13

1. G. J. Linford, E. R. Peressin, W. R. Sooy, and M. L. Spaeth, "Very Long Lasers," Applied Optics 13, pp 379--390, (1974).

2. L. A. Rososha, et al., "Aurora Multi-kJ KrF Laser System Prototype for ICF," Fusion Technology 11, pp. 497-531, (1987).

5.3.14 Critical Issue No. 14: Demonstration of Large-Scale Non-Linear Optical Laser Driver Architecture

Description of Problem - The fundament of the Non-Linear Optical Subsystems proposed for the Prometheus-L driver is based upon the very strong experimental and theoretical bases 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 properly 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
(2) The SBS pulse compressors

Numerous key non-linear optical (NLO) subscale experiments and analyses have been performed in the last twenty years which demonstrate the capabilities of these two types of NLO devices. In order to properly implement them, however, each needs to be supplied a Stokes seed beam, and therein lies most of the questions regarding the success of the architecture reliabilities and lifetimes.

Generation of Stokes Seeds for Raman Accumulators - To achieve highest efficiency while averaging excimer laser intensities across the accumulator aperture, the proposed Prometheus Raman accumulator system uses crossed stimulated rotational Raman scattering. This architecture sets limits on the bandwidth, Δv_{lasers} of the excimer pumps, on the crossed Raman angle, θ, and on the dimensions of the gain length (to avoid generating higher order Stokes beams). The physics is relatively well understood. A detailed design could be made now using present understanding. Tests at full scale could be made if approximately 30 two-kilojoules KrF excimer laser amplifiers were available as pump sources.

The required Stokes seeds can be derived from taking a small portion of the available excimer pump light, injecting the pump light into a Raman oscillator filled with the same gas used in the Raman amplifier. This process generates an automatic frequency shift, Δv_R, equal to the required Raman shift. Injecting this Stokes seed beam into the Raman amplifier at an angle θ to the pump beams permits a high quality (in the case of the Prometheus-L design, 80 kJ) output beam to be generated following path matching of the seeds to the original pump beams.

If stimulated rotational Raman scattering proved to be too difficult to control under the required test conditions (higher order Stokes, etc.), stimulated vibrational Raman scattering could suffice, at a slight reduction in overall operating efficiency. The Raman accumulators should be able to achieve high degrees of reliability.

Generation of Stokes Seeds for SBS Pulse Compressors - The Stokes seeds for the SBS pulse compressors are generated electronically by "chirping" (acoustical-frequency shifting) the leading edges of the 80 kJ output beams from the Raman accumulators. Some technological development needs to take place to permit full aperture "chirpers" to be installed, but subscale tests with small crystals have produced promising results. Work at the Lawrence Livermore National Laboratory has already produced Pockels cells having conducting electrodes with apertures of approximately 30 cm. Experimental verifications need to be made of theoretical predictions of compressed pulse shapes and conversion efficiencies given the specific requirements on pulse shape established by the Target Working Group.

In the same vein, fast, large aperture (~100 cm) Pockels cells to be used for pulse-shaping the depleted pump beams from the SBS pulse compressors for synthesizing the required precursor pulses need to be demonstrated.

Although the development of large aperture Pockels cells may prove difficult, there do not appear to be any serious technological problems associated with synthesizing large aperture electro-optical (E/O) switches from smaller components. This synthesis may have significant advantages, for example, in the suppression of transverse SBS losses in the Pockels cells.

The SBS pulse compressors and attendant E/O switchyards currently represent the highest risk elements in the Prometheus-L driver design. Failure of any of the Pockels cells or "chirper" modulators would mean the loss of an entire 80 kJ beamline, with consequent failure of direct drive targets. In some cases, continued operation with indirect drive targets could be considered even if one of the 80 kJ beamlines went down.

5.3.15 Critical Issue No. 15: Demonstration of Cost Effective KrF Amplifiers

Description of Problem - One of the key elements associated with developing a cost effective KrF laser driver for the Prometheus reactor design 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. These KrF amplifiers need not only meet requirements of output energy, pulse duration, beam quality, beam diameter, wavelength, bandwidth, etc., but also stringent requirements on reliability, consistency of operation, etc. In order to prevent catastrophic failure of the IFE reactor, the Prometheus has designed a laser driver which can permit the occasional failure of a KrF amplifier without requiring the concomitant shutdown of the reactor. As this freedom from KrF amplifier failure is predicated upon the choice of IFE reactor operation with direct drive targets, a limit is placed upon the laser energy delivered by each KrF amplifier such that the 1% direct drive target illumination uniformity requirement is met. Given 60 beams arranged symmetrically around the spherical direct drive target, together with a nominal laser driver energy of 5 MJ, the loss of 5 kJ (or approximately 6%) from each of the 60 beams from time to time should still permit target illumination uniformity to be maintained, at least for tangential target illumination schemes. KrF amplifier output energies of 5 kJ represent a significant derating of current designs and successful development of reliable amplifier prototypes should be achievable during the next decade if sufficient funding is made available.

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, and
(2) Electric discharge excimer laser amplifiers with the excitation of the KrF excimer achieved along the neutral channel for geometries involving moderate (V < 200 liters) volumes.

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. Each of these two KrF amplifier design configurations has its supporters and detractors. 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 c. 10^9 over long periods of time at repetition rates of 3-10 Hz is crucial, the potentially higher reliability of the EDEL makes this configuration of greater interest than formerly.

During the course of the reactor design study (including reviews with Government scientists), the question has been raised whether or not KrF amplifiers can be designed to fulfill all the technical requirements (summarized below), while still achieving a cost effective level of performance to permit the overall cost of electricity (COE) for the IFE reactor to be competitive. Our design should significantly reduce the risk of developing a cost-effective KrF final amplifier design for three reasons:

(1) The amplifier output energy has been reduced from the 250 kJ level suggested for EBELs down to levels of the order of 5 kJ,
(2) Since the dimensions of the laser amplifier are of the order of 30x30x200 cm, parasitic oscillations and superfluorescent losses are more easily controlled,
(3) Optics costs and risks are significantly reduces as the effective aperture of the amplifier is reduced to 30 cm.

The new non-linear optical beam combination design approach which has made it technically feasible to relax the energy, volume, and aperture requirements for the KrF laser amplifiers is the implementation of forward stimulated rotational Raman scattering amplifiers for beam combination, larger aperture synthesis, and improved beam quality. Nonetheless, there remain a series of developmental problems associated with both types of amplifiers.

In evaluating the relative risks associated with the two excimer laser designs, the requirement performance parameters of each is summarized below in Table 5.3.15-1 and Table 5.3.15-2.

Note that the large volume EBEL amplifier module must have a saturating laser pulse passing through the active volume in order to prevent serious superfluorescence and parasitic oscillation losses associated with the high (13.8 neper) small signal gain of the amplifier.

Table 5.3.15-1 Design Requirements for EBEL

Requirement Description	Design Value
Output Energy	240 kJ
Amplifier Aperture	3x3 m
Pulse Duration	500 ns
Amplifier Volume	54 m^3
Amplifier Gain Length	6 m
Amplifier Gain Coefficient	.023/cm
Energy Storage Density	7 J/liter
Energy Extraction Efficiency	0.7
Final Anode Voltage	3.3 MV
Overall Efficiency	10%
Bandwidth	1% or 10^{13} Hz
Laser Wavelength	248 nm
Active Medium	KrF
Total Gas Pressure	760 torr
Pulse Compressor	Angular Multiplexing
Laser Beam Quality	1.4 XDL
Peak to Peak Laser Beam Homogeneity	20%
Number of Shots Between Failures	10^{10}
Repetition Rate	5 Hz

Table 5.3.15-2 Design Requirements for EDEL

Requirement Description	Design Value
Output Energy	4 kJ
Amplifier Aperture	30x30 m
Pulse Duration	200 ns
Amplifier Volume	0.18 m^3
Amplifier Gain Length	2 m
Amplifier Gain Coefficient	0.05/cm
Energy Storage Density	22 J/liter
Energy Extraction Efficiency	0.7
Final Anode Voltage	50 MV
Overall Efficiency	12%
Bandwidth	10^{10}Hz
Laser Wavelength	248 nm
Active Medium	KrF
Total Gas Pressure	760 torr
Pulse Compressor	Chirped SBS
Laser Beam Quality	1.1 XDL
Peak to Peak Laser Beam Homogeneity	5%
Number of Shots Between Failures	10^9
Repetition Rate	5 Hz

Comparison between Table 5.3.15-1 and Table 5.3.15-2 will indicate that the requirements for the EBEL are generally much more difficult to attain than those listed for the EDEL, with regard to the required optics, the pulsed power, and the performance of the amplifiers themselves. The key developmental problems associated with each of these two types of excimer laser amplifiers are summarized below in Tables 5.3.15-3 and 5.3.15-4.

Table 5.3.15-3 EBEL Developmental Problems

#	Description of Problem Area	Possible Solution
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

These EBEL developmental problems are relatively well understood in view of the extensive theoretical and experimental studies of these amplifiers carried out by both the DOE and the DoD. For successful implementation into an IFE reactor, the most important development for the EBEL is the need for a dramatic increase in the mean number of amplifier firings between failures. As summarized below in Table 5.3.15-4, there are also significant problems associated with the EDEL approach, but since the amount of research and development for these amplifiers is relatively small, larger uncertainties in this excimer laser design exist:

Table 5.3.15-4 EDEL Developmental Problems

#	Description of Problem Area	Possible Solution
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

Compared with the EBEL, the developmental problems for the EDEL appear to be more tractable although relatively little work to date has been completed for these devices.

<u>Summary</u> - Considerable developmental work has been carried out during the last decade on EBEL amplifiers. Although much progress has been made in achieving the ambitious design goals for EBEL amplifiers, these devices are currently not believed to be capable of meeting a 10^9 shots-between-failure requirement. Moreover, the primary advantage of the EBEL design over the EDEL is the ability of the e-beam excitation to scale to larger amplifier volumes. This is not desirable for a reactor design since it causes the excimer laser amplifier to become the cause of a single point failure.

It must be emphasized that significant KrF amplifier development work must be carried out in the next decade if the demanding requirements for the KrF driver amplifiers are to be met. Thus, the essence of this Critical Issue is that substantial development effort will be required in order to provide the KrF amplifiers which will be the workhorses of the future IFE reactor. Details will be defined in the associated Research and Development section.

References for 5.3.15

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

5.3.16 Critical Issue No. 16: Demonstration of Low Cost, High Volume Target Production Techniques

Description - Target production for IFE reactors will require technologies which are presently either nonexistent 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 reaction chamber and, in the case of indirect drive, 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.