Technical Issues
For IFE Reactors

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Introductory Remarks

- This presentation focuses on brief Description of Critical Issues for IFE Reactors
- The work was performed as part of the PROMETHEUS Reactor Study lead by MDAC
- PROMETHEUS Accomplishments:
  - Developed 2 Conceptual Designs, one is Laser Driven (-L), the other is Heavy-Ion Driven (-H)
  - Identified and Characterized Critical Issues (16)
  - Identified and described a large number (>100) of detailed key technical issues; identified key operating environments
  - Conducted R&D Assessment that included characteristics of facilities, cost and time required to construct IEPR
  - Developed Evaluation Methodology to Compare IFE Options and to Compare IFE to MFE
  - Applied the Methodology to Comparing Laser- and Heavy-Ion-Driven Reactors
- Issues and R&D were kept generic to some extent

References

Detailed description of results can be obtained from:

1. L. Waganer et al., "Inertial Fusion Energy Reactor Design Studies: PROMETHEUS-L and PROMETHEUS-H," McDonnell Douglas Company Report, MDC 92 E 0008/DOE/ER-541001 (March 1992).

2. M.A. Abdou et al., "Critical Technical Issues, Research and Development Assessment, Evaluation and Comparison Studies for Inertial Fusion Energy Reactors," to be published in Fusion Engineering & Design (1993).

Table I Major Design Parameters and Features of the Prometheus Plants

Parameter	Prometheus-L	Prometheus-H
Net Electric Power (MWe)	972	999
Gross Electric Power (MWe)	1382	1189
Driver Power (MWe)	349	137
Auxiliary Power (MWe)	36	28
Cavity Pumping Power (MWe)	25	25
Total Thermal Cycle Power (MWt)	3264	2780
Blanket Loop Power (MWt)	1782	1597
Wall Protection Loop Power (MWt)	1267	1162
Usable Driver Waste Heat (MWt)	193	N/A
Usable Pumping Waste Heat (MWt)	22	21
Thermal Conversion Efficiency	42.3%	42.7%
Recirculating Power Fraction	30%	16%
Net System Efficiency	31%	36%
Fusion Power (MW)	2807	2543
Neutron Power (MW)	2027	1818
Surface Heating Power (MW)	780	725
Thermal Power (MWt)	3092	2797
Thermal Power to Shield (MWt)	43	38
Cavity Radius (m)	5.0	4.5
Cavity Height (m)	15.0	13.5
First Wall Protection/Coolant Media	Liquid Lead	Liquid Lead
In/Out Temp.,^{o}C	375/525	375/525
Breeder Material	Li$_2$O Pebbles	Li$_2$O Pebbles
Structural Material, Wall and Blanket	SiC	SiC
Blanket Heat Transfer Media	1.5 MPa Helium	1.5 MPa Helium
In/Out Temp.,^{o}C	400/650	400/650
Cavity Pressure (mTorr, Pb)	3.0	10
Neutron Wall Load, Peak/Ave (MW/m^2)	6.5/4.3	7.1/4.7
Energy Multiplication Factor	1.14	1.14
Tritium Breeding Ratio (TBR)	1.20	1.20

Table I Major Design Parameters and Features of the Prometheus Plants (Con't)

Parameter	Prometheus-L	Prometheus-H
Target Illumination Scheme	Direct Drive, Symmetric	Indirect Drive, Two Sided
Number of Beams	60	18 in LINAC (12 MAIN +6 in 2 prepulses)
Driver Output Energy (MJ)	4.0	7.8 (7.0 transmitted to target)
Overall Driver Efficiency (%)	6.5	20.6
Ion Accelerated	N/A	Lead
Charge State	N/A	+2
Final Energy (GeV)	N/A	4.0
Type of Accelerator	N/A	Single Beam LINAC
Type and Number of KrF Amplifiers	Electric Discharge, 960	N/A
Beam Combining Technique	Raman Accumulators	N/A
Pulse Compression Technique	Stimulated Brillouin Scattering	N/A
Final Beam Transport Efficiency (%)	100	90
Target Gain	124	103
Target Yield	497	719
Repetition Rate (pps)	5.65	3.54
Plant Availability (%)	79.4	80.8
Cost of Electricity (mills/kWh, 1991$)	72.0	62.6

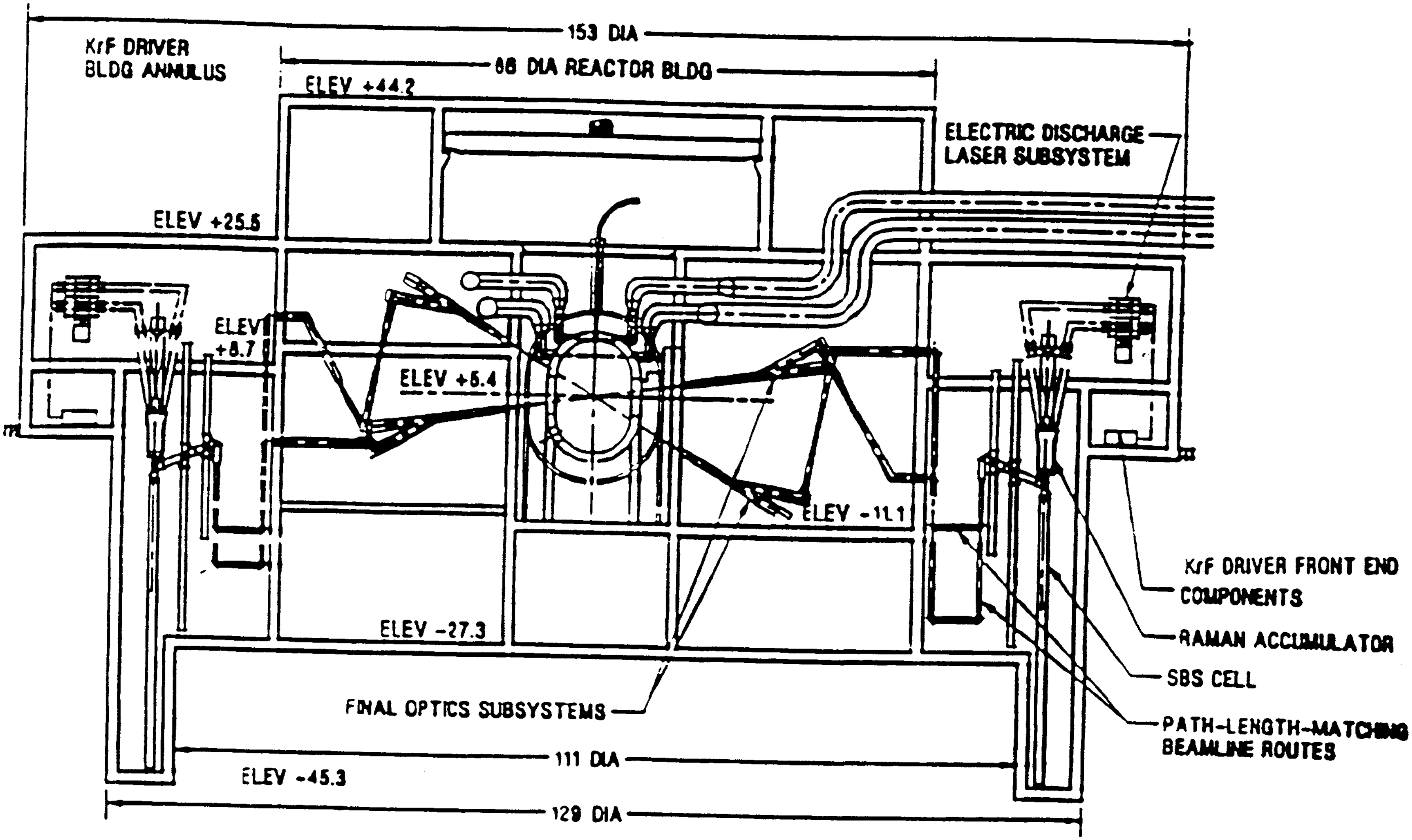


Figure 1. Prometheus-L Reactor Building Provides Space for Shielded Beamlines. Driver Building Surrounds Reactor Building. (all dimensions in meters)

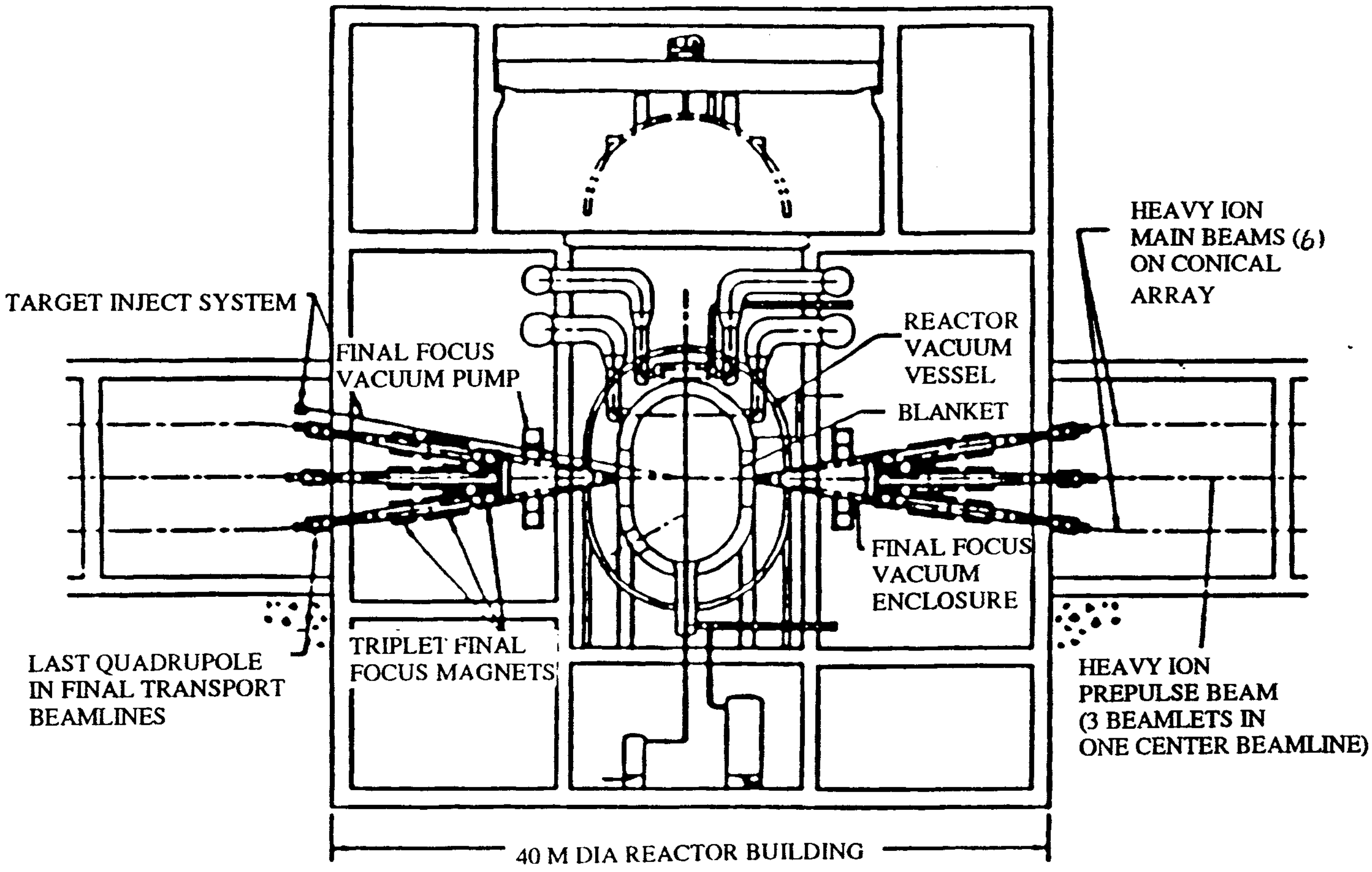


Figure 2. Prometheus-H Reactor Building is Relatively Compact

List of Critical Issues

1. Demonstration of Moderate Gain at Low Driver Energy
2. Feasibility of Direct Drive Targets
3. Feasibility of Indirect Drive Targets for Heavy Ions
4. Feasibility of Indirect Drive Targets for Lasers
5. Cost Reduction Strategies for Heavy Ion Drivers
6. Demonstration of Higher Overall Laser Driver Efficiency
7. Tritium Self Sufficiency in IFE Reactors
8. Cavity Clearing at IFE Pulse Repetition Rates
9. Performance, Reliability and Lifetime of Final Laser Optics
10. Viability of Liquid Metal Film for First Wall Protection
11. Fabricability, Reliability and Lifetime of SiC Composite Structures
12. Validation of Radiation Shielding Requirement, 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

Critical Issue 1: **Demonstration of Moderate Gain at Low Driver Energy**

- Developing physics and engineering test facilities of affordable small to moderate size (fusion power < 100 MW) is crucial for an IFE R&D pathway that is practical in terms of cost and time.

- Reactor Design Studies have focused on high-gain, multi-mega joule incident energy target concepts that are appropriate for economic power production

- However, for Development Pathway, target designs that provide moderate gain (20-50) at low driver energy (< 1-2 MJ) must be considered.

- Also, Separate Facilities for Physics and for Technology (rather than combined physics and technology facilities) should be evaluated. Separate facilities path could be cheaper and faster. Reactor Component Development requires only the approximate output distribution (neutrons/debris/x-ray) at low fusion power (<100 MW)

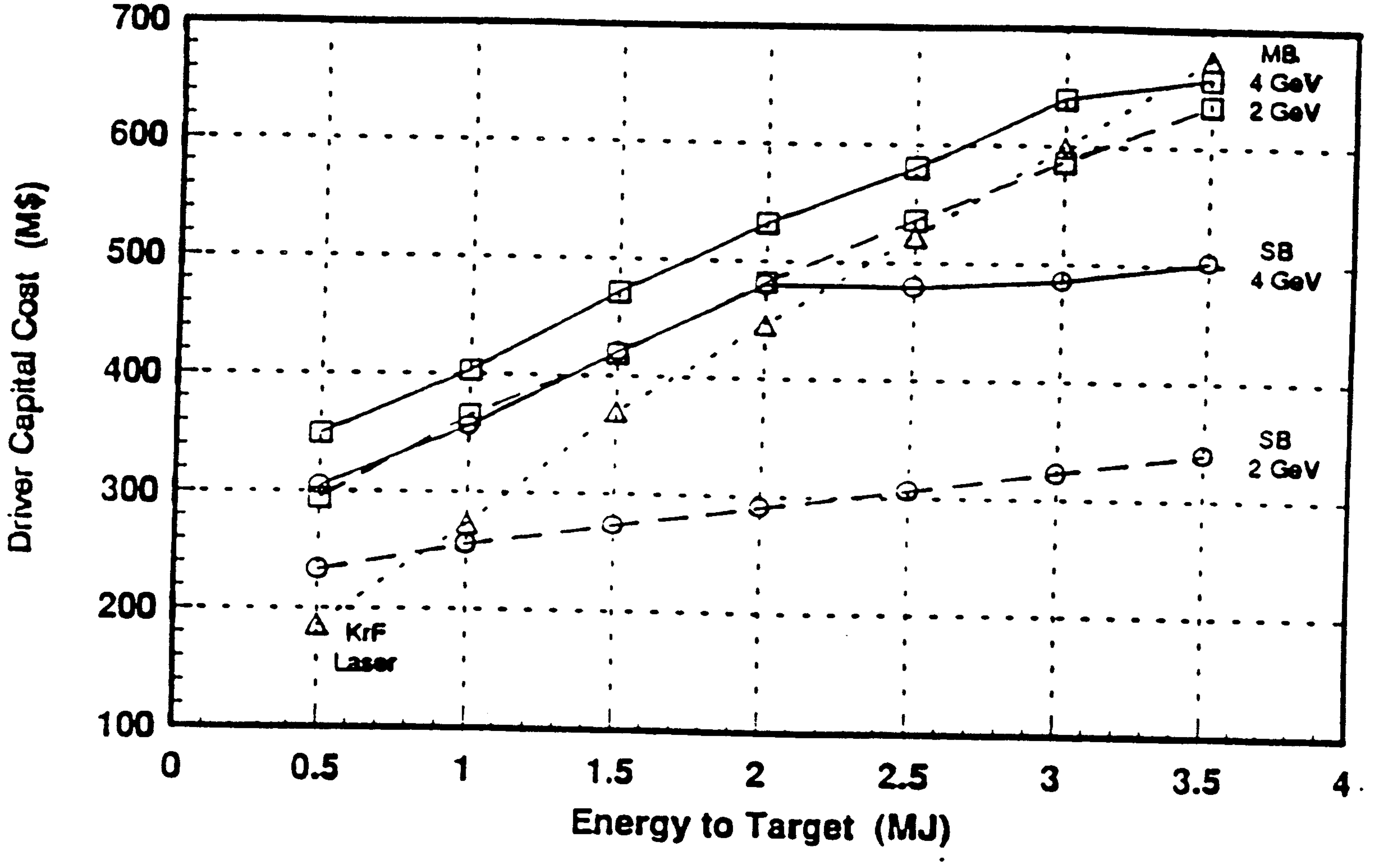


Figure 4. Projected Cost Scaling for Small-Size KrF Laser and Heavy-Ion LINAC Drivers

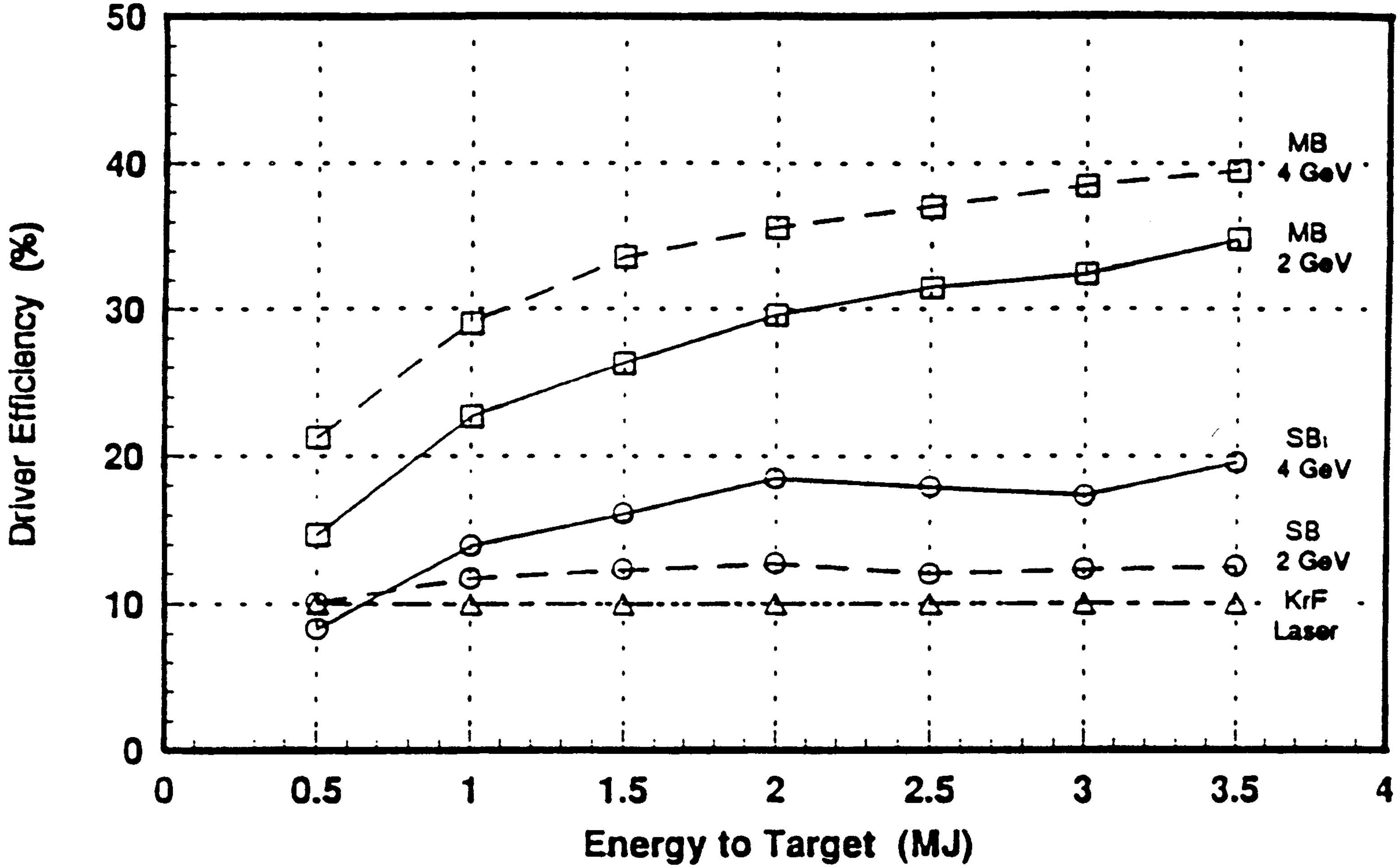


Figure 5. Projected Efficiency Scaling For Small-Sized KrF Laser And Heavy-Ion LINAC Drivers

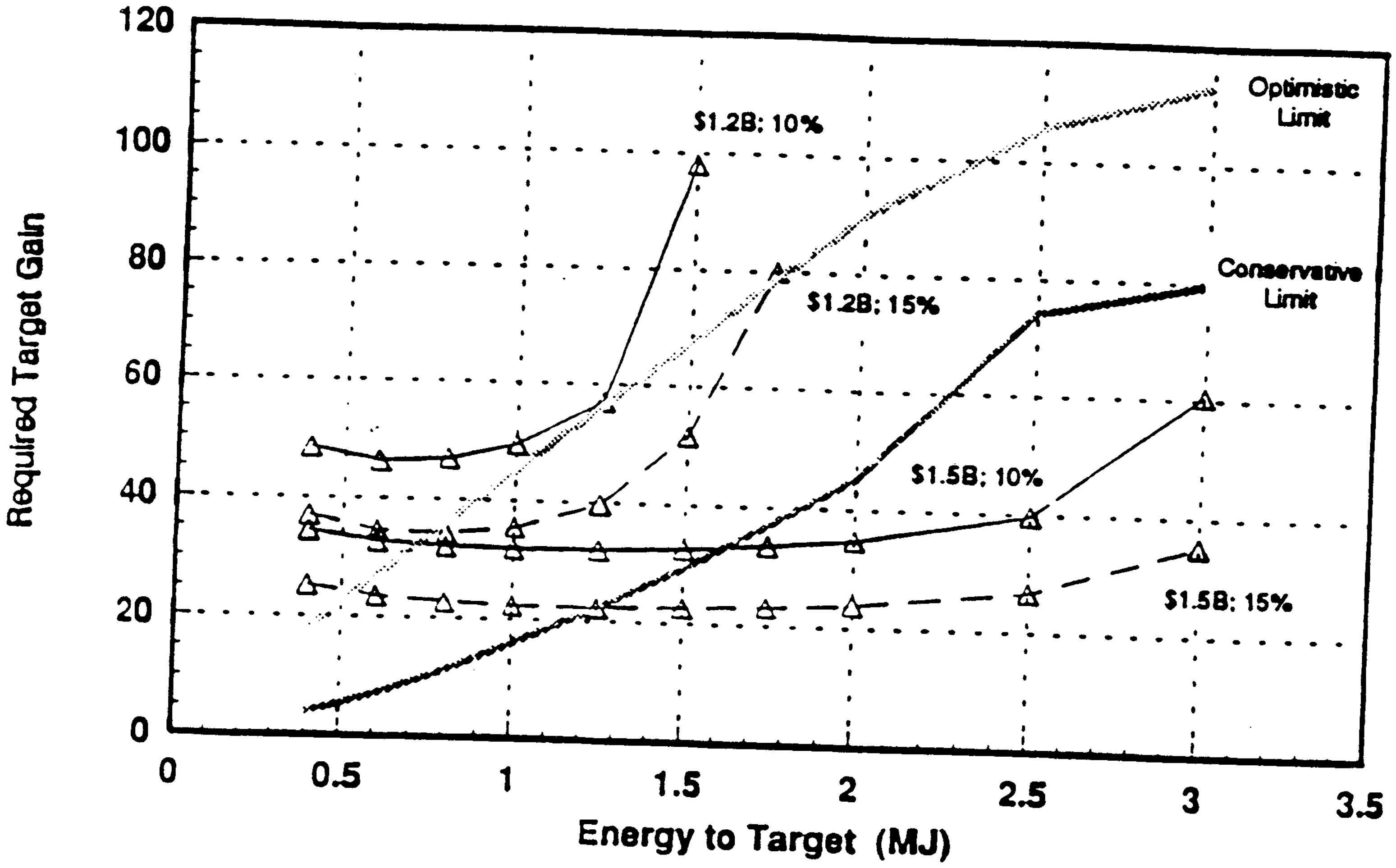


Figure 6. Projected 100 MWe Demonstration Power Plant Gain Space Windows for the Prometheus-L Driver Configuration. Values Indicated Only Include Direct Costs.

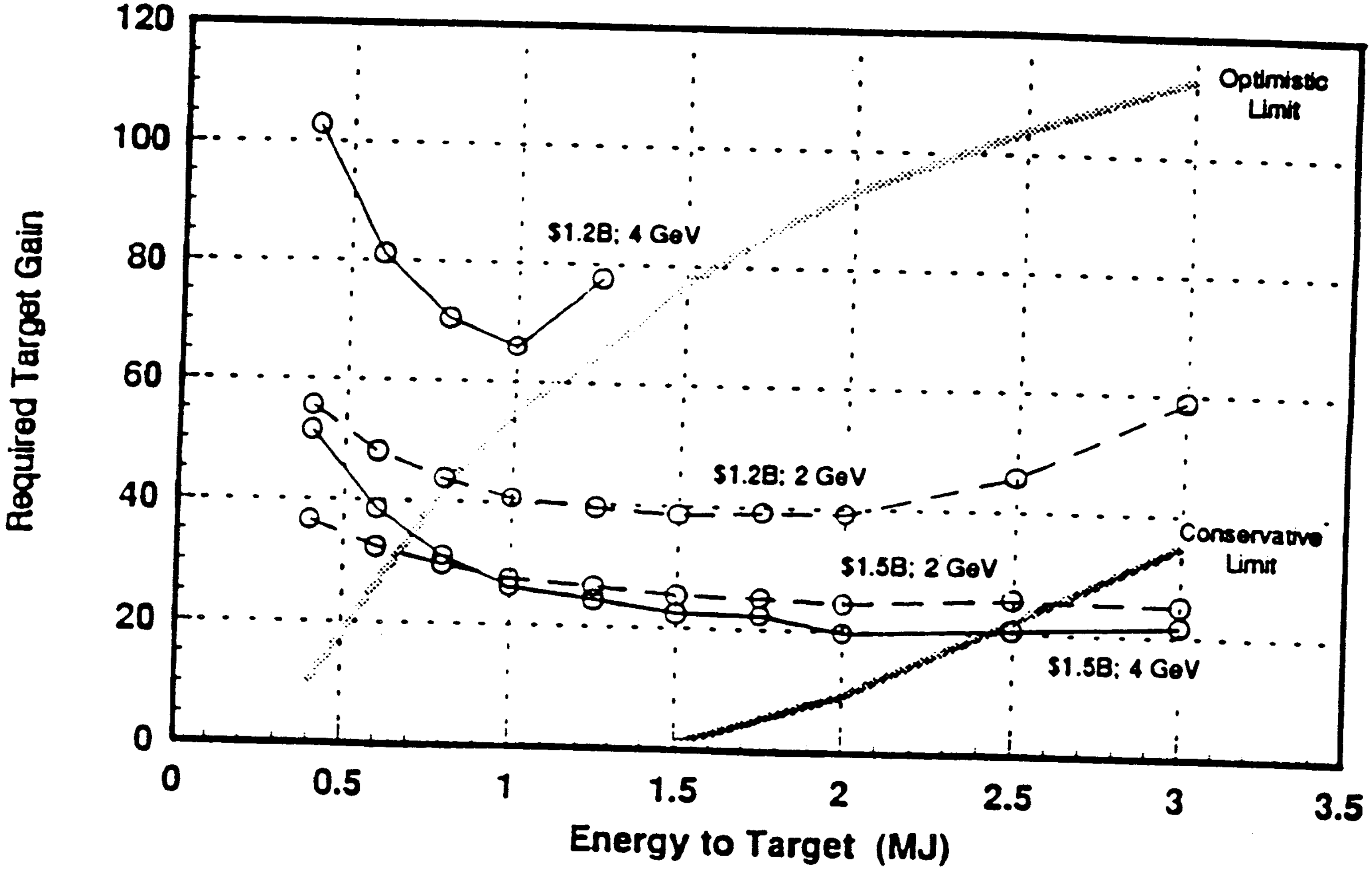


Figure 7. Projected 100 MWe Demonstration Power Plant Gain Space Windows for the Single Beam Prometheus-H Driver Configuration. Values Indicated Only Include Direct Costs.

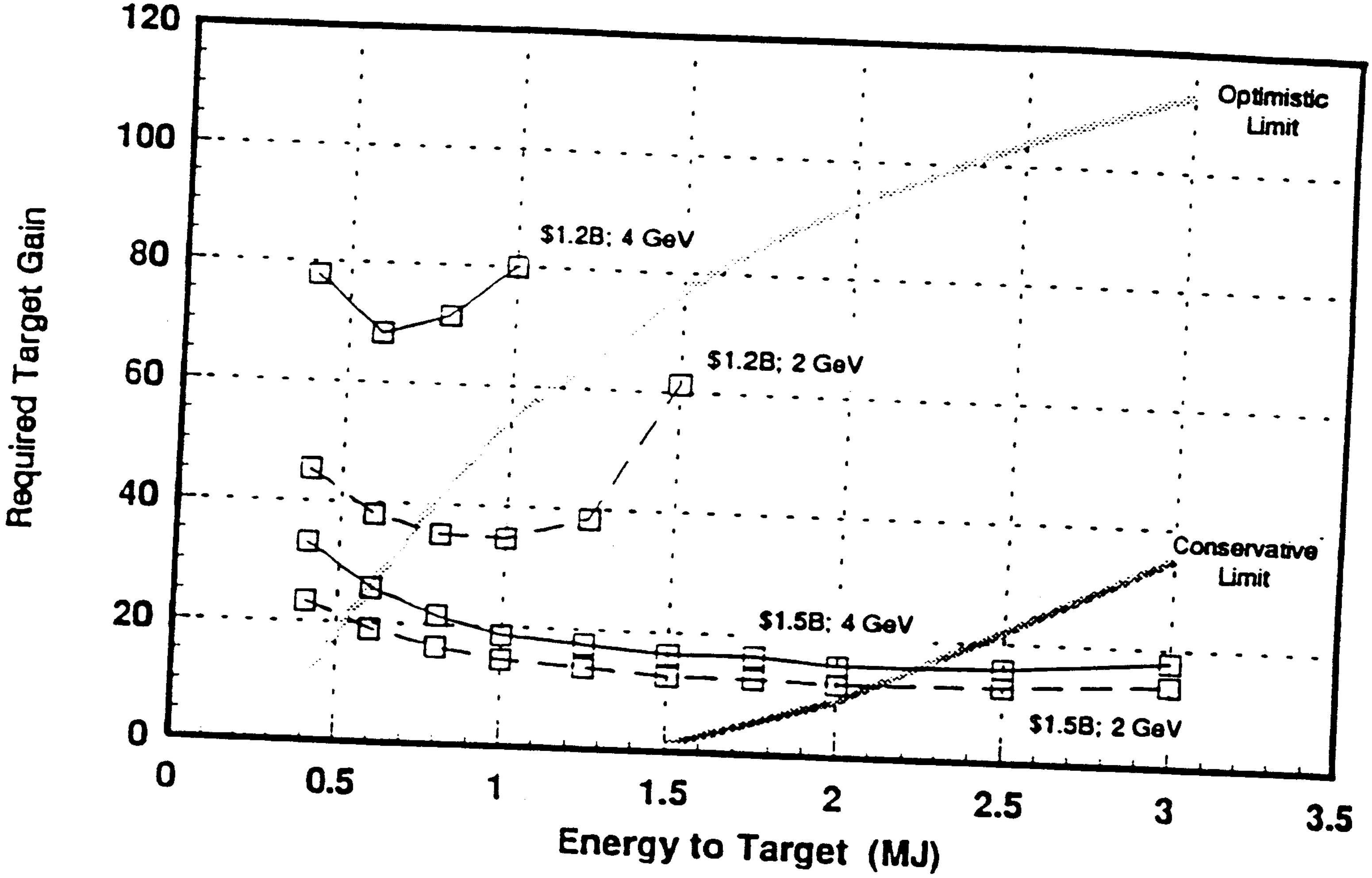


Figure 8. Projected 100 MWe Demonstration Power Plant Gain Space Windows for a Multiple Beam LINAC Driver. Values Indicated Only Include Direct Costs.

Analysis (Critical Issue 1)

- Considered a 100 MWe DEMO
  Evaluated region of required gain space versus driver energy for a fixed capital cost

- Driver Cost
  MB Linac> Laser > 5B 2 GeV

  Fixed Driver Direct Cost of $400M limits Driver Energy:

MB Linac:	< 1MJ
Laser:	< 1.6 MJ
SB 2 GEV:	< 3.5 MJ

- Efficiency plays a key role in minimizing cost for small plants when net power is required

  (recirculating power = $P_{th}/M\eta_d G$)
  In such a case, cost scales directly with η_d

- For Laser Driver DEMO is possible with:
  Gains of 30-50 at Driver Energy of 1-2 MJ

- For SB LINAC Driver (PROMETHEUS-H type):
  Gains of 20-30 at Driver energy of 1-2 MJ
  (2.5 MJ conservative)

- For MB LINAC Driver:
  Gains of 10-20 at Driver Energy of 1-2 MJ

- An early demonstration of low drive energy (1-2 MJ) target designs with repeatable gains comparable to those projected here would provide a lower cost, faster IFE development pathway

Critical Issue 2: **Feasibility of Direct Drive Targets**

- Incentive for DD Targets: Higher Gains
- However, Feasibility and Performance of DD targets are uncertain:
  - Physics of implosion
  - Target Illumination Requirements
  - Efficiency of coupling driver energy into the target
  - Target injection and tracking
- Present data on DD targets is at only a few KJ of laser energy

  Need Data at 100's of KJ to Mega joule to permit realistic assessment

Critical Issue 3: **Feasibility of Indirect Drive Targets for Heavy Ions**

- Properties of the method used to transport and focus the HI beam to the target

- Accuracy and reproducibility of the repetitive HI target launch system which injects the ID targets to the center of the target chamber

- Ability of the high-2 hohlraum cavity to efficiently convert and smooth the radiation incident on the DT capsule

Critical Issue 4: **Feasibility of Indirect Drive Targets For Lasers**

-accurate target tracking and pointing of the multiple laser beams to coincide with the two entrance apertures of the moving ID target

-accurate and reproducible indirect drive target propagation from the pellet factory to the center of the target chamber

-overcoming the problems of plasma closure of the two entrance apertures to the Hohlraum

Critical Issue 5: **Feasibility of Cost Reduction Strategy For Heavy Ion Driver**

•Technical Feasibility of HI driver is assured
Existing accelerators have exhibited 25-yr lifetime with 95% availabilities

•The Problem is Cost
A lo GeV linear accelerator with today's technology costs billions of dollars

Two Key Issues for Cost Reduction

1) Space Charge limited transport of a bunched beam
-Transporting beams for several kilometers at their space charge limit should be possible, with little emittance growth. However, this HI beam transported has only been demonstrated with low energy, low power, unbunched beams.

2) High Current Storage Rings for HI beams
-Linear Accelerators can run at high average power and much higher repition rate than an IFE reactor can allow for DT pellet ignition.
-This uneconomical situation can be improved if the beams for the LINAC can be stored for a short time. The issue here is demonstrating that a HI beam of the required intensity can be stored in a storage ring for the requisite time, typically about 1 to 2 milliseconds.

Critical Issue 6: **Demonstration of High Overall Laser System Efficiency**

The major problem is the Excimer Laser Amplifiers. The major obstacle is the lack of precious work on moderate-sized (2-6KJ output) excimer laser amplifier modules. R&D program with the goal of producing a 2 to 4 KJ excimer laser amplifier with a wall plug efficiency of 12% (and a mean time between failures of between 10^9 and 10^{10} shots) is required.

7. Tritium Fuel Self Sufficiency

Self-sufficiency condition: $\Lambda_a \geq \Lambda_r$

Achievable TBR (Λ_a)

- Uncertainties in design: wall coverage, amount of structural materials, wall protection scheme, blanket details

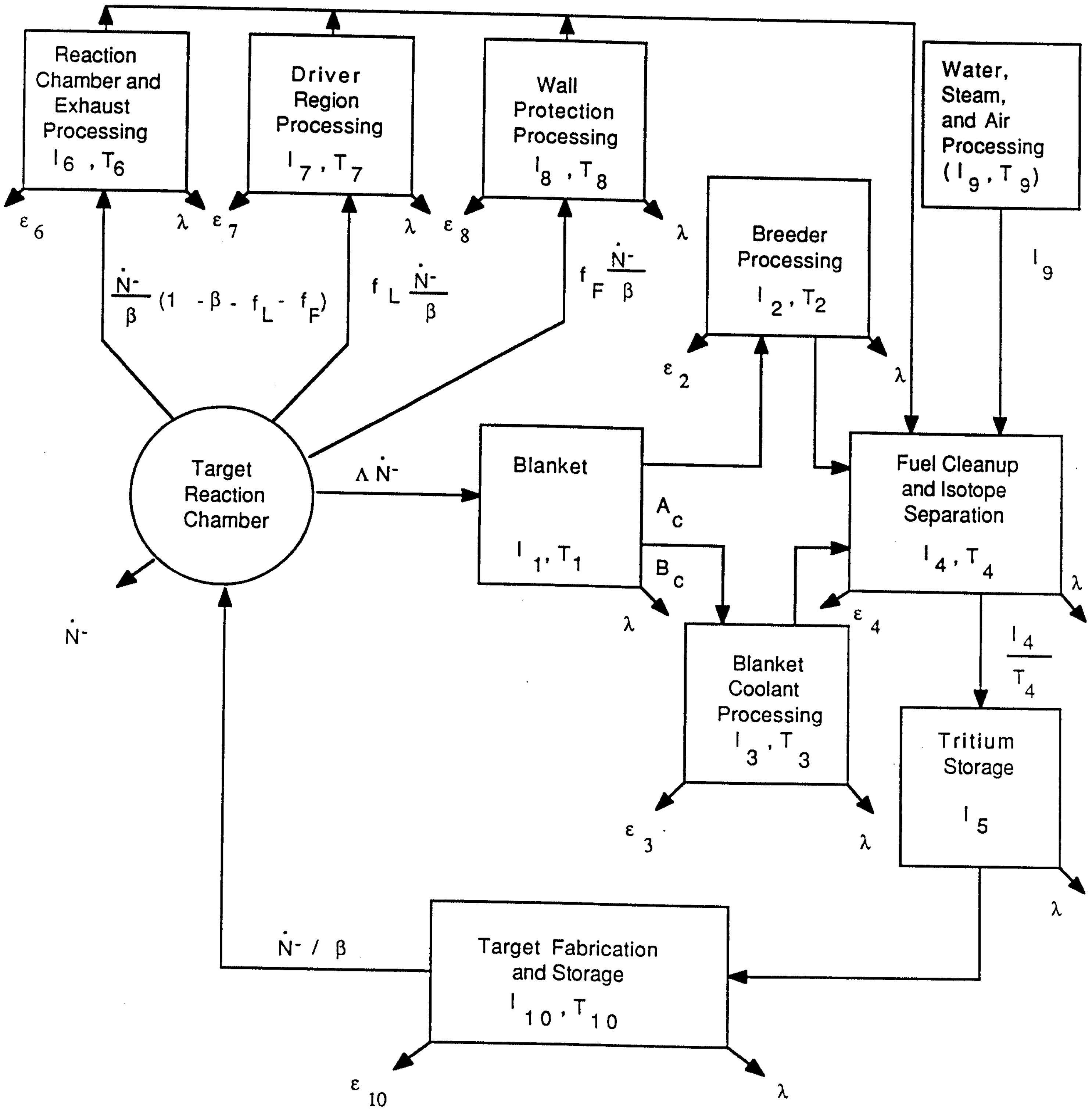
- Uncertainties in prediction capabilities: nuclear data, geometric modelling in neutron transport

Required TBR (Λ_r)

- Uncertainties in tritium mean residence time in components of the fuel cycle, e.g. in target factory

- efficiency of tritium extraction in various parts of the fuel cycle

Figure 5.14: Schematic Model of the Fuel Cycle for IFE Reactor Operated on the DT Cycle



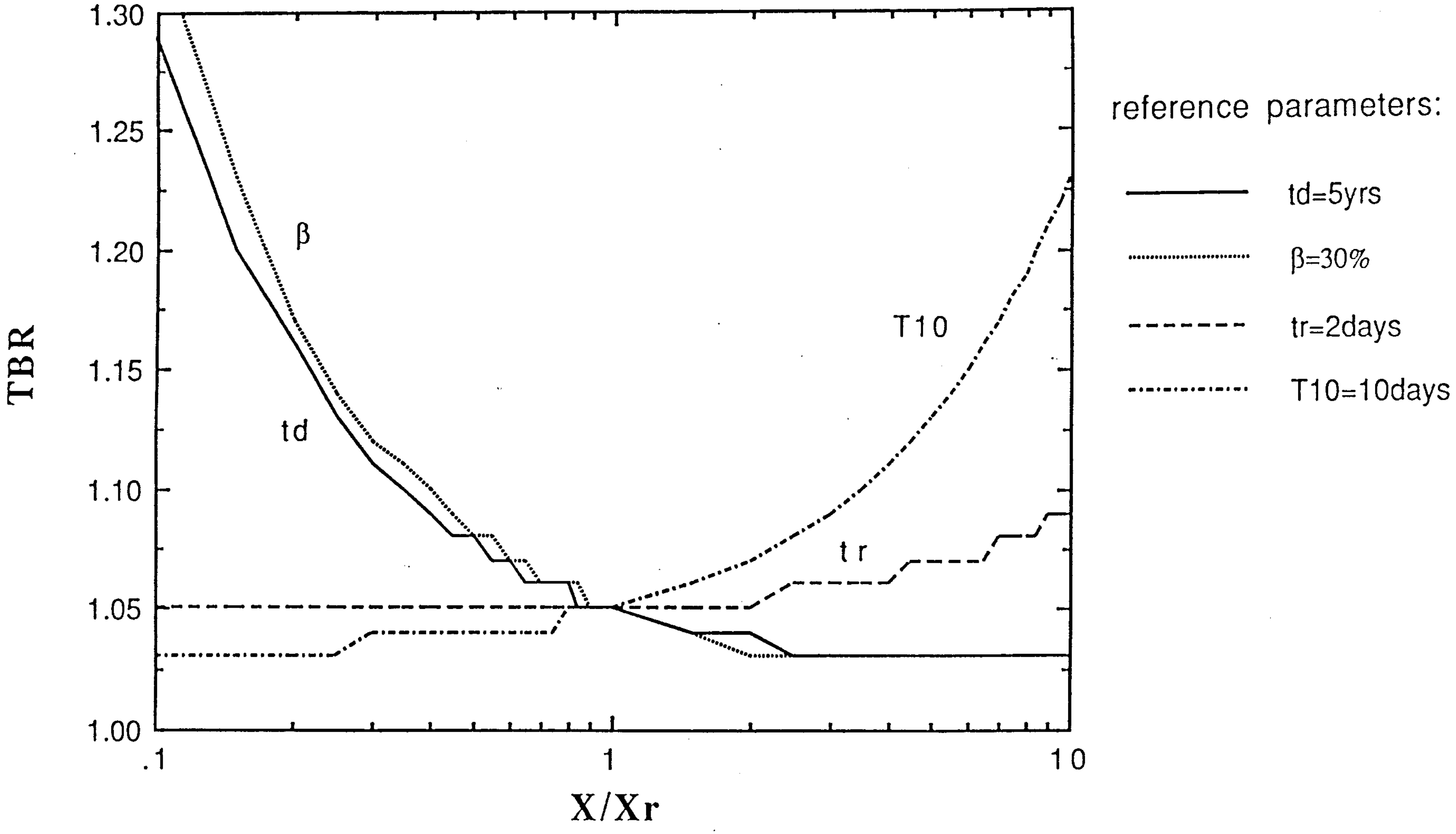


Figure 5.15a Variation of Required TBR with Reactor Parameters

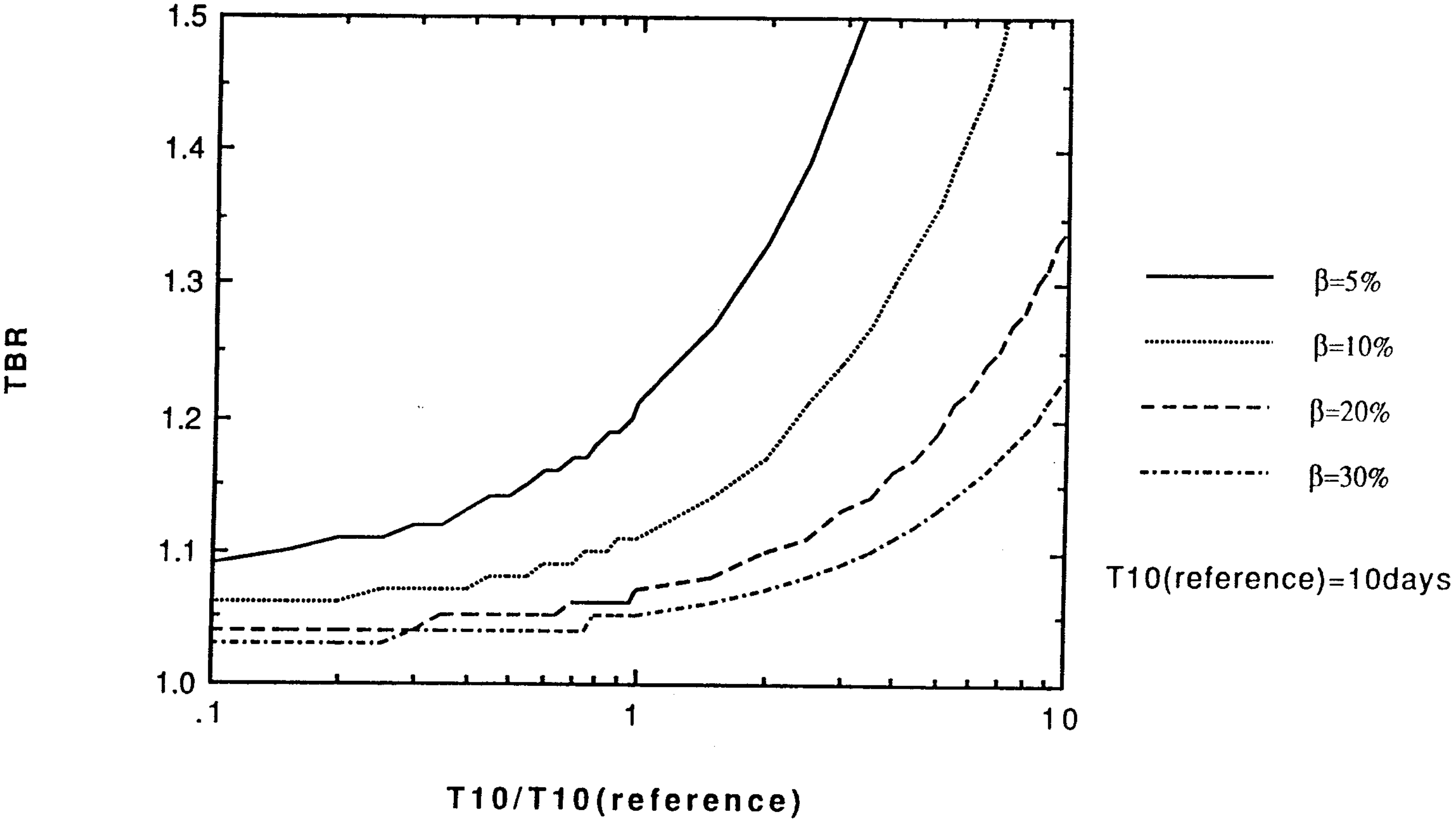


Figure 5.15b Variation of Required TBR as a Function of T_{10} (Residence Time in Target Factory) for Various Values of the Tritium Fractional Burnup (β).

Critical Issue 8: **Cavity Clearing for High Repition Rate (~ 5-10 per second)**

-Target Debris and material evaporated from the cavity surfaces must be removed from the cavity before the next target is injected
-Cavity is cleared generally by recondensing condensable gases on first wall surfaces and by pumping non-condensible gases through large vacuum ducts

Key issues are:

- Propagation limits for both targets and driver energy

- Requirements on background gas pressure for protection of the first wall and final optics

- Achievable Chamber Pressure:
  - -Physics of energy and mass transport and vapor recondensation
  - -Impact of vacuum system requirements, e.g. size of ducts affects blanket coverage and radiation streaming

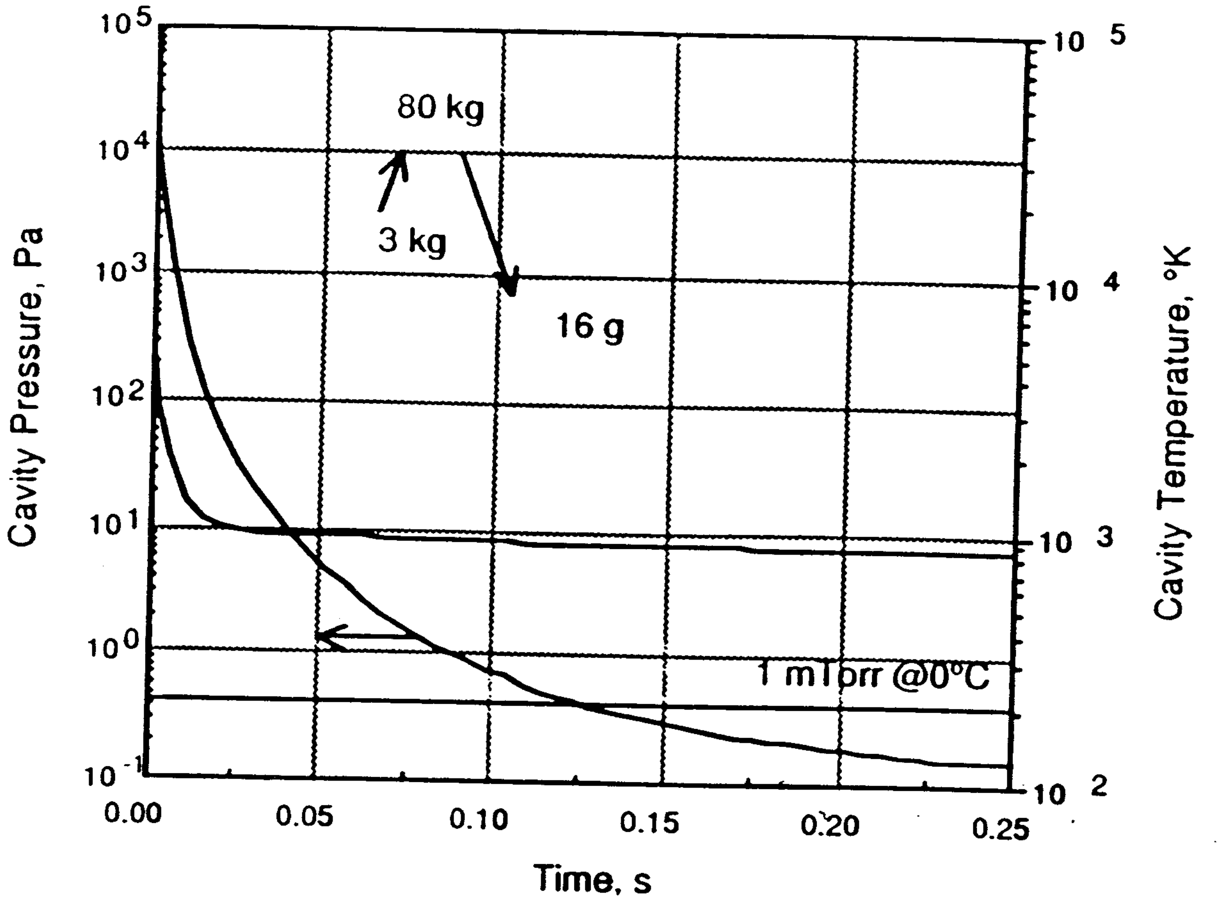


Figure 19. Cavity Vapor Pressure and Temperature Histories Following the Blast.

Critical Issue 9: **Performance, Reliability, and Lifetime of Final Laser Optics**

- Need to develop and test designs with reliable, longlife [PROMETHEUS attempted navel design concepts for the dielectric turning mirror and the final Grazing Incidence Metal Mirror (GIMM)]

- GIMM Thermomechanical and Material Design
  -The key for successful design is to decouple the optical and structural functions of the mirror (e.g. try aluminum alloy deposited on top of a composite Si C support structure)

  -Radiation load (nuclear heating and fluence)

  -Determination of deformation due to thermal load and radiation effects (e.g. creep and fatigue damage)

- Dielectric Turning Mirror

  -Shield Design to minimize collided flux

  -Radiation Limits on Selected materials (effect of radiation on the optical properties of the dielectric materials)

Critical Issue 10: **Viability of Liquid Metal Film for First Wall Protection**

[OR, more generally, successful development of a viable First Wall Protection Scheme]

-Unprotected Solid First Wall is <u>not</u> viable because of extremely high instantaneous heat and particle leads
-several protection schemes proposed. None is tested
-In Prometheus Design: a thin liquid metal film wets the first wall. 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. Dry spots will suffer serious damage in about 10 minutes.

Uncertainties in Liquid Metal Film:

-Film feeding and thickness control (affects surface temperature and condensation rate)
-Blast effects
-Flow around geometric perturbations
(e.g. around beam penetrations)
-Film flow stability on inverted surfaces
(e.g. upper hemisphere)

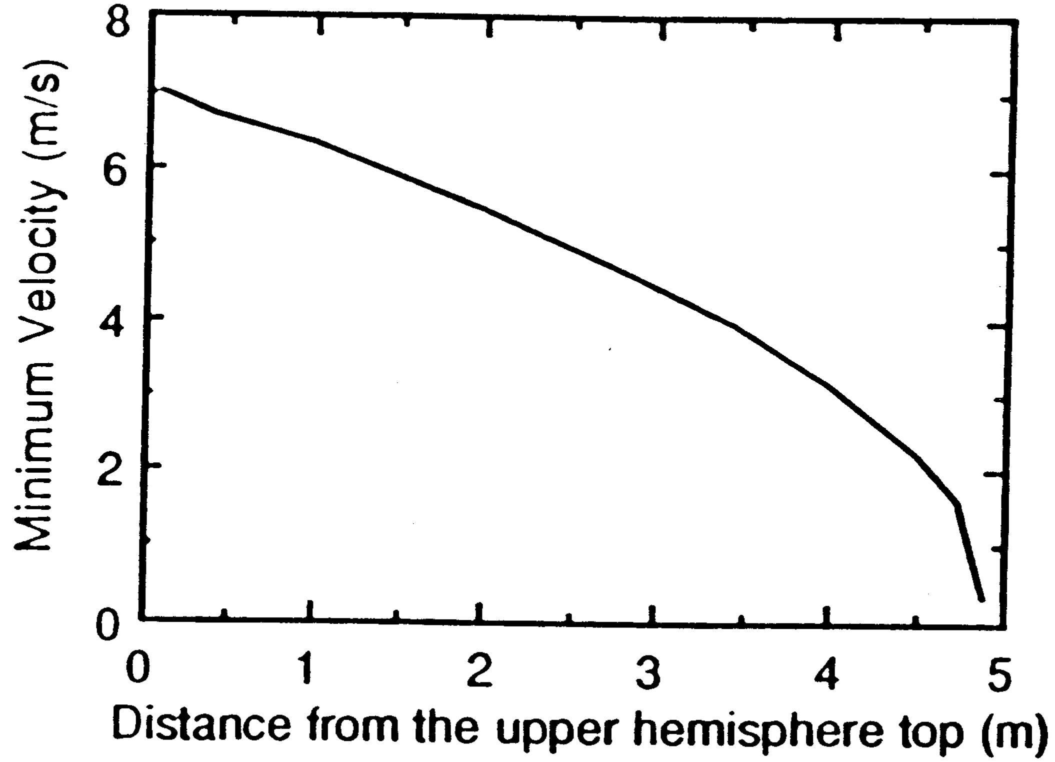


Figure 20. Minimum Velocity Required for Film Attachment on the Upper Hemisphere

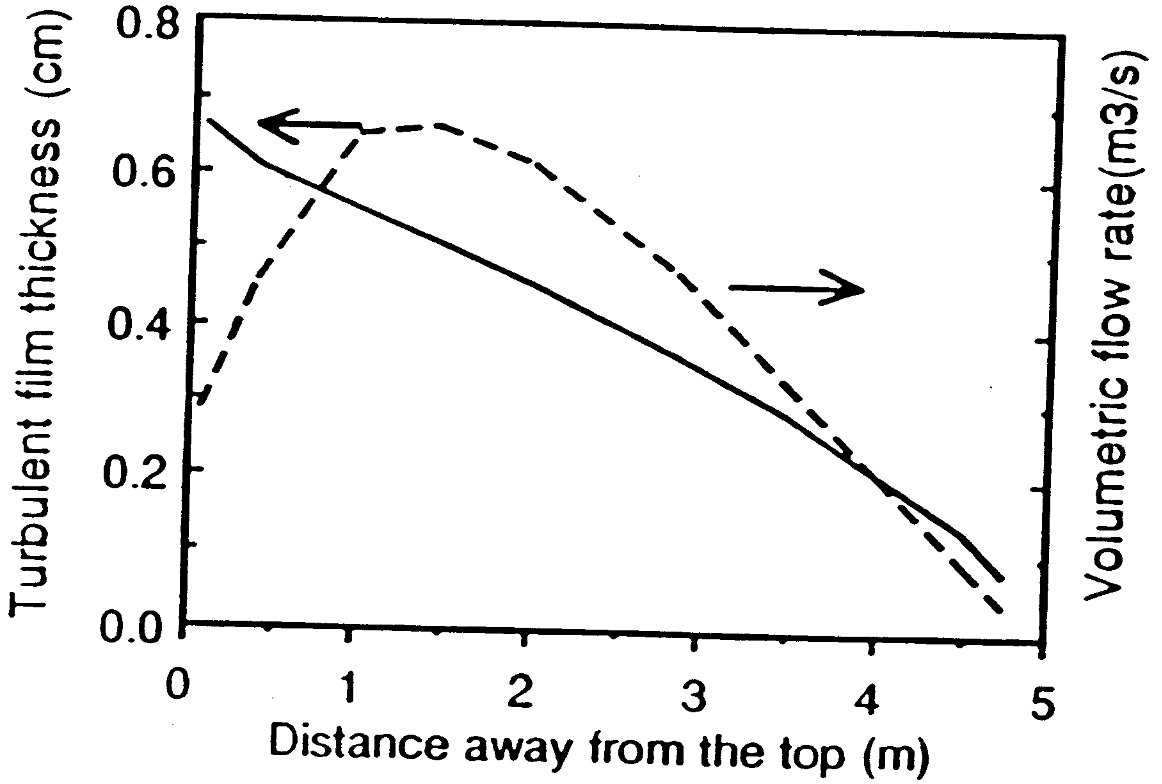


Figure 21. Turbulent Film Thickness and Minimum Flow Rate Required for Film Attachment on the Upper Hemisphere

Critical Issue 11: Fabricability, Reliability, and Lifetime of SiC Composite Structures

[OR, more generally, the successful development of suitable, longlife, low-activation structural material

- SiC was selected in PROMETHEUS to minimize long-term radioactivity. However, data base is seriously limited with virtually no data on behavior in the IFE operating environment. Without such a data base, system reliability, safety and economics can not really be assessed.

- Areas of Uncertainties
  - Manufacturing Methods and Costs
  - Radiation Effects and Fatigue: Life
    (e.g. swelling, embrittlement, fiber shrinkage and/or detachment from the matrix, creep crack propagation, and crack bridging)

Critical Issue 12: **Validation of Radiation Shield Requirements, Design Tools, and Nuclear Data**

-Quantifying Shielding Requirements
  e.g.-for final optics in Laser-Driver
    -magnets in HI driver

-Design of low activation, low cost shield

-Improvement and Verification of Prediction Capability
    -Accuracy of neutron transport calculations with deep radiation penetration, in void regions, and in specialized geometry
    -Accuracy of Nuclear Data

Critical Issue 13: **Reliability and Lifetime of Laser and Heavy Ion Drivers**

(See References)

Critical Issue 14: **Demonstration of Large Scale Non-Linear Optical Laser Driver Architecture**

(See References)

Critical Issue 15: **Demonstration of Cost Effective KrF Amplifiers**

(See References)

Critical Issue 16: **Demonstration of Low Cost, High Volume Target Production Techniques**

-IFE reactor needs ~ 10^8 targets per year

-Difficult to estimate production costs of targets. (Need for Sabot to deliver the target to the reaction chamber, and in the case of indirect drive, for an outer case that must meet stringent requirements, ..will increase cost)

-Economic Feasibility requires reasonable target cost

Detailed Key Issues

-See References for Full Details

-Following Page shows only type of information included

Table 5.1

List 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

Table 5.2 IFE Key Issues Summary Table

Issue/Technical Area	Reactor Concept	Potential Impact	Design Specifity	Level of Concern	Operating Environment		Relevance to MFE
					Neutron	Parameters	
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						
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.b.2 Channel Formation for Heavy Ion	HI						
A.c Fabrication							
A.c.1 Manufacturability of High Quality, Low Cost DD and ID Targets	L/HI	UL, RP, IC, RS	Generic	High		H, TWI, N	Medium

Table 5.2 (continued)

Issue/Technical Area	Reactor Concept	Potential Impact	Design Specifity	Level of Concern	Operating Environment		Relevance to MFE
					Neutron	Parameters	
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
E.a.7 Pb/Sic Wettability	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,TG,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,T,G,T_G,C,t ,P_t	High
E.b.3 Breeder/Structure Mechanical Interactions	L/HI	RL, RP	SiC, SB	High	H, R	F,T,C,I,s,t, N,σ,P	High

Evaluation Methodology and Comparison of IFE Reactors

[Only Examples are given here. See References for Details]

Fig. 7.1: Evaluation Methodology Approach

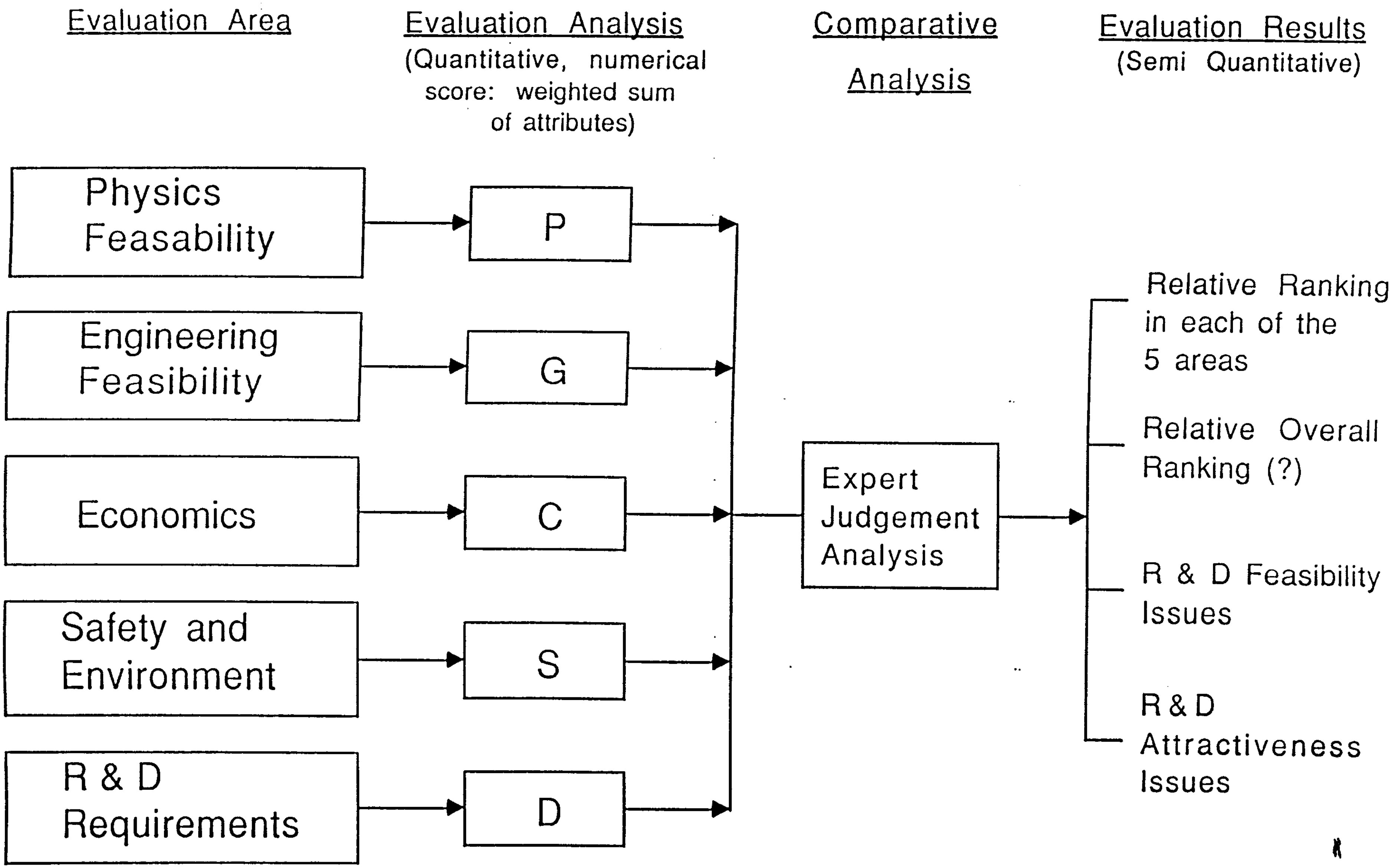
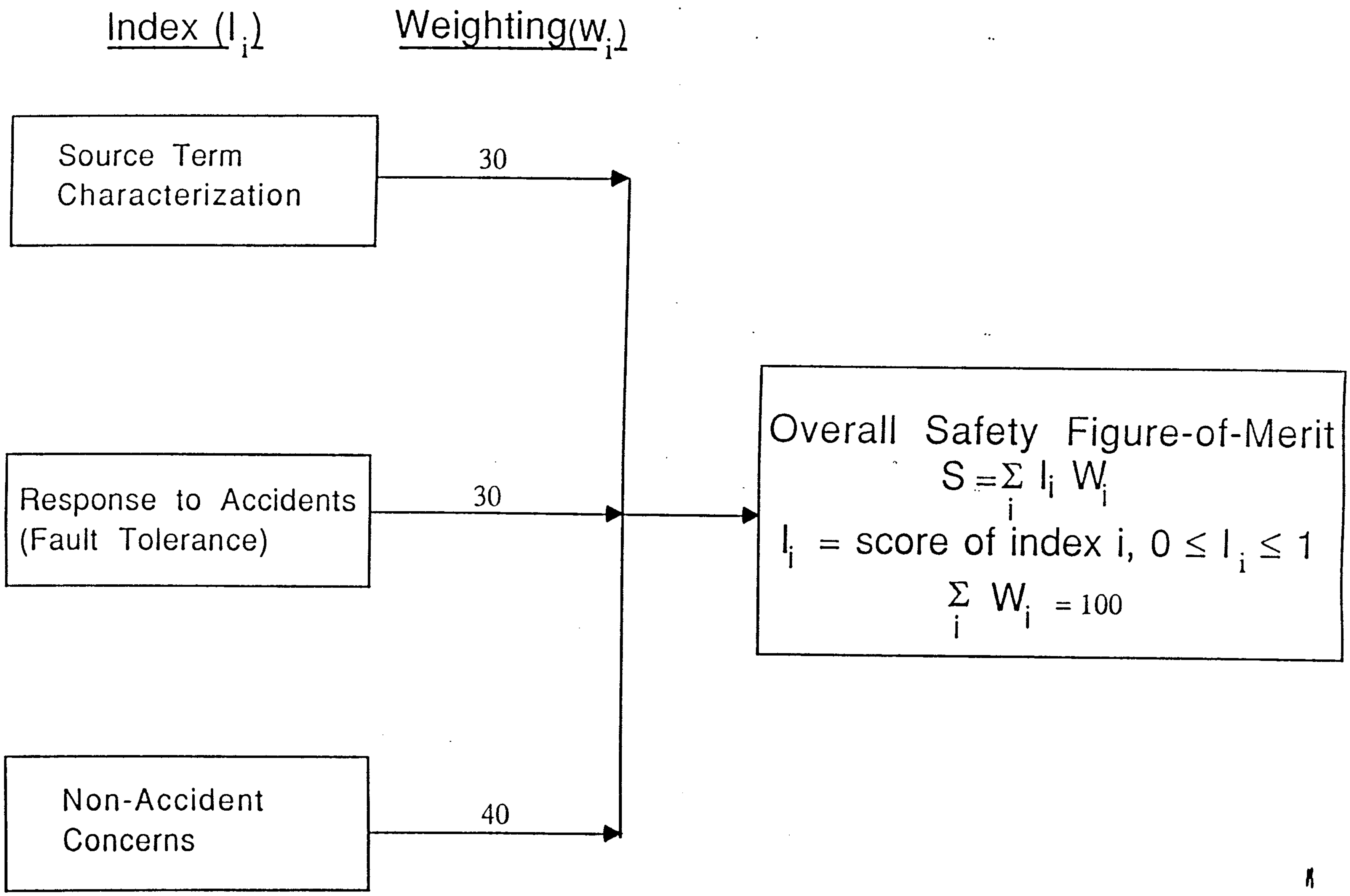


Fig. 7.2: Safety and Environment Evaluation Approach



Engineering Feasibility

Ability to Meet Design Goals (60%)

- Component Fabricability
- Subsystem Performance Goals
  - -Cavity
  - -Driver
  - -Target
  - -etc.
- Tritium Self Sufficiency
- Reliability Goals
- Maintainability
- Lifetime Goals
- Cost Projections

Ultimate Potential (40%)

- Potential for inherent safety
- Potential for low long-term activation
- Engineering Simplicity
- Operating Requirements
- Potential for enhanced energy conversion efficiency

Evaluation Methodology for R&D Requirements

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

- R_c = figure of merit for Cost

  Cost
  -average annual operating cost
  -capital cost of required facilities
  (new or upgrades)

- R_t = Figure of merit for Time

  Time = total time to complete the R&D

- R_r = Figure of merit for Risk

  measure of relative risk in not successfully resolving key issues weighed by the potential consequence of negative results

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