TABLE OF CONTENTS – CHAPTER 2

CHAPTER 2
STUDY OVERVIEW

This chapter provides a brief overview of the basis for and the results of the two IFE conceptual design studies of commercial central station power plants conducted for the Department of Energy, Office of Energy Research.

2.1 Introduction

In late 1990, the Department of Energy, Office of Energy Research, awarded a contract to McDonnell Douglas Aerospace (MDA) and its team of subcontractors to develop two inertial fusion energy conceptual designs of commercial central station power plants. Two different drivers were selected by the MDA contract team during the proposal period; namely, a KrF excimer laser and a heavy ion induction LINAC. The conceptual design effort included the defintion and optimization of the driver system, reactor system, target factory, balance of plant systems, and plant facilities.

In addition to the design study contract awarded to the MDA team, a second and parallel design study with the same objectives was awarded to a design team headed by W. J. Schafer Associates (WJSA). The WJSA team also chose the same set of drivers as the basis for their reactor power plant designs.

To assure comparable designs and a degree of normalization of physics, technology, and economics, DOE commissioned an Oversight Committee. The Committee established common groundrules and guidelines for the two study teams. All studies were to be unclassified with wide distribution to the fusion community. Since inertial fusion has evolved from the classified arena of Defense Programs, much of the target data and target interactions with the drivers and reactor cavities are sensitive in nature. To accomplish the objective of an unclassified study, DOE formed a Target Working Group (TWG) to assemble unclassified parametric data for use by the teams as common design data and groundrules. A kickoff meeting for the two design teams was held to introduce the guidelines. Frequent technical interchange with the Oversight Committee and the Target Working Group refined the guideline data. A supplement of the guideline document was issued to help answer some questions. Chapter 3 summarizes these provided guidelines. Members of the Oversight Committee and the Target Working group also attended the regular project design review meetings and provided helpful technical critiques and guidance.

A brief description of the statement of work may assist the reader in understanding the presentation style of the report and the data contained within the report. There are six main project tasks in addition to tasks associated with regular meetings and reports. These are:

- Establish project groundrules, requirements, and criteria sufficient to meet the intent of comparability and provide design guidance to the team.
- Develop a systems code to help select and design major system and subsystem options and determine specific design points for the design teams to begin the detailed design process. This code would also be used to conduct system level parametric trade studies.
- Develop conceptual engineering designs for the KrF and the heavy ion beam drivers and the inertial fusion power reactors and establish descriptions of the support facilities, plant systems, and major components.
- Prepare capital and operating cost estimates and the projected cost of electricity for the two power plants.
- Identify and analyze the major technical issues confronting the two designs and the associated research and development needs for the two systems.
- Evaluate and compare the two IFE plant designs to each other.

This Study Overview chapter is a brief synopsis of the entire study and its results. At the end of this chapter, a section will discuss the conclusions to be drawn from this study.

2.2 Key Objectives, Requirements, and Assumptions

The primary objective of the Prometheus study is to develop two conceptual designs for commercial fusion electrical power plants based on inertial confinement; one with the KrF laser driver (Prometheus-L) and the other with the heavy ion beam driver (Prometheus-H). In addition, the study has emphasized the following goals: (1) advancement of the state-of-the-art in IFE power plant design; (2) improvements in physics and engineering credibility and enhancement of potential economic, safety, and environmental attractiveness of IFE reactor power plants; (3) identification and characterization of key technical issues and the R&D required to resolve them; and (4) comparison of the two IFE reactor design concepts.

A set of requirements and guidelines was developed from the onset of the project to help meet the above objectives and goals. The requirements and guidelines were developed partly by an oversight committee, particularly in areas related to targets and target-driver coupling, and partly by the study management. Details of the study requirements, guidelines and assumptions are presented in Chapter 3 and are briefly summarized below.

- The IFE plant is to serve as a commercial central station electric power plant; the only product is electricity.
- The reactor is operated on the deuterium-tritium fuel cycle; fuel self-sufficiency conditions in a mature power economy must be satisfied.
- The net electric power output is 1000 MW.

- The data base of physics, technology and economics will be extrapolated by about 30-40 years.
- The design is for tenth-of-a-kind commercial power plant.
- The plant lifetime is 40 years for engineering design and 30 years for economic analysis.
- The study should perform and document tradeoff studies for key design choices.
- The study is to focus on key IFE reactor components such as target, driver, cavity, and fuel cycle. Effort on balance-of-plant should be limited.
- Safety and environmental aspects of the design should be emphasized.
- Target factory is on site.

Target and Driver Guidelines - The Oversight Committee and the Target Working Group (TWG) provided the study with specific guidelines and information regarding the target and driver. Examples of these are the yield versus driver energy for direct- and indirect-drive targets with KrF and heavy ion beams, illumination uniformity requirements, and requirements on power balance and beam alignment. The details of such guidelines and information are given in Chapter 3. Because this information is specific and spans several areas, no summary is given here.

2.3 Systems Modeling and Trade Studies

Optimization of an inertial fusion power plant involves trade studies of several major systems including reactor plant, driver plant, target plant, and balance of plant. The rationale for choosing between design options for these major systems and for selecting an operating point for a given set of options involves complicated trade-offs between many issues including economics, safety, engineering feasibility, technical risk, etc. In many instances, design choices can be made without considering how they might impact the overall system performance. However it often is useful (and sometimes essential) to consider an overall figure of merit when selecting design options. The Inertial COnfinement systems performance and COst MOdel (ICCOMO) was updated to assist the design process for this study. This code has evolved over many years. The models were originally developed as part of the STARFIRE reactor design study.[1] Later they were adapted to IFE as part of the HIFSA project.[2] The code contains parametric scaling and cost models for all major fusion power plant subsystems and design options, and as such, it evolved along with the design. It includes both KrF laser and heavy ion LINAC drivers, reactor cavity systems, and main heat transport systems, target energetics and manufacturing plant, fuel stream and waste processing, and all remaining balance-of-plant systems.

The IFE power plant performance is directly tied to the product of the driver efficiency, η, and the target gain, G, at a given driver energy. The basis for this is illustrated by the simple power flow diagram shown in Figure 2.3-1. Economic power generation requires that ηG exceed $1 / \varepsilon M'$, where ε is the plant thermal efficiency and M' the

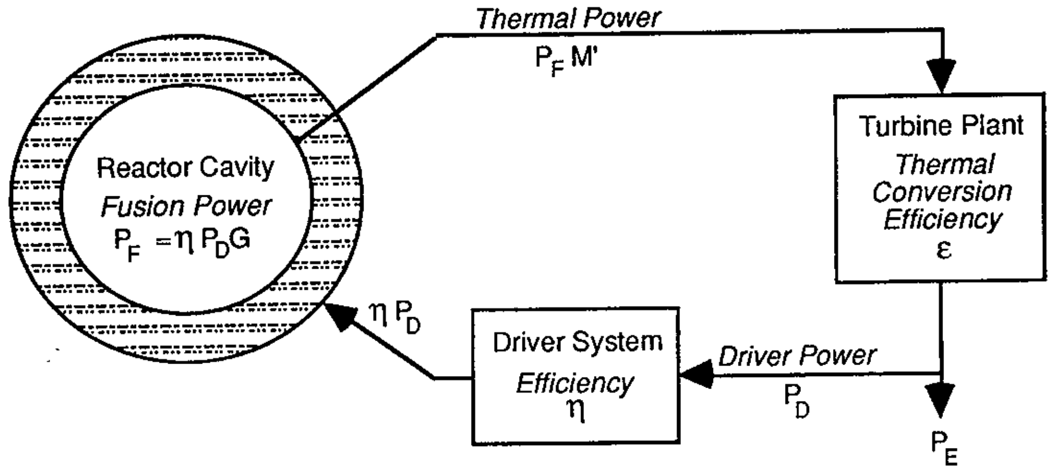

Figure 2.3-1. Simple Power Flow Diagram for an Inertial Fusion Power Plant

effective blanket power multiplication, typically by a factor of two or more. Advanced thermal conversion efficiencies of 40% and effective blanket multiplications of 1.1 thus imply a minimum ηG of ~6 for economic power generation. A 6% efficient driver requires target gain greater than 100. If the driver efficiency improves to 20%, a gain greater than 30 will suffice.

The systems modeling provides a basis for deciding how large an ηG is economically warranted. The target gain curves provided for this study are shown in Figure 2.3-2 for the KrF laser and heavy ion beam drivers. The constant focal spot (CS) gain curve is the TWG-recommended arithmetic mean of the Optimistic Gain curve and the Conservative Gain curve provided (see Figure 3.3-2 and the related discussion for details). These figures show that target gain typically increases with driver energy. This improves ηG, but implies a more costly driver. For a fixed-size plant, however, there can be a net cost savings because the driver is pulsed less frequently and therefore requires less input power. The size, hence cost, of the supporting plant equipment (reactor, steam generators, turbines, etc.) is thus reduced. The systems code quantifies this trade-off by parametrically modeling the size and cost of all major power plant systems. Incremental driver cost can then be weighed against the cost savings provided by higher target gain to determine the optimum size driver for the anticipated target gain curves.

The trade studies were also valuable in choosing between design options for some subsystems. This was particularly true for the heavy ion driver where the single beam LINAC was compared to a more conventional multiple beam system. This comparison involved a complex tradeoff between driver efficiency, which favored the multiple beam approach, and driver cost, which favored the single beam. The systems code quantified this trade and led to the selection of a single beam LINAC with storage rings for the baseline Prometheus-H driver concept. Finally, the systems code was useful in assessing the sensitivity of overall system performance to changes in key system performance assumptions. Cases were run at the minimum and maximum expected

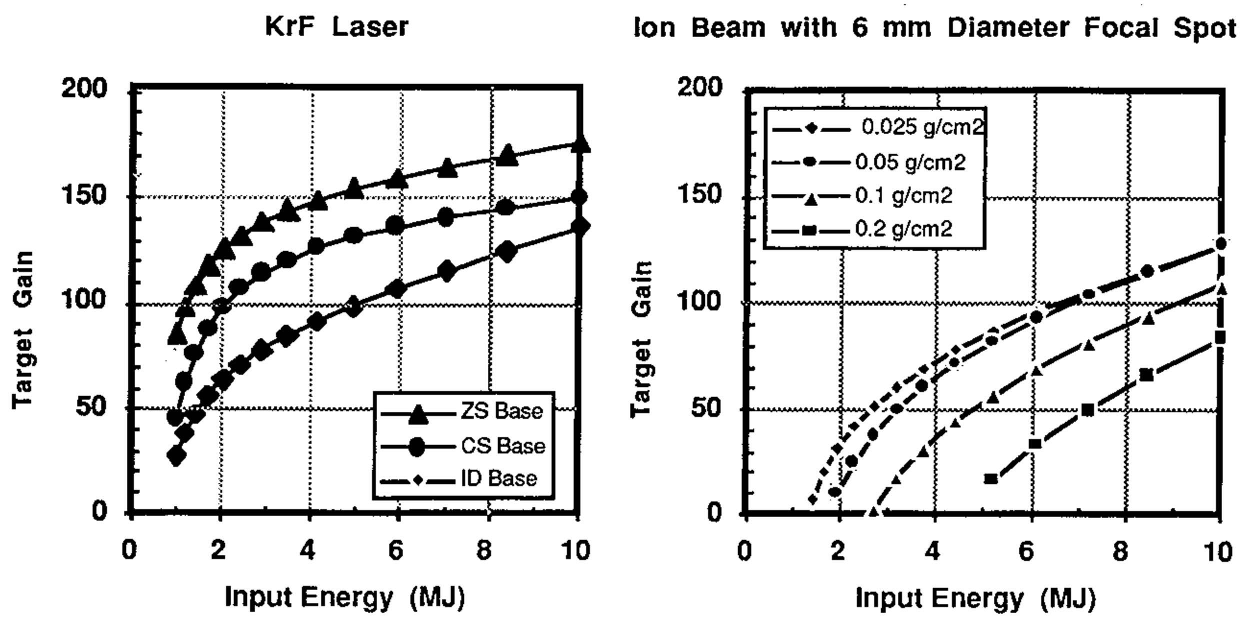

Figure 2.3-2. Comparison of Baseline Gain Curves for KrF Laser and Heavy Ion Systems. Laser Curves are for Direct Drive (Zoomed and Constant Focal Spot) and Indirect Drive Targets. Heavy Ion Curves Show Variation with Ion Range.

range of key parameters. These studies help provide a measure of the relative importance of research and development work in various areas.

2.3.1 Prometheus-L Design Point Selection - Figure 2.3.1-1 compares projected system performance for the three baseline laser target gain curve options. This figure highlights the strong preference for direct drive option predicted by the baseline gain curves provided for this study. The minimum cost of electricity is ~10% higher for indirect drive and the requisite driver energy increases from 4 to 6 MJ. The driver is thus more complex (2160 discharge lasers as compared to 960 for the direct drive case) and costly (~$250M). This is a direct result of the ηG penalty for the baseline indirect-drive gain curve. For the projected Prometheus-L driver efficiency of 6.5%, the 4 MJ direct drive system has an ηG of 8.2 compared to only 7.0 for the 6 MJ indirect drive case. Illumination symmetry requirements complicate the reactor plant design for direct drive, however the detailed design analyses led to the conclusion that for 60 beams, the cost implications of direct drive illumination are not significant. This was further reinforced by TWG guidance that indirect drive illumination, while not symmetric, would also require roughly 60 beams arrayed on two 60° half-angle cones. Direct drive targets were thus selected for the Prometheus-L system design.

Figure 2.3.1-1 also highlights the basis for selecting a 4 MJ driver energy. The COE is relatively flat between 3 and 5 MJ; however, the number of discharge lasers jumps from 960 to 2160 at 5 MJ in order to keep their output energy below 6 kJ that was selected as an upper limit on discharge laser technology. This complicates the driver design for no performance payoff. Conversely, at 3 MJ the same 960 discharge lasers

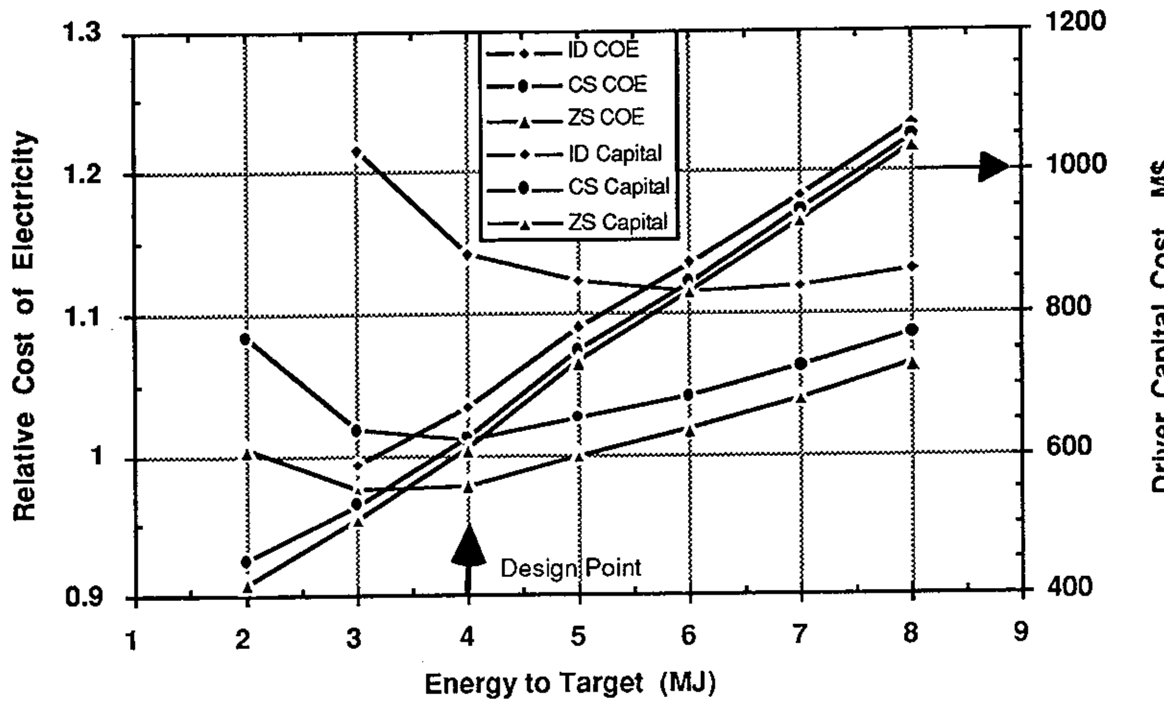

Figure 2.3.1-1. System Performance Comparison for the Three Laser System Target Options Using Baseline Gain Curves. Solid Curves Show COE, Dashed Curves Show Driver Capital Cost.

need only produce 4.4 kJ as compared to 5.9 kJ at 4 MJ. This is attractive from a laser design standpoint, but the pulse repetition rate increases from 5.6 pps to 8.2 pps at 3 MJ. This repetition rate does not provide sufficient cavity clearing time between pulses for the 3 mtorr laser pressure requirement. As a result, a 4 MJ driver energy was selected for the Prometheus-L design point.

The possibility of zooming the focal spot to improve target gain as suggested by the TWG was also considered. To assess the attractiveness of this possibility, the trade study shown in Figure 2.3.1-1 was conducted assuming no added driver cost to provide for zooming. The result of this study shows that a zoomed focal spot potentially leads to ~3% lower COE. For the Prometheus NLO laser architecture, the only viable way to zoom the focus involves modifying the rf-driven frequency chirpers for the SBS cells to enable them to introduce a time-varying wavefront curvature. This requires an annular rf field variation around the chirper that significantly complicates its design and would add to the capital cost. The benefit of focal spot zooming was deemed not sufficient to warrant this added complexity.

The results of the Prometheus-L sensitivity studies of the major parameters are highlighted in Figure 2.3.1-2. The data displayed in the figure is summarized in Table 2.3.1-1 together with the parameters that were varied and their range of variation. The adopted baseline gain curve was recommended by the TWG as the mean of the provided Optmistic and the Conservative Gain curves. Hence, these two were used as the maximum and miniumum gain curve values. This figure shows that COE depends most strongly on the gain curve assumption and the discharge laser intrinsic efficiency. The projected COE is 10% higher at the minimum value considered for these two parameters and drops 5% below the baseline value at their upper limit. These are sensitive parameters because there is very little ηG margin for the KrF laser driver since the overall efficiency is only 6.5%.

Table 2.3.1-1. COE Sensitivity to Variations in Key Prometheus-L Design Parameters

Parameter	Baseline Value	Minimum Value	Change in COE (%)	Maximum Value	Change in COE (%)
Gain Curve (Conservative, Optimum)	126	86	+10.6	165	-4.8
Laser Intrinsic Efficiency (%)	15	10	+10.3	20	-4.7
Optical Damage Limit (J/cm^2)	10	5	+3.2	15	-1.1
Num Dischg Lasers, Energy (kJ)	960, 6	240, 20	+0.6	2160, 2	+0.3
Number Final Beamlines	60	30	-1.7	90	+1.7
Cavity Radius (m)	5	4.5	-2.2	5.5	+2.3

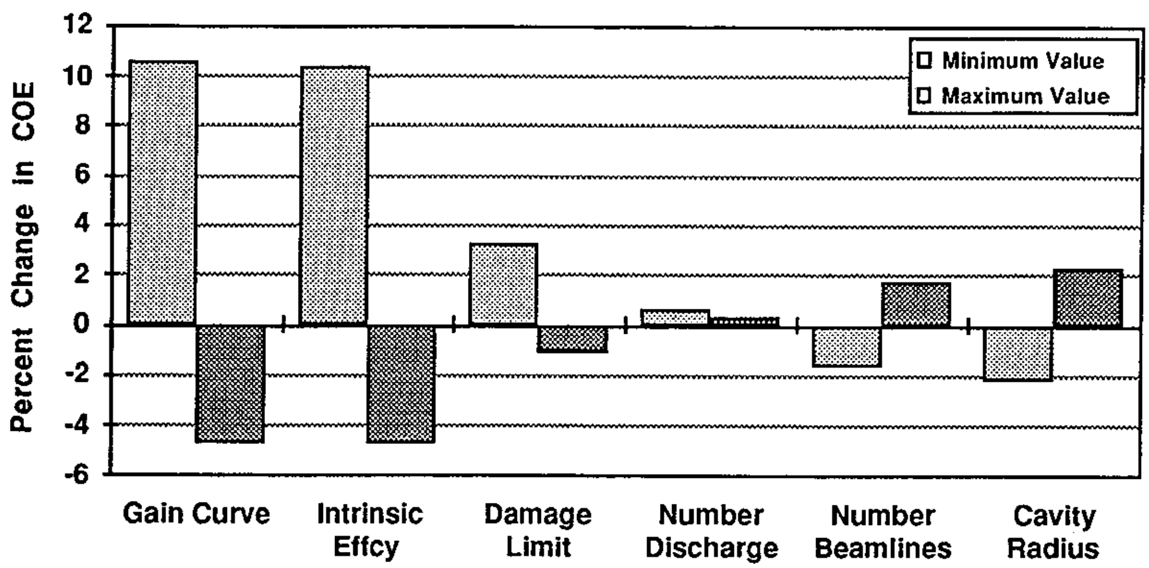

Figure 2.3.1-2. COE Sensitivity to Prometheus-L Design and Performance Assumptions

Sensitivity to optical damage limit shows that lowering it to 5 J/cm^2 causes a 3% increase in COE, while raising it to 15 J/cm^2 only decreases COE by 1%. There is thus little incentive to improve optical coatings beyond the 10 J/cm^2 point and this is why a 10 J/cm^2 fluence limit was adopted for the present study. Studies of discharge laser output power show that COE is virtually independent of this parameter even though the number of discharge lasers varies from 2160 down to 240. This is because the lasers are producing the same amount of total energy (4 MJ) in either case. Hence, the pulsed power energy requirement is the same and it is the major cost contributor. Finally, a decrease in the number of beamlines from 60 to 30 or a reduction in cavity radius from 5 to 4.5 m would each lower COE by 2%. Conversely, COE would increase by 2% for 90 beamlines or if a 5.5 m cavity radius was needed to lower cavity vapor pressure.

2.3.2 Prometheus-H Design Point Selection - The primary issue for the heavy ion beam system design trade studies involved the choice between a multiple beam LINAC and the single beam system with intermediate storage rings. The parametric scaling and cost basis for this comparison is discussed in detail in Section 4.1.2, but the result is repeated in Figure 2.3.2-1. This comparison uses lattice scaling suggested by Ed Lee[3], since it was thought to be most favorable for multiple beam systems. The final single beam design uses an alternative lattice scaling discussed in Section 6.2 that leads to lower capital cost and higher single beam efficiencies than those presented here. Nevertheless, this figure still highlights the significant advantage projected for the single-beam approach in spite of its lower efficiency, 15% as compared to 37% for the multiple beam. Driver capital costs are roughly half those for the multiple beam system and this leads to a 12% reduction in COE. The single beam system was, therefore, selected for the baseline driver in the Prometheus-H design study.

It should be noted, however, that the multiple-beam system remains a viable driver option. Its COE is comparable to that for the KrF laser system, and the alternative transport lattice scaling discussed in Section 6.2 also leads to significantly lower MB capital costs than those presented here. In addition it avoids technical issues associated with beam stability and particle loss in the storage rings. These are critical R&D concerns for the single beam approach and they are highlighted in Section 5.

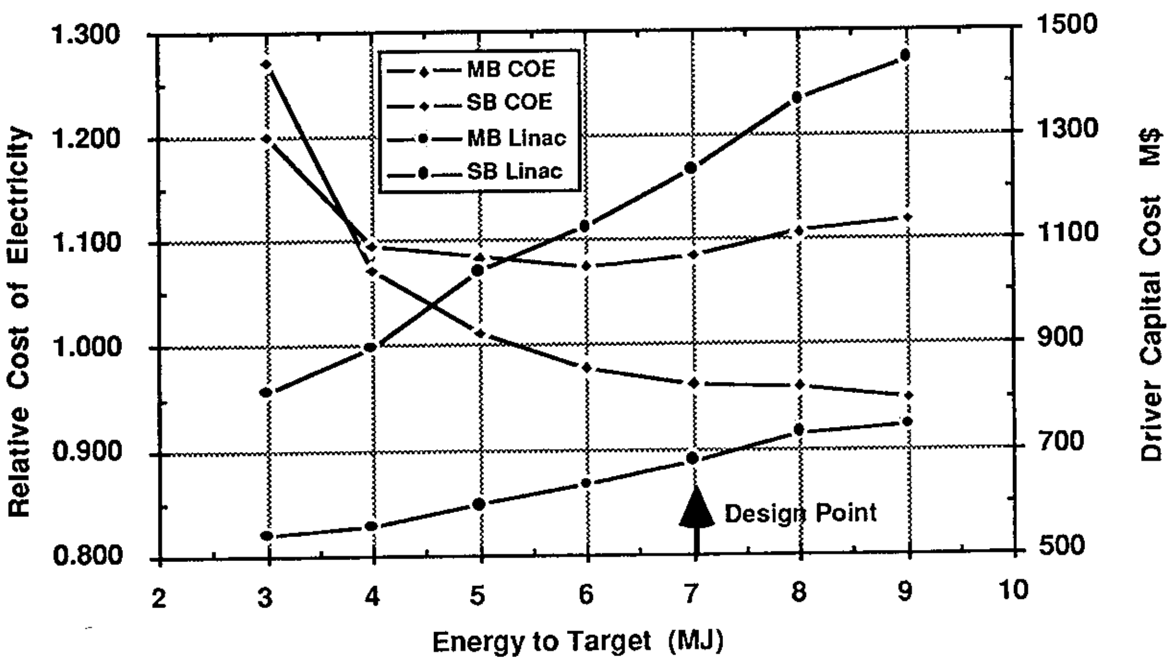

Figure 2.3.2-1. Comparison of Projected COE and Driver Capital Cost for Multiple and Single Beam LINACs. Systems are all 4 GeV, +2 Lead with 3 mm Radius Focal Spot.

A number of other significant design parameters, such as ion range, ion type/charge, spot size, illumination, ion energy, and incident beam energy, were evaluated in arriving at the reactor and HI beam driver design point. Section 6.2.2 discusses these factors and trade studies in detail. However the trade study to determine the incident beam energy on the target is worthy of discussion here. Figure 2.3.2-1 illustrates that the COE continues to decrease, with increasing energy delivered to the target although the gains above 7 MJ are becoming increasingly small. The cost of the driver continue to increase above this level. And as the energy increases, the gain curves indicate a continued improvement in the utilization of the energy within the target. This effect causes the lowering of the COE regardless of the capital cost increases. The increase in incident energy comes at the expense of more beamlets and magnet quads in the accelerator system, hence more complexity and risk. It was felt that pushing the design point past 7 MJ on target (7.8 MJ out of the driver) would represent a significant developmental risk for the driver system and entail significant technical risk with declining economic benefits. Further driver development may allow this design envelope to extend to higher energy levels on target at a future date.

The results of the Prometheus-H sensitivity studies are highlighted in Figure 2.3.2-2. The data displayed in the figure is summarized in Table 2.3.2-1 together with the parameters that were varied and their range of variation. These results highlight several key aspects of the Prometheus-H driver design. The primary one involves the improved cost and performance characteristics provided by the reduced ion kinetic energy. As is indicated, COE is 18% higher for a 7 GeV design due to the increased length of accelerator required at this energy. The number of beamlets is reduced from 18 to 6 at 7 GeV, but the single beam approach, coupled with the alternate transport scaling, eliminates most of the complication (hence cost) of added beamlets at 4 GeV. The results also indicate that there is little motivation to further reduce ion energy. COE is 3% lower at 3 GeV but 32 beamlets are required at this energy which complicates the final transport and lowers driver efficiency by 13%.

It is worthwhile here to note that the alternative lattice transport scaling really opens a more attractive heavy ion LINAC design window that previously was not accessible due to the large number of required beamlets. This can be understood by referring to the gain curves shown in Figure 2.3-2. The gain falls off rapidly for ion energies above 5 GeV and is almost a factor of 2 lower for the 10 GeV ions typically proposed in the past. In addition, lower energy ions are much less sensitive to variations in focal spot size. The results show that a 7 GeV system is twice as sensitive to spot size variations as the 4 GeV design point. This is important because it minimizes the effect that the poorly understood transport channel reimaging properties may have on system performance.

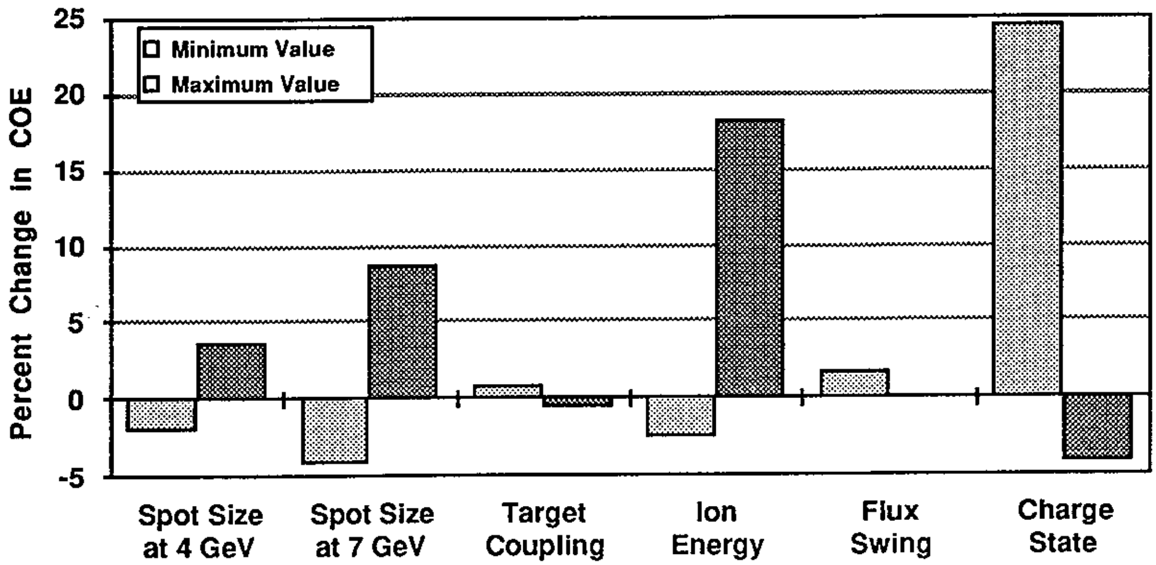

Figure 2.3.2-2. COE Sensitivity to Prometheus-H Design and Performance Assumptions

Table 2.3.2-1. COE Sensitivity to Variations in Key Prometheus-H Design Parameters

Parameter	Baseline Value	Minimum Value	Change in COE, Effcy*	Maximum Value	Change in COE, Effcy*
Focal Spot Radius (mm)	3	2	-2.1	4	+3.6
Spot Radius Change at 7 GeV**	3	2	-4.3	4	+8.6
Final Beam Transport Effcny (%)	90	80	+0.8	100	-0.6
Ion Kinetic Energy (GeV)	4	3	-2.7, -13.0	7	+18.2, +21.4
Core Flux Swing (T)	1.5	1.0	+1.7, +8.4	2.0	+0.1, -9.3
Ion Charge State	+2	+1	+24.5, +2.8	+3	-4.2, -4.4

* Change in driver efficiency is indicated only for parameters that influence it significantly

** Changes are normalized to 7 GeV system with 3 mm radius spot which is 18% higher than 4 GeV COE

Insensitivity to transport channel properties are reinforced by the weak COE dependence on final beam transport efficiency (beam energy loss in the transport channel). A doubling of energy loss (from 10 to 20%) only increases COE by 1%. The results also indicate very weak COE dependence on Metglas flux swing. A low flux swing of 1.5 T was selected for the baseline design to reduce induction core energy losses since this was thought to be a key factor in the design of a single beam LINAC where the cores are recycled several times per pulse. Indeed, the driver efficiency changes by ± 9% as flux swing is varied from 1 to 2 T, however this causes only a 1% change in COE.

Finally, the results highlight that there is still a significant advantage to higher charge states for the single beam system, but that the payoff is limited beyond +2. The cost of electricity is 24% higher for singly charged ions while it drops by 4% for charge state 3. Unfortunately, the number of beamlets increases to 36 for +3 ions that may offset the indicated cost advantage once the engineering details of final transport and focusing are evaluated.

In spite of concerns about beam stability in the storage rings, the Prometheus-H design point represents a tantalizing development goal for heavy-ion drivers. This is underscored by Table 2.3.2-2 that compares the projected Prometheus-L driver costs with those for a 4 GeV, 7 MJ multiple beam driver design using the Lee lattice scaling[3] that was the starting point for this design study. This comparison highlights the potential advantages of the configuration. The single beam accelerator column reduces accelerator structure costs by $200M and focusing magnet costs by $320M. In addition, the alternate transport lattice scaling reduces the number of beamlets from 34 to 18; that leads to cost savings of $120M in the final transport and focus sections. Pulsed power costs are assumed to be ten times those for the MB system per joule, but the overall SB pulsed power cost is only $20M higher because the system only provides energy for one beamlet at a time. All of these savings are at the expense of a stack of 14 storage rings that are projected to cost ~$20M.

The net result is a $700M reduction in projected cost and a significant simplification in required LINAC technology development. It should be noted that this comparison is not entirely fair because the MB system would not have considered a design at 4 GeV due to the large number of required beamlets. However, this raises another important point, namely that the proposed design has extended the heavy-ion LINAC design window to a more attractive region of parameter space. The 4 GeV ion energy provides improved target performance due to the reduced range at this energy, and it reduces LINAC costs because it corresponds to a shorter accelerator. Significant issues need to be resolved concerning the storage rings, but the starting point is much more appealing than any previously envisioned for induction LINAC drivers.

Table 2.3.2-2. Projected Single and Multiple Beam LINAC Cost Comparison for 4 GeV, 7 MJ Drivers

Component	SB Cost (M$)	MB Cost (M$)
Injector System	10.0	40.0
Accelerator Structure	100.5	292.4
Focusing Magnets	61.4	387.6
Cryogenic System	12.3	18.2
Storage Rings	18.5	0.0
Final Transport	76.2	194.1
Pulsed Power	214.1	194.4
Vacuum System	13.7	13
Instrum & Control	27.0	58.5
Maint Equipment	33.1	33.1
Misc Equipment	10.8	23.4
Tunnel and PFN Bldg	38.3	49.8
Total System Cost	615.9	1304.5

Note: These costs are for a first production unit, not tenth of a kind.
SB = Single Beam, MB = Multiple Beam, PFN = Pulse Forming Network.

References for 2.3

1. C.C. Baker, et al., "STARFIRE - A Commercial Tokamak Fusion Power Plant Study," ANL/FPP-80-1 (1980).

2. February 1988 special issue, *Fusion Technology,* **13**, 2 (1988).

3. Dr. Edward Lee, Lawrence Berkeley Laboratory, Private Communication.