FUSION TECHNOLOGY 1992
C. Ferro, M. Gasparotto, H. Knoepfel (editors)

# PROMETHEUS DESIGNS FOR LASER-DRIVEN AND HEAVY-ION-DRIVEN FUSION REACTORS

Mohamed A. Abdou[1], Lester Waganer[2]

[1]University of California, Los Angeles, 405 Hilgard Avenue, Los Angeles, Ca 90024
[2]McDonnell Douglas Missile Systems Company, St. Louis, MO 63166

## Abstract

A comprehensive system analysis and reactor design study of inertial fusion commercial power reactors has been completed. The study developed two complete conceptual designs, one for a laser-driven (PROMETHEUS-L) and the other for heavy-ion-driven (PROMETHEUS-H) reactor. The critical technical issues have been identified and analyzed and the R&D needs to resolve these issues have been characterized. Both reactor power plants produce 1000 MW of electric power. The two reactor design features and parameters were selected based on system and tradeoff studies to minimize cost of energy and to enhance safety and environmental features. For PROMETHEUS-L, a direct drive target was selected because of higher gain with an optimum driver energy of 4 MJ delivered in 60 beamlines at a 5.6 HZ repetition rate. PROMETHEUS-H has indirect drive target with 7.8 MJ of heavy ion energy at a repetition rate of 3.5 HZ. Novel concepts for both laser and heavy ion drivers have been investigated and are shown to greatly increase the potential attractiveness of IFE reactors. The PROMETHEUS power plants can be classified as totally passively safe (LSA = 1 in ESECOM study classification). Careful selection of materials, e.g. SiC, has made PROMETHEUS waste disposal meet Class C requirements or better. An evaluation methodology has also been developed and applied to compare the laser- driven and heavy-ion-driven reactors.

## 1. Introduction

A comprehensive system analysis and reactor design study[1] of inertial fusion reactors was conducted by a team of industry and universities in the U.S.A. Two conceptual designs were developed, one is laser-driven, called PROMETHEUS-L, and the other is heavy-ion-driven, called PROMETHEUS-H. The study was supported by the U.S. Department of Energy. An oversight committee established ground rules and guidelines for the study. Since the study is unclassified while much of the target-related data is classified, a Target Working Group (TWG) consisting of experts in this area provided unclassified parametric data for the target and target interaction to the study team.

In addition to developing the two conceptual reactor designs the study has emphasized the following goals: 1) advancement of the state of the art in inertial fusion energy (IFE) power plant design, 2) improvements in physics and engineering credibility and enhancement of potential economic, safety, and environmental attractiveness of IFE reactors, 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 detailed description of the study results is given in reference 1. In this paper, we briefly highlight some of the results of the study.

## 2. PROMETHEUS-L Design Point Selection

The TWG provided the study with the target gain (G) curves shown in Figure 1. Figure 2 compares projected system performance for the three baseline laser target gain curve options. This figure highlights the strong preference for direct drive 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 $\eta G$ penalty ($\eta$ is driver overall efficiency and G is target gain) 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 $\eta G$ 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. Direct drive targets were thus selected for the PROMETHEUS-L system design.

Figure 2 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 which 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 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

Table 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 (Conspot, Optm) | 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 |

Table 2. 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 |
| Target Energy Coupling (%) | 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 3mm spot which is 18% higher than 4 GeV COE

for the 3 mTorr laser pressure requirement. As a result, a 4 MJ driver energy was selected for the PROMETHEUS-L design point.

The results of the PROMETHEUS-L sensitivity studies are highlighted in Figure 3. The data displayed in the figure are summarized in Table 1 together with the parameters which were varied and their range of variation. 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 $\eta G$ margin for the KrF laser driver since the overall efficiency is only 6.5%.

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.

## 3. PROMETHEUS-H Design Point Selection

The primary issue for the heavy ion 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 reference. 1, but the result is summarized in Figure 4. This figure 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.

The results of the PROMETHEUS-H sensitivity studies are highlighted in Figure 5. The data displayed in the figure are summarized in Table 2 together with the parameters which 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 from18 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%.

Insensitivity to transport channel properties is reinforced by the weak COE dependence on target coupling 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 dependance 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.

## 4. PROMETHEUS-L Reactor Plant Design Overview

The PROMETHEUS-L power plant is a KrF excimer laser-driven commercial central station power plant. These designs are based upon an extrapolation of today's technology advanced some 20-30 years into the future. The necessary technology and engineering basis is assumed to have been developed previously. The design emphasizes safety, environmental attractiveness, economic competitiveness, soundness of physics and engineering data, and a high degree of reliability, maintainability, and availability.

The major PROMETHEUS-L design parameters are summarized in Table 3. The plant produces a net power output of 972 MWe to the electric grid from a total thermal power of 3,091 MWt, for a net system efficiency of 31%. The gross power of 1,382 MWe is derived from 3,264 MWt which is comprised of 3,049 MWt form the fusion power core and 215 MWt of waste heat from the driver and lead pumping systems. Thirty percent of the gross power supports in-plant requirements for the laser driver (342 MWe), auxiliary systems (36 MWe), and liquid lead pumping (25 MWe). Helium-flow through the blanket is provided by steam-driven circulators. The fusion core power results from a target yield of 497 MJ at a pulse repetition rate of 5.65 per second with a blanket energy multiplication factor of 1.14. The liquid lead first wall loop handles 1,267 MWt of this power with the remainder going to the blanket loop. The power in the first wall loop is significantly higher than the surface heating of 780 MWt due to neutron interactions in the lead coolant channels.

The reactor cavity radius and height of 5.0 and 15.0 m are determined from the need to conduct the surface heat energy through the first wall support structure into the coolant, with a surface temperature that enables the lead vapor pressure in the cavity to reach the level required for laser propagation without breakdown (~3 mTorr) before the next pulse. This is driven by the available surface area so the cavity is elongated slightly by inserting a one-radius high cylindrical section between the hemispherical ends. This shortens the recondensation time without introducing a large difference between the peak and average wall loading.

With the attention to selection of materials, innovative design approaches and careful design practices, PROMETHEUS-L is rated as a Level of Safety Assurance (LSA) = 1, which means safety is assured by passive mechanisms of release limitations no matter what the accident sequence. The radioactive inventories and materials in PROMETHEUS-L preclude a fatal release regardless of the reactor's condition. This definition is extracted form the ESECOM study[2]. The usage of low-activation materials, such as SiC, will allow all material disposal to be classed as Class C or better.

## 5. Reactor Cavity Features

The reactor cavity for the PROMETHEUS-L design includes the first wall system, blanket, coolant manifold, vacuum vessel, and shield. The main purpose of the cavity is to contain the radiation and blast effects from the inertial fusion reaction, transform that nuclear energy into a more useful form of energy, and to breed tritium for sustaining fuel supplies. Since the reactor cavity is exposed to a very harsh radiation environment, it is the component which would have the most impact on the safety and on environmental impact associated with the plant.

Table 3. PROMETHEUS -L Major Design Parameters and Features

| Parameters | PROMETHEUS - L |
|---|---|
| Net Electric Power (MWe) | 972 |
| Gross Electric Power (MWe) | 1382 |
| Driver Power (MWe) | 349 |
| Auxiliary Power (MWe) | 36 |
| Cavity Pumping Power | 25 |
| Total Thermal Cycle Power (MWt) | 3264 |
| Blanket Loop Power (MWt) | 1782 |
| Wall Protection Loop Power (MWt) | 1267 |
| Usable Driver Waste Heat (MWt) | 193 |
| Usable Pumping Waste Heat (MWt) | 22 |
| Thermal Conversion Efficiency | 42.3% |
| Recirculating Power Fraction | 30% |
| Net System Efficiency | 31% |
| Fusion Power (MW) | 2807 |
| Neutron Power (MW) | 2027 |
| Surface Heating Power (MW) | 780 |
| Thermal Power (MWt) | 3091 |
| Thermal Power to Shield (MWt) | 43 |
| Cavity Radius (m) | 5.0 |
| Cavity Height (m) | 15.0 |
| 1st Wall Protctn/Clnt Media (In/Out Temp., °C) | Liquid Lead (375/525) |
| Breeder Material | $Li_2O$ Pebbles |
| Structural Material, Wall and Blanket | SiC |
| Blanket Heat Transfer Media (In/Out Temp., °C) | 1.5 MPa Helium (400/650) |
| Cavity Pressure (mTorr, Pb) | 3.0 |
| Neutron Wall Load, Peak/Ave ($MW/m^2$) | 6.5/4.3 |
| Energy Multiplication Ratio | 1.14 |
| Tritium Breeding Ratio (TBR) | 1.20 |
| Target Illumination Scheme (Symmetric) | Direct Drive |
| Number of Beams | 60 |
| Driver Output Energy (MJ) | 4.0 |
| Type & No. of KrF Amplifiers | Electric Discharge, 960 |
| Beam Combining Technique | Raman Accumulators |
| Pulse Compression Technique | Stimulated Brillouin Scattering |
| Target Energy Coupling | 100% |
| Target Gain | 124 |
| Target Yield | 497 |
| Repetition Rate (pps) | 5.65 |
| Plant Availability (%) | 79.4 |
| Cost of Electricity (mills/kWh, 1991$) | 73.2 |

Safety and environmental impact played a significant role in the choices of material and the design approaches employed. Many concepts and materials were evaluated for inclusion. Silicon-carbide (SiC) composited material was chosen as the primary structural material for the first wall, blanket, and coolant piping. This material offers both low, long-term, and short-term activation which minimizes the waste disposal difficulties and provides low decay heat. Lead offers excellent heat transfer properties and neutron multiplication, although it has both toxicity and radioactivity concerns. Even with these concerns, it is thought to be superior to other liquid metals in the reactor cavity. A composite shield material is employed to lessen the activation in the bulk shield and the component shielding. A few applications require more traditional metals such as aluminium and steel and in those cases the alloys are tailored to reduce the activation properties.

A cylindrical cavity with the hemispherical ends was chosen to improve the maintainability of the reactor components. A wetted wall with a layer (0.5 mm) of liquid lead on the surface was chosen as the first wall protection scheme, shown in Figure 6. Rectangular coolant channels for the liquid lead cool the surface and bulk material. The composite SiC material is also graded in density with fully dense at the back face to 10% porosity at the front face. This porosity allows the lead to migrate from the coolant channels to the surface. A portion of the lead film is evaporated by the target explosion and is subsequently recondensed on the surface. A separate Pb film injector is used near the top of the cavity to establish and maintain a film in contact with the wall surface in that area. The lead coolant is introduced at the top of the cavity and it flows downward to the bottom of the cavity.

The lead coolant channels are also sized at 50 mm to help provide good neutron multiplication. The thickness of SiC behind the liquid film is 5 mm to assist heat conduction into the coolant flow. The heat deposited in the first wall system is 1,267 MWt which is over 40% of the generated thermal power. The mass flow rate is 54,422 kg/s with an inlet bulk temperature of 375°C and an outlet bulk temperature of 525°C.

The recondensation of the lead on the first wall surface is the primary mechanism providing vacuum pumping in the cavity. The surface temperature of the lead determines the vapor pressure of the lead in the cavity. With a repetition rate of 5.6Hz, it is calculated that the base pressure of the cavity will be 3 mTorr.

The expected lifetime of the first wall panel has been estimated in the range of five years. This is primarily due to radiation damage in the SiC and to surface damage and fatigue caused by the pulsed operation. The blanket modules are attached to the front face of the blankets. The blanket region is directly behind the first wall systems. The chosen design builds upon the existing data and design base developed by MFE. The general blanket arrangement is shown in Figure 7. The structural material is SiC composite material serving all the structural functions including coolant tubes, pebble bed container, outer blanket module wall, reflector region and coolant plenum. Helium at 1.5 MPa is the coolant media extracting heat from the blanket region. The tritium is bred in a $Li_2O$ pebble bed breeding zone. A low pressure helium gas removes the tritium gas for processing.

## References

1. L. Waganer et. al., Inertial Fusion Energy Reactor Design Studies: PROMETHEUS-L and PROMETHEUS-H, McDonnell Douglas Company Report, March 1992.

2. J.P. Holdren, Chair, et. al., Report of the Senior Committee on Environmental, Safety, and Economic Aspects of Magnetic Fusion Energy, UCRL-53766, 25 September 1989.

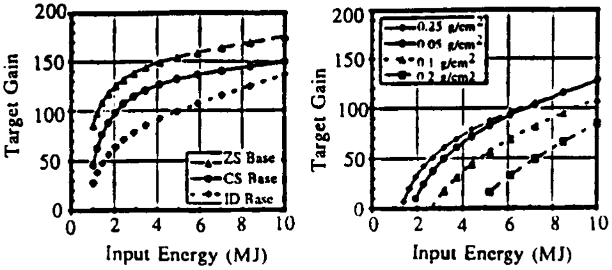

Figure 1. Comparison of Baseline Gain Curves for Krf Laser and Heavy Ion Systems. Laser Curves are for Direct Drive (Zoomed and Constant Focal Spot) and Indirect Drive Targets. Heavy Ion Curves Show Variation with Ion Range.

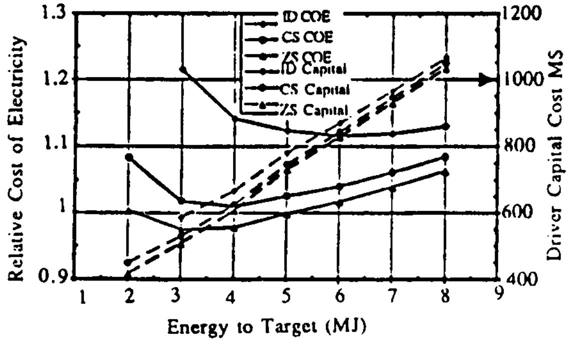

Figure 2. System Performance Comparison for the Three Laser System Target Options Using Baseline Gain Curves. Solid Curves Show COE, Dashed Curves Show Driver Capital Cost.

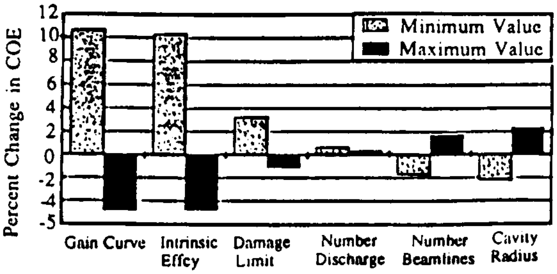

Figure 3. Sensitivity of Design Point COE to Variation in System Performance Assumptions.

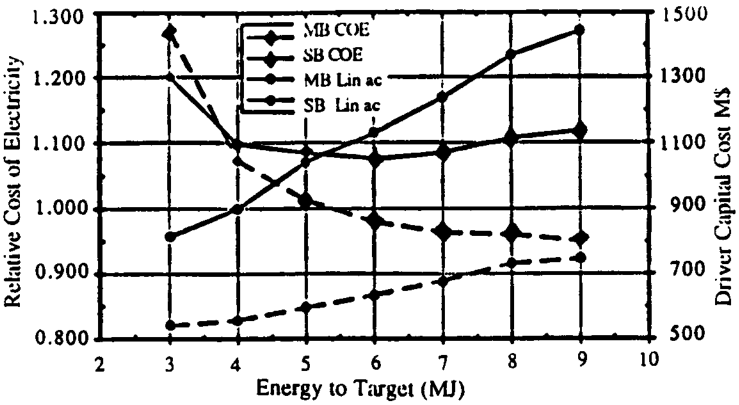

Figure 4. Comparison of Projected COE and Driver Capital Cost for Multiple and Single Beam Linacs. Systems are all GeV, +2 Lead with 3mm Focal Spot.

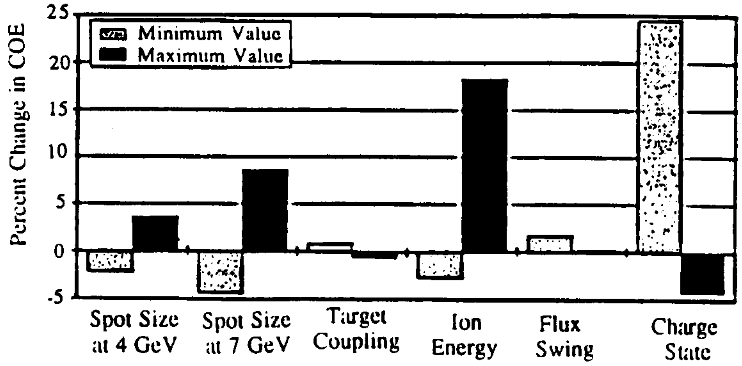

Figure 5. Design Point Sensitivity to Variations in Key System Design Assumptions.

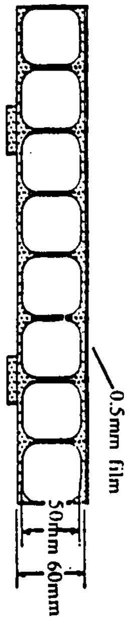

Figure 6. First Wall Panel; Cross Sectional View.

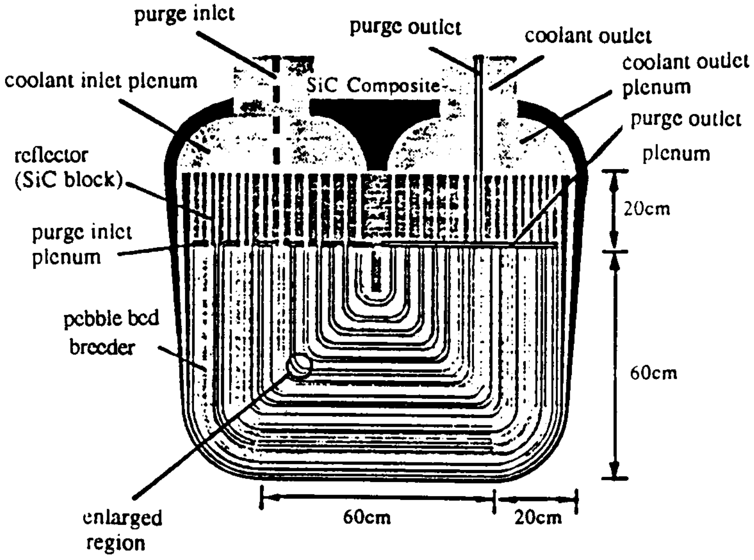

Figure 7. Schematic of a Blanket Module.