

EXECUTIVE SUMMARY

This report addresses the conceptual design and analysis of two commercial central station electric power plants. These plants use Inertial Fusion Energy (IFE) technologies employing the latest advances in KrF excimer laser and heavy ion drivers. These two drivers are integrated with an advanced reactor cavity concept to offer power plants with the highest level of safety assurance and low environmental impact. Advanced thermal conversion systems yield highly efficient plants capable of high reliability and capacity. Current target technologies are extrapolated in both performance and manufacturing capabilities. Fuel cycle systems are built upon a solid foundation of existing IFE technologies. The two power plant designs represent a wealth of information to help assess and develop a strategy and development plan for a future of energy independence. In that spirit, the reactor designs were named Prometheus in honor of the Greek god who gave fire to mortals.

In late 1990, the Department of Energy, Office of Energy Research, selected a design team to conduct these two conceptual design studies. The team was lead by McDonnell Douglas Aerospace (MDA) and included Canadian Fusion Fuels Technology Project; Ebasco Services, Inc.; KMS Fusion, Inc.; SPAR Aerospace, Ltd.; TRW Space and Electronics Group; and the University of California at Los Angeles. The team also had the consulting services of Dr. Mohamed Abdou. An Oversight Committee was appointed to advise and assist the team in conduct of the study. A Target Working Group was formed to provide normalized, unclassified target data to the team.

During the design development, key physics and engineering issues were addressed, analyzed, and results documented. Additional research and development needs have been identified to help resolve issues. Both generic technology and design specific issues were identified and documented. Design specific issues include target coupling with the beam energy, target heating from cavity environment, heavy ion beam channel formation, cavity structural response, film flow stability, and silicon carbide/metal piping transition interface. Issues are identified and described as to: applicability, impact, design specificity, level of concern, operating environment, and relevance to Magnetic Fusion Energy (MFE).

Critical Issues for IFE development are also identified which are broader in scope and have a higher level of importance. These critical issues may encompass several key issues. The design team described 16 critical issues as follows:

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

The key features of the two Prometheus power plants are summarized in Table ES-1. The site plans for the two plants are shown in Figures ES-1 and ES-2.

**Table ES-1
The Prometheus Power Plants Have Valuable and Attractive Features**

Common Features

- Low Activation Structural Material (SiC) in First Wall and Blanket
- More Environmentally Attractive Shield Material in Place of Concrete
- Helium Coolant Minimizes Stored Energy and Chemical/Activation Hazards
- Lower Pressure Helium Coolant Increases Inherent Blanket Safety
- Lead First Wall Protectant/Coolant Reduces Corrosion and Fire Hazard
- Double-Walled Steam Generators Maintain Low Tritium Permeation to Environment
- Reactor Plant Equipment is Easily Maintained with Remote Maintenance
- Plant Level of Safety Assurance is Rated as One
- Waste Disposal is Considered to be Class C or Better

Laser Plant Features

- Electric Discharge Lasers Offer High Reliability
- Illumination Requirements Are Maintained with Loss of One or More Amplifiers
- NLO Architecture Improves Optics Lifetime/Reliability and Beam Quality
- SBS Cells and Delay Lines Provide Efficient Beam Pulse Shapes to Target
- New GIMM Design is Long-Lived
- Direct Drive Target Offers High Gain at Reasonable Driver Energies

Heavy Ion Plant Features

- Single Beam LINAC w/Storage Rings is Simple, Flexible, and Less Expensive
- Low 4 GeV Ion Energy Reduces the Number of Required Beams
- Triplet Coil Sets Ballistically Focus Beams on Focal Spot Outside Blanket
- Channel Transport Offers Minimal Blanket Penetrations and Maximizes Shielding
- Indirect Target Uses Radiation Case to Protect DT Capsule During Acceleration

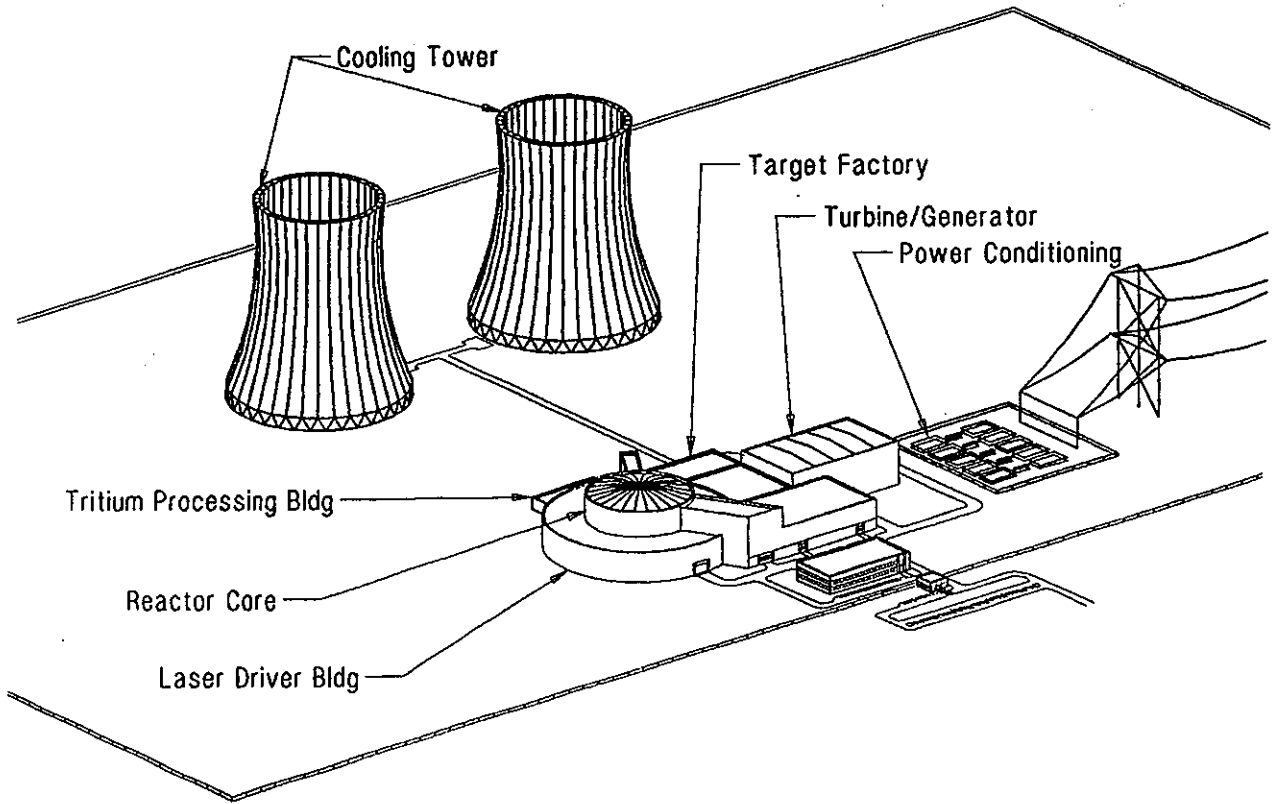


Figure ES-1. Prometheus-L Plant Site Trimetric View

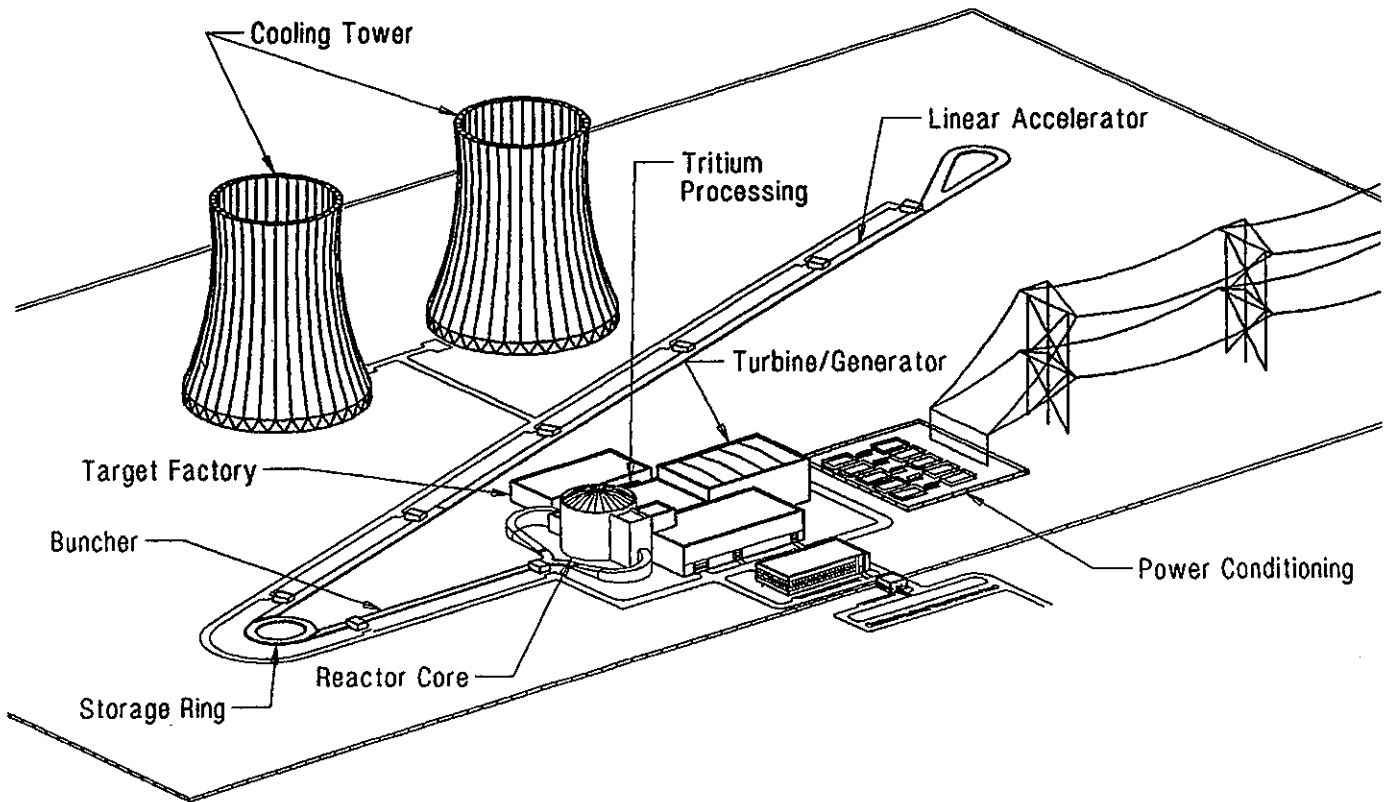


Figure ES-2. Prometheus-H Plant Site Trimetric View

Both Prometheus IFE power plants were designed to supply a net power output of 1000 MWe. Key parameters of the two power plants are presented in Table ES-2. The laser driver is less efficient than the heavy ion driver in producing the required energy to the target, which increases the thermal power, gross electric power, and recirculating power requirements for the laser-driven plant. The nominal pulse rate is 5.65 Hertz. The type and number of laser amplifiers are selected to enable the achievement of a nominal plant availability of 79.4%. The cost of electricity for this laser-driven plant is estimated to be 72.0 mills/kWh expressed in 1991 dollars.

The system efficiency for the heavy ion driver is higher in producing the required energy delivered to the target. This effect translates into a lower recirculating power requirement, physically smaller systems, and lower capital costs in most cost accounts. The nominal pulse rate for the heavy ion plant is 3.54 Hertz. The heavy ion driver has an advantage in inherent availability that raises the plant availability to 80.8%. The resultant cost of electricity is estimated to be 62.6 mills/kWh expressed in 1991 dollars.

The capital costs for the major plant elements of the laser and the heavy ion plant options are compared in Figure ES-3. The Structures and Site Facilities' heavy ion costs are lower mainly due to the smaller Reactor Building size. The reduced fusion, thermal, and electric power requirements for the heavy ion option, resulting from the more efficient driver, have lower related Reactor Plant Equipment, Turbine Plant Equipment, and Electric Plant Equipment costs as indicated. Reactor Plant costs also benefit from the simplified beamline interface for the heavy ion system. The more complex indirect-drive heavy ion target results in a slightly higher Target Manufacturing Plant Equipment cost, but the lower repetition rate keeps the overall cost comparable to that for the laser-driven plant. Interestingly, the resultant costs for the two Driver Plant Equipment approaches are virtually identical despite drastically different design approaches and delivered energy (4 MJ laser, 7.8 MJ heavy ion). The result is a 10 mills/kWh cost of electricity advantage for the heavy ion option as compared to the laser option.

The power plant designs were based upon today's known technology and physics extrapolated some 20-30 years into the future. Safety and environmental attractiveness were key design requirements to enhance the public's perception of fusion. Technical credibility is stressed in order to gain acceptance of the fusion community. Innovative concepts were encouraged to help foster and nurture developmental areas that may enhance the overall economics of fusion.

Table ES-2 Major Design Parameters and Features of the Prometheus Plants

<u>Parameter</u>	<u>Prometheus-L (Laser)</u>	<u>Prometheus-H (Heavy Ion)</u>
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	NA
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
Fusion Thermal Power (MWt)	3092	2797
Thermal Power to Shield (MWt)	43	38
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Cavity Radius (m)	5.0	4.5
Cavity Height (m)	15.0	13.5
First Wall Protection/Coolant Media (In/Out Temp., °C)	Liquid Lead (375/525)	Liquid Lead (375/525)
Breeder Material	Li ₂ O Pebbles	Li ₂ O Pebbles
Structural Material, Wall and Blanket	SiC	SiC
Blanket Heat Transfer Media (In/Out Temp., °C)	1.5 MPa Helium (400/650)	1.5 MPa Helium (400/650)
Cavity Pressure (mtorr, Pb)	3.0	100
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	1.20	1.20
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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 to target)
Overall Driver Efficiency (%)	6.5	20.6
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
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
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

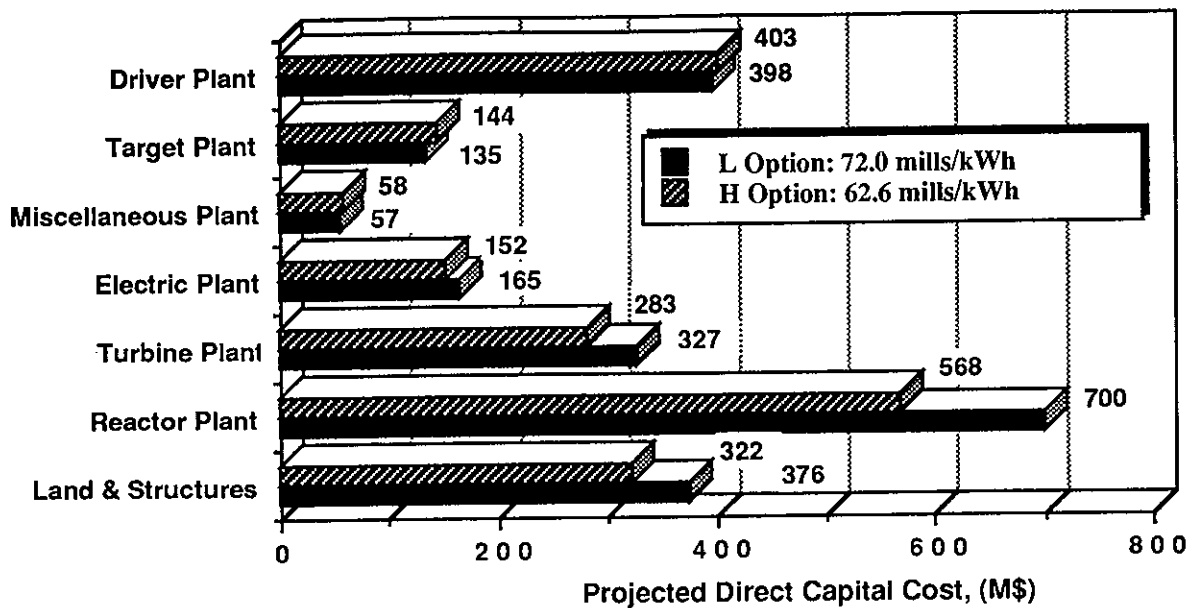


Figure ES-3. Capital Cost Comparison Between the Laser and Heavy Ion Plant Designs

A single reactor cavity concept was judged acceptable for servicing both the laser and the heavy ion reactor power plants. A cylindrical reactor cavity is used to maximize the maintainability of the first wall and blanket and keep a reasonable balance of peak to average neutron wall loading. Modular construction and support techniques were analyzed to assure development of a maintainable design. The cavity aspect ratio was determined by a trade study.

SiC was chosen as the major structural material within the high radiation environment of the reactor cavity to provide low activation and safety enhancement. The first wall is protected by a thin film of liquid lead that is evaporated by each microexplosion and is recondensed between explosions, thus providing protection and vacuum pumping. The first wall is constructed as tubular panels of porous composite SiC structure, which is cooled with liquid lead. Behind the first wall, a lithium oxide solid breeder is cooled with a low pressure, high temperature helium coolant. A low pressure helium purge extracts the tritium generated in the breeder. The tritium breeding ratio of the blanket is 1.20. All the lead and helium coolant piping within the bulk shielding is a SiC low-activation material. The lives of the wall and the blanket are five and ten years, respectively. The peak to average neutron wall load is 6.5/4.3 and 7.1/4.7 for the laser and heavy ion reactors.

Detailed calculations of the nuclear performance of the first wall, blanket and the shield were performed by UCLA. The bulk shield was analyzed for both a concrete and a composite shield of B₄C, Pb, SiC, Al, and H₂O. The composite shield was

chosen to provide a lower and more predictable activation level. In the case of the laser, the beamlines are protected by shielding all the way out beyond the final optics. The heavy ion final focus coils are also protected by internal shielding.

An elevation view of both the laser driver and the reactor buildings is shown in Figure ES-4. The Reactor Building is 86 meters in diameter, dictated by the length of the shielded beamlines. The Driver Building contains all the laser systems and surrounds the Reactor Building. The laser driver option uses 960 electric discharge lasers to provide a highly reliable power amplifier system. Non-linear optical (NLO)

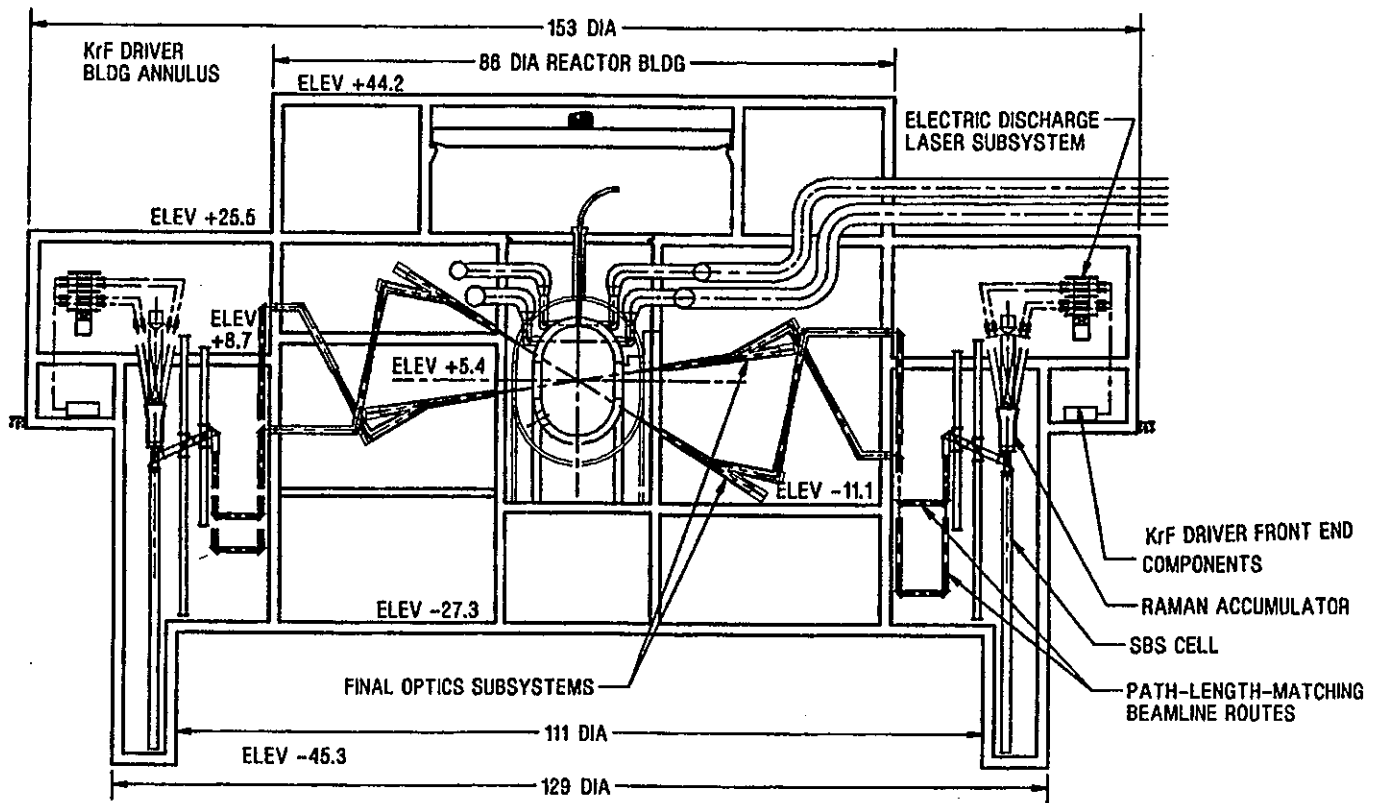


Figure ES-4. Prometheus-L Reactor Building Provides Space for Shielded Beamlines. Driver Building Surrounds Reactor Building.

laser elements provide the beam combining and compression functions to deliver high quality beams on the target. The laser driver delivers 4.0 MJ of 250 nm wavelength energy in 60 symmetrical beams onto a 6-mm diameter target. Beams are combined and quality is enhanced with Raman Accumulator cells with an 88% conversion efficiency. Beams are compressed with Stimulated Brillouin Scattering (SBS) cells. Optical delay switch yards maximize the utilization of the unused energy in the SBS to provide a proper prepulse shape for the target. The 60 beams pass through an optical focus at a neutron pinhole to minimize neutron activation in the driver building. One of the final optical elements is a final focus mirror to focus and turn the beams. A grazing incidence metal mirror (GIMM) is the final optical element that lies in the direct line of sight of the center of the cavity. Innovative design and choice of material offer the possibility of a life-of-plant for this component in a high radiation environment. This is especially difficult as this component is only 20 meters from the center of the cavity. The vapor pressure of the lead in the cavity must be approximately 3 mtorr or less for propagation of the laser beams through the cavity to the target.

An innovative design was chosen for the heavy ion driver. Heavy ion LINAC drivers have previously been thought to be very capital intensive, resulting in an unattractive cost of electricity. Several developments were investigated to reduce the driver costs. A single, rapidly pulsed beam LINAC was chosen as the baseline design. Eighteen beams are accelerated to 4 GeV and then are stored in storage rings for a time less than a millisecond. At the appropriate time, beams are extracted and sent to bunchers to compress the beams. Six of the 18 beams are designated as prepulse beams to prepare the target for the remaining 12 beams. Beams are divided into two sets and delivered to opposite sides of the reactor cavity. This final focus system is displayed in the elevation view of the heavy ion Reactor Building shown in Figure ES-5. The main heavy ion pulse beams are arranged in an 8.54° conical array with the precursor beams on axis. All beams are ballistically focused to a spot size of 3 mm radius at the back of the blanket. The two precursor beams establish 3 mm radius, self-formed transport channels across the cavity to the target. This channel transport concept has the obvious advantage of minimal penetration through the blanket, affording full and uninterrupted blanket coverage.

Two entirely different target concepts are used in the two design studies. The laser driver is using a direct-drive, symmetrically illuminated target with 60 beams. The target capsule is roughly 6 mm in diameter. Laser beams are focused beyond the target to fully illuminate the target and provide a 1% illumination uniformity. The target is a CH plastic shell with beta-layered, solid DT on the interior surface. The target gain is predicted to be 124, based on the beam energy of 4 MJ. The direct drive targets are protected with a sabot during the electromagnetic injection process. The target and sabot are separated prior to reactor cavity entry.

Note: This figure is shown at the same scale as the laser building, Figure ES-4.

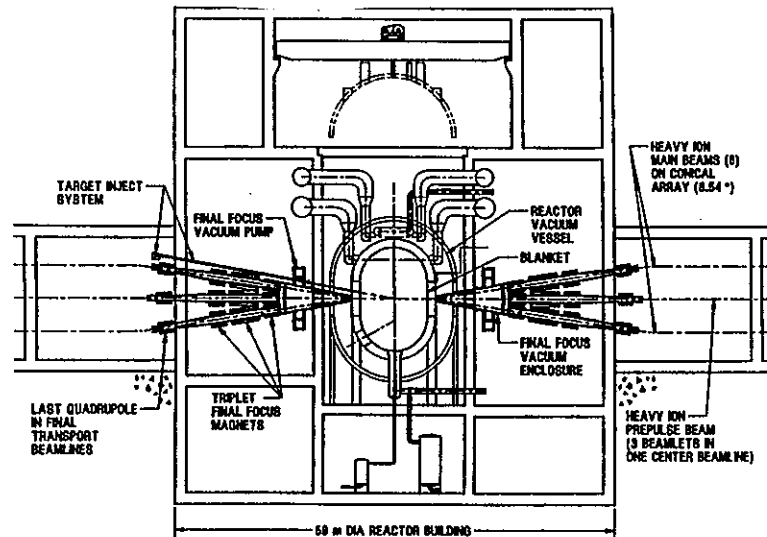


Figure ES-5. Prometheus-H Reactor Building Is Relatively Compact

The heavy ion, indirect-drive target uses a similar DT capsule, but it is enclosed in a radiation case. The case is cylindrical with an energy converter region in each end to convert the heavy ion energy into X rays bathing the interior of the case and the DT capsule. The case has high-Z material (lead) to enhance the capture and distribution of the X rays. The two opposing heavy ion beams are focused on the two end energy converter regions of the target. A gain of 103 is expected for a beam energy of 7 MJ. The indirect drive targets are injected with a pneumatic system and no sabot.

The energy conversion system used in both IFE systems is an advanced Rankine cycle. Two coolant streams, first wall lead and blanket helium, are used as shown in Figure ES-6. Waste heat from the KrF amplifier gas flow system is utilized to improve the laser system efficiency. Steam-driven helium circulators minimize the power required to circulate the helium coolant.

Features of Plant and Design Studies

- Because of the choice and utilization of the materials, the plant is rated at the highest level of safety assurance.
- The drivers contribute to the high level of reliability and availability.
- Innovative driver technologies and design concepts offer cost-effective pathways to economic fusion.

- Two IFE target design approaches have been employed to evaluate their relative merits.
- Non-linear optical laser system architecture offers performance improvements over more conventional systems.
- A single beam LINAC plus storage rings provides a lower cost HI IFE facility option.
- Key Technical Issues and R&D Needs identify areas for development.
- Critical Needs help focus emphasis toward more generic developmental areas.
- Evaluation and comparison of the two studies will help assess IFE program goals.

Power Flows for Laser and Heavy Ion Systems

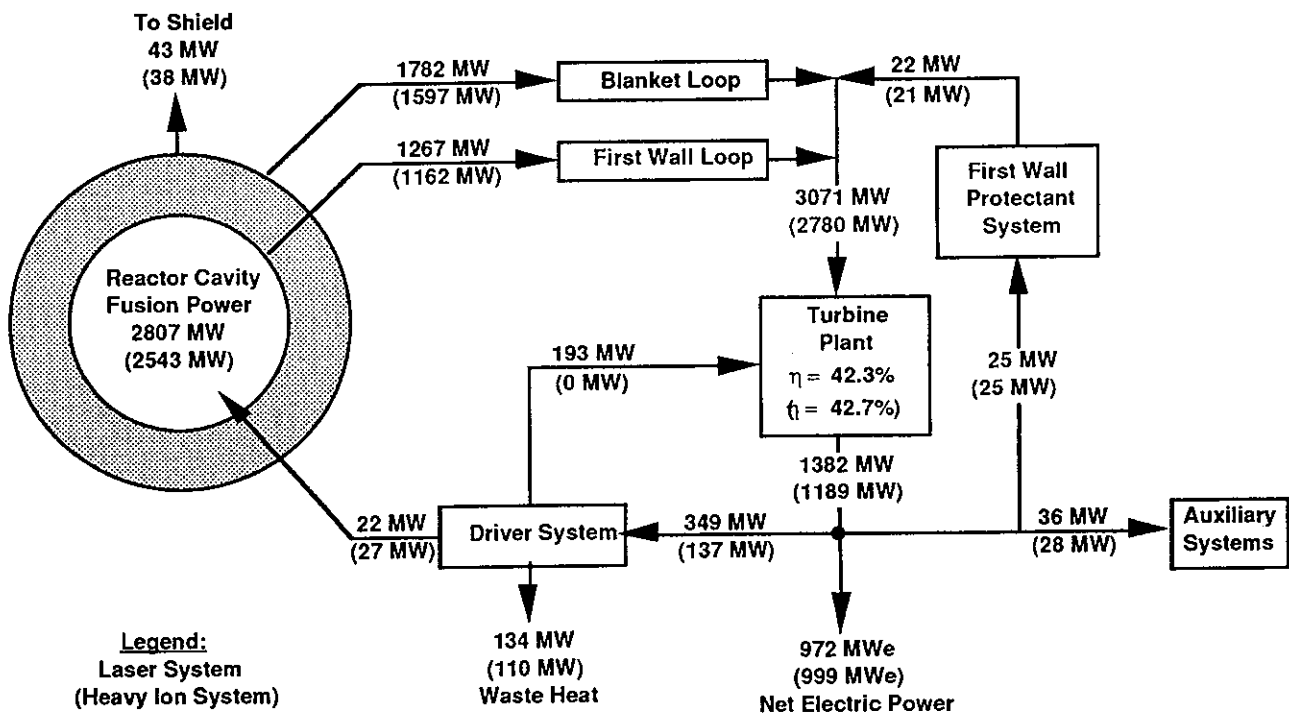


Figure ES-6. Overall Plant Power Flow for Prometheus Baseline Designs