The Prometheus IFE Reactor Cavity*

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ABSTRACT

The design of a wetted wall reactor cavity was undertaken at UCLA as a part of the Prometheus Inertial Fusion Energy (IFE) reactor study. In this paper, we review the final design concept and summarize the results of detailed analysis on several of the key aspects of the cavity design. A more complete description of the design and analysis is contained in the study final report [1].

INTRODUCTION

The cavity consists of the components directly surrounding the exploding targets, including the first wall system, blanket, coolant manifolding, vacuum vessel, and shield. These components contain the energy of the blast, absorb the neutrons produced, convert energy into usable heat, breed tritium to sustain the DT fuel cycle, and shield components and personnel from the high radiation environment. Thus, it has a central role in determining the major attributes of the reactor, such as cost, safety and environmental features, engineering attractiveness, and technical feasibility.

Several fundamental principles were established at the beginning of the Prometheus cavity design process, and guided the major design decisions throughout the study. A top priority was the desire for inherent safety and minimum activation. This desire influenced the material choices for the first wall, blanket, and shield. The first wall employs low-activation SiC composite. Both long-term and short-term activation is small, thus minimizing waste disposal problems and providing negligible decay heat. Li and LiPb were rejected for safety reasons in favor of a Pb wall protectant. Pb has toxicity and radioactivity concerns, but these were carefully estimated and minimized in the design. The blanket also uses SiC structure and reflector, with low-activation Li_2O breeder and He coolant. The tritium inventory in the breeder was minimized. Use of He at relatively low pressure, together with multiple containment barriers, makes blanket failures unlikely and the consequences benign. The shield material also was chosen to reduce activation. Instead of concrete, Prometheus uses an innovative, highly-effective shield consisting of Al structure, water coolant, and B_4C, Pb, and SiC absorbers.

Another major guiding principle was the incorporation of a sound engineering basis. While not all of the design choices use proven technologies, an attempt was made to minimize required R&D and technical risk by adopting near-term technologies that can be extrapolated from existing data. SiC composites are commercially available today, although some development will be required for use in a neutron radiation environment. Pb has been used as a coolant in the past and technologies for using liquid metal as a coolant are well-developed. Similarly, in the blanket, He cooling is an established technology. The data base for Li_2O is being rapidly developed for the MFE fusion program. While not a driving force in the design, the relevance of Prometheus technology to MFE allows an effective R&D program to be developed with minimum cost and time to completion. The R&D needs are bounded and predictable, since the extrapolation from existing technologies is minimized. Cost penalties can be expected as compared with design concepts which are novel, or even radical; however, this was judged to be a reasonable strategy given the time schedule for fusion development.

DESIGN DESCRIPTION AND MAJOR DESIGN CHOICES

A. Overall Configuration

Following a careful review of existing designs in both the IFE and MFE literature, a wetted-wall design was adopted with separate first wall and blanket. Wetted walls have many potential engineering advantages, including good beamline accommodation, relaxed repetition rate limitations (as compared with thick films), flexible engineering features, and low inventory and flow rate of the liquid film.

Both laser-driven and heavy-ion driven versions were examined. It was concluded that the wetted-wall concept could be adapted to both driver designs. Figure 1 shows a cross section of the cavity with the heavy ion driver. The overall configuration of Prometheus is a low aspect ratio cylinder with hemispherical end caps. This configuration was selected for several reasons:

(1) Maintenance of a cylinder is easier than a sphere. Maintenance paths are all straight vertical lines and the configuration allows independent removal of FW panels and blanket modules.
(2) A cylinder provides better control of film flow. Problems protecting the upper hemisphere can be reduced with higher aspect ratio, in which the distance from the blast to the upper end cap can be maximized.
(3) A cylindrical configuration is more consistent with conventional plant layouts.

The main disadvantage of this concept is nonuniform power distribution and higher peak loads. The higher peak-to-average loading leads to larger size and higher cost for a given total reactor power. To minimize these disadvantages, the aspect ratio is kept relatively low — of the order of 1-2; however, this also limits the advantage of upper end cap protection.

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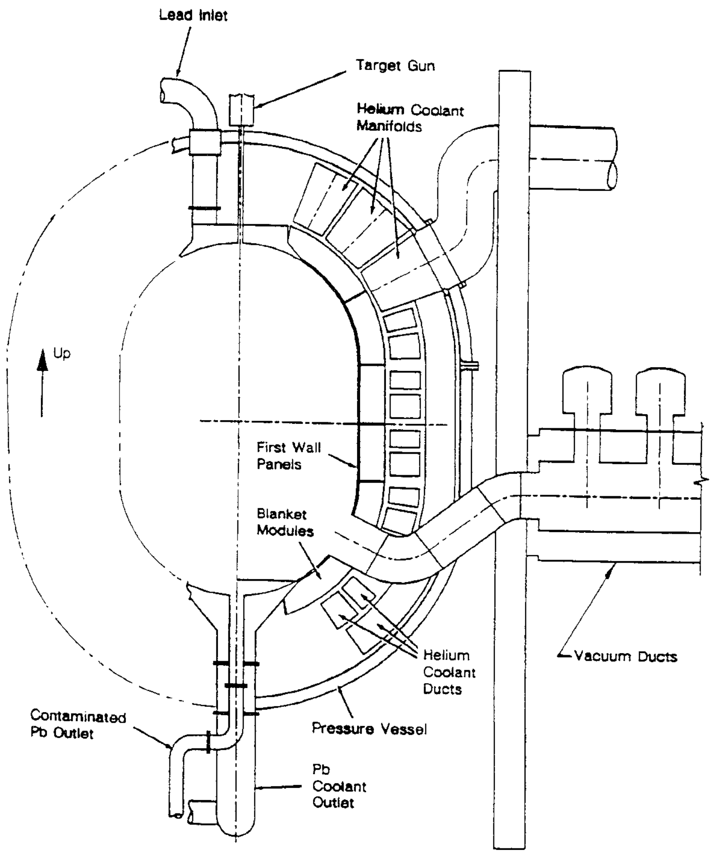

Fig. 1. Reactor Cavity Cross Section

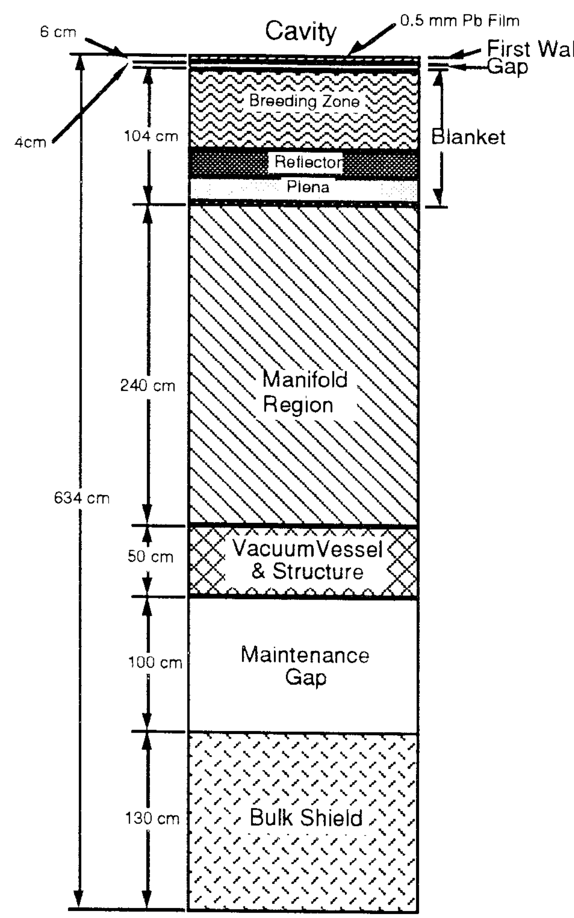

Fig. 2 Radial Build of the Cavity

The first wall system and blanket are physically separated. The environmental conditions and functions performed by these two components are very different; separation allows for better optimization of performance, more flexibility, and good maintenance features. The blanket is protected from the blast and is designed to optimize breeding, energy conversion, reliability, and maintainability. The major penalty is the need for an attachment and locking mechanism and more complicated maintenance scheme.

The first wall and blanket are maintained by removing the upper end cap. The first wall panels can then be removed separately, or the entire blanket rings can be lifted. Preliminary analysis suggests that the first wall service life is of the order of five years, whereas the blanket might last ten years.

Figure 2 shows the radial build from the first wall through the shield which is typical for both the -L and -H option. The cavity radius is nominally 4.5 m for the Prometheus-H cavity. Relatively large manifolding is needed behind the blanket to keep the He coolant pressure drop low. The manifolding is made from SiC composite up to the vacuum vessel and shield, where a transition is made to more conventional ferritic/martensitic steel. The vacuum vessel is also made of steel.

B. Loading Conditions

The release of energy from the blast comes in the form of prompt x-rays and debris from the target, which are absorbed in the first wall and cavity gas, and bulk nuclear heating from neutrons and gammas. The blast characteristics (neutron and x-ray spectra, target gain curves) were adopted from previous studies in the literature. Transport calculations were carried out to determine the deposition rates throughout the cavity structures. The energy deposited in the cavity gas is eventually redeposited into the first wall by thermal radiation and mechanical energy from the blast. Table I summarizes the power sources incident on the cavity.

All neutronics parameters in the cavity were calculated in one-dimensional spherical geometry using the ANISN 1-D discrete ordinates transport code with the MATXS5 (30-g neutrons, 21-g) library based on ENDF/B-V nuclear data. Fig. 3 shows the resulting neutron and gamma heating profiles in the first wall, blanket and shield.

TABLE I
Reactor Energy Balance

	Laser	HI	
Total Yield	497	719	MJ
X-ray Yield	31	46	MJ
Debris Yield	107	159	MJ
Repetition Rate	5.6	3.5	Hz
Surface Power	780	725	MW
FW Nuclear Heating	487	437	MW
Blanket Nuclear Heating	1782	1597	
Net Energy Multiplication	1.14	1.14	

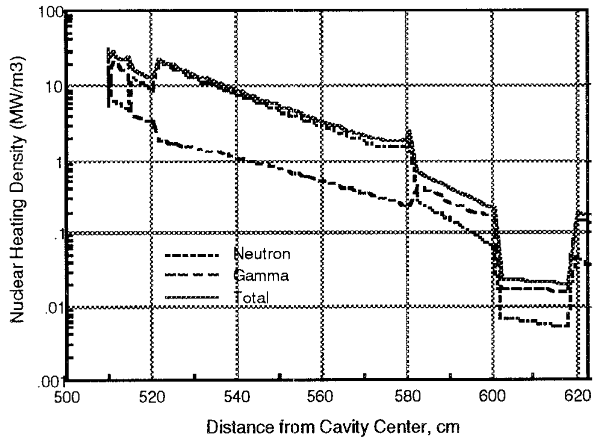

Fig. 3. Nuclear Heating Rate Profile in the First Wall, Blanket, & Shield

Transport of x-ray and debris energy through the cavity gas was analyzed using x-ray spectra of SIRIUS [4] and LIBRA [5], and assuming all ions are ejected at a single velocity. The background gas pressure is 3.5×10^{13} cm^{-3} for the laser case and 3.5×10^{15} cm^{-3} for the laser case. In both cases, a substantial amount of x-ray energy reaches the first wall. Evaporation of the lead takes place to a depth determined by a simple energy balance. When the local energy density exceeds the energy required for raising the temperature to the boiling point plus the latent heat of evaporation, then the film is assumed to evaporate. Virtually all of the debris energy is absorbed by the cavity gas for the heavy ion case, whereas 20% reaches the wall for the laser-driven reactor cavity. Since the debris reaches the wall after the x-rays initiate a vapor cloud, the debris energy is expected to be completely shielded from the Pb film.

TABLE II
Mass and Thickness of Layer Vaporized by X-Rays

	Laser	HI	
X-ray Energy Absorbed in Vapor	9.9	28.9	MJ
X-ray Energy Deposited in Film	21.1	8.1	MJ
X_{vap}	0.6	0.5	μm
X_{bp}	5.5	5.9	μm
Vaporized Film Thickness, X_{tot}	1.3	1.6	μm
Surface Area	471	382	m^2
Vaporized Mass	5.9	6.4	kg

Thermal re-radiation is a major source of energy from the cavity gas to the first wall, and partly determines the rate at which pellets and beams can be injected. Cavity clearing rates were analyzed with the RECON computer code, developed for this study. RECON models energy deposition in the film and chamber, thermal radiation, film evaporation/recondensation and conduction into the coolant. For example, Figure 4 shows a typical time history of the cavity pressure and mass for the heavy-ion case. Extensive parametric studies performed with RECON helped to fix the major dimensions of the cavity.

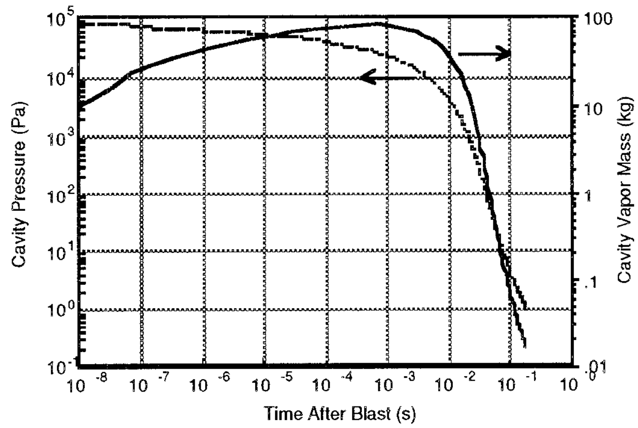

Fig. 4. Typical Cavity Pressure Response for Prometheus-H

C. First Wall System

The wall protection scheme chosen for Prometheus uses a thin liquid Pb film supplied from Pb coolant tubes through a porous structure of SiC composite material. A film nominally 0.5 mm in thickness is allowed to form on the surface facing the pellet explosions. The porosity of the bulk SiC is tailored to allow Pb from the cooling channels to slowly seep onto the surface. Wetting of SiC by Pb is assisted by coating the SiC with a metal as part of the chemical vapor deposition (CVD) process. Protection of the upper end cap is a particularly difficult problem. In order to maintain a fully-wetted surface without Pb falling off into the cavity, we inject a thin Pb jet at the top of the upper end cap. The jet injector structure (SiC) is exposed to the blast effects and is made easily accessible for repair or replacement, as required. The fluid leaves the injector and flows along the surface.

The surface film evaporates in response to the intense heat flux from the target explosions and then recondenses prior to the next shot. The first wall coolant must have acceptable neutronic properties (either breed, multiply neutrons, or be transparent), such that the choices are limited to Li-bearing materials and neutron multipliers. Pb was selected for a number of reasons. Pb has a safety advantage over Li, good neutron multiplication, and chemical compatability with SiC. Its thermophysical properties provide good operating temperature ranges. Its relatively high saturation temperature leads to good conduction heat transfer into the coolant, its boiling point is not too high for materials temperature limits and compatibility, and the relatively high bulk coolant temperature gives good thermal conversion efficiency. Bi and BiPb were considered as alternate multipliers, but they have much higher radioactivity. Some of the outstanding disadvantages of Pb include high density and activation.

The first wall system consists of a series of panels 2-m wide which are lowered into the cavity vertically and locked into a support system attached to the blanket. The ability to provide removable panels which lock into the blanket is essential to allow more frequent maintenance of the first wall panels and still mitigate the mechanical effects of the blast by absorbing the loads into the blanket and support system. Fig. 5 shows a cross sectional view of a first wall panel. The cooling channels are 5-cm thick to provide neutron multiplication needed for tritium breeding. The first wall is kept thin (5 mm) to provide good heat conduction into the coolant. The film thickness is also minimized for good heat transfer as well as to reduce the problem of liquid entering the cavity.

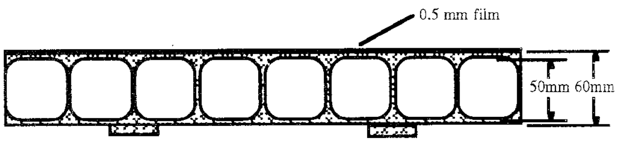

Fig. 5. First Wall Panel; Cross Sectional View

The SiC structure must be flexible enough to withstand cyclic loading from the blast, but strong enough to support itself and the internal pressure of the film. A supply region behind the porous structure serves to slowly feed the liquid and also to remove the heat from the first wall (40% of the total fusion power). Blast energy is removed from the cavity initially by evaporation. During the recondensation phase of each pulse, heat is conducted through the relatively thin film and into the first wall coolant.

In the Prometheus design, cavity clearing requires good conduction heat transfer into the cooling channels. Prometheus-L requires the cavity vapor to drop below 1 mTorr before the laser beams are fired, whereas Prometheus-H has a window of 10-100 mTorr. The lower limit is needed to establish proper channel transport conditions, and the upper limit is based on target injection constraints. Adequate clearing times are predicted for both reactors.

D. Blanket

The blanket consists of several rings through the cylindrical and hemispherical sections. Blanket modules are pre-assembled into the rings, which stack vertically on top of one another. At laser penetration holes, the corresponding module length is shortened to allow for penetration space. The blanket modules are made of SiC and contains a number of U-bend woven SiC tube sheets inside which the pressurized He coolant flows. The Li_2O is placed in packed bed form between the tube sheets and is purged by He flowing along the axis of the module. Use of Li_2O in conjunction with the first wall Pb coolant provide the potential for adequate tritium breeding without the need for Be as a multiplier.

A schematic of a module is shown in Figure 6. It consists of a simple layered configuration. The module is made of SiC and contains a number of U-bend woven SiC tube sheets inside which the pressurized He coolant flows. The Li_2O is placed in packed bed form between the tube sheets and is purged by He flowing through the U-bend Li_2O regions.

The breeder region thickness increases with the distance from the plasma based on the local heat generation and minimum and maximum Li_2O operating temperature limits. These limits were conservatively set at 400°C and 800°C based on considerations of LiOT precipitation and sintering, respectively. For comparison, the corresponding temperature limits assumed in the ITER CDA design study were 320°C and 1000°C, respectively.

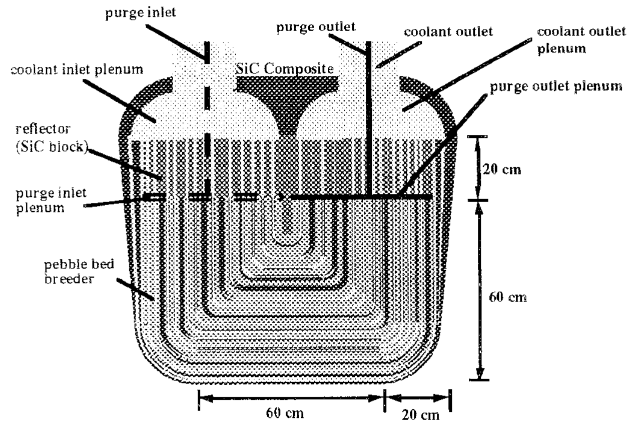

Fig. 6. Schematic of a Blanket Module

The final blanket performance parameters are summarized in Table III for both the Laser and Heavy Ion reactor concepts, the main difference being small changes in the fusion and blanket loop powers.

TABLE III
Final Blanket Performance Parameters

	Laser	Heavy Ion
Blanket Loop Power	1782 MW	1627 MW
Helium Inlet/Outlet Temp.	400/650 C	400/650 C
Helium Inlet Pressure	1.5 MPa	1.5 MPa
Helium Velocity	46 m/s	42 m/s
Pressure Drop	24 kPa	19 kPa
Li_2O Min./Max. Temp.	425/800 C	422/765 C
SiC Min./Max. Temp.	400/800 C	400/765 C
TBR	1.2	1.2
Tritium Inventory	100 g	100 g
Purge Pressure	1 MPa	1 MPa

REFERENCES

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