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Fusion Reactors: Technology Aspects of  
Power Conversion Chambers**

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**Electricity Production from Laser Driven Fusion Reactors:  
Technology Aspects of Power Conversion Chambers**

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## Abstract

One of the most important considerations for laser driven fusion power plants is the safe and efficient operation of the chamber that contains the thermonuclear energy released from the target. Several approaches to the design of such a chamber are described in this paper and the critical issues associated with protection of the first wall, the performance of the structural materials, and the cost are discussed. Presently, the need for direct drive (symmetric) illumination of the cryogenic targets makes the use of liquid first wall protection problematical at best. The use of dry first walls protected with a few torr of an inert gas seems to hold the most promise.

## Introduction

There are four main components of any Inertial Fusion Energy (IFE) power plant: 1) Driver, 2) Target, 3) Reaction Chamber, and 4) Balance of Plant (BOP). While the main objective of this paper is to address the technological aspects of reaction chamber designs, it is first necessary to review the other components.

Presently, there are two main driver concepts for IFE: lasers and heavy ions. Other drivers that are considered include light ions and pulsed power driven Z pinches. This paper will generally concentrate only on lasers.

There are currently three main approaches to IFE targets [1]:

- Direct drive
- Indirect drive
- Fast ignition

Only the first and the third targets are presently favored for use in laser driven reactors and only the direct drive targets will be assumed for the purposes of this paper.

Finally, the BOP depends mainly on the choice of the coolant. If a liquid coolant is used, then a Rankine cycle is favored. This cycle usually involves intermediate heat exchangers and the production of steam to make electricity, generally with moderately high thermal efficiencies. The use of a gaseous coolant usually favors a Brayton cycle. Such a cycle involves the use of high temperature gas turbines and generally higher efficiencies. If a "solid" coolant is chosen (this usually means a flowing particle bed), then the conversion of the energy from the chamber could involve either a Rankine or a Brayton cycle.

## General Considerations

There have been over 50 IFE reactor studies published since 1972 (see Figure 1) but 80% of the studies are now over 15 years old and need to be updated [2-3]. As can be seen in Figure 1, over 60% of the studies have been on laser driven concepts with the remaining emphasis split equally between heavy and light ion concepts. The most recent published laser studies include two from the U. S., (SOMBRERO [4] and Prometheus-L [5]), and one from Japan (KOYO [6]).

A brief summary of the key parameters for a few of the laser fusion reactor designs which represent a breadth of options is given in Table 1 [4, 6-9]. The parameters of particular interest to the designers of the reactor chamber include:

- Geometry of the laser illumination
- Repetition rate
- Neutron wall loading
- Structural material

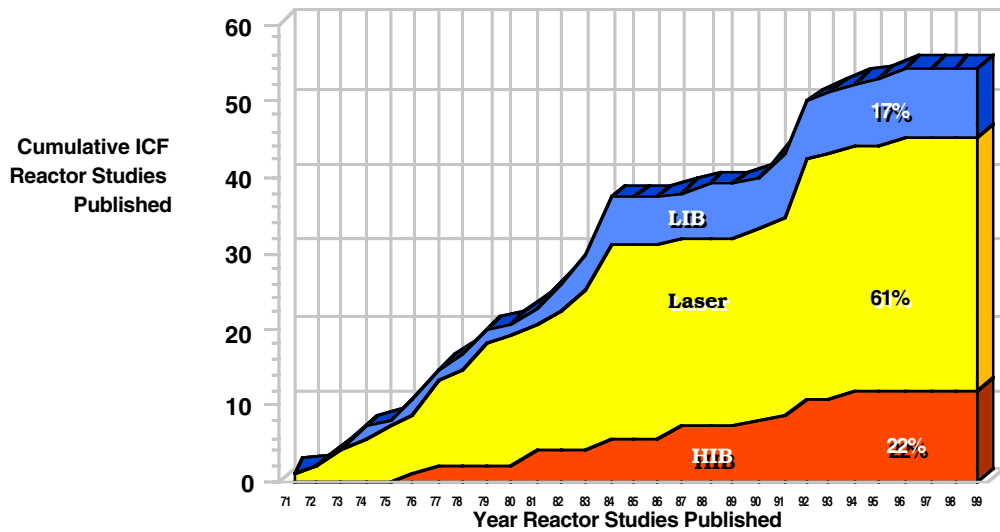


Figure 1. The majority of IFE power plant designs have used a laser driver.

The illumination geometry is particularly important with respect to the first wall protection schemes. Inertial fusion is unique because it offers the opportunity to use thick streams of flowing liquid metals inside the chambers to protect the first walls from the plasma and neutrons released by the fusion reaction [10]. The internal thick liquid metal concept is particularly well suited for one or two-sided illumination of the target (indirect drive).

However, if the targets must be symmetrically illuminated (direct drive) with 100 or more laser beams, it is very difficult to cover the first wall area with flowing metals without interfering with many of the beams. Since it is now felt that direct drive targets will be necessary for early laser fusion reactors [1,3], there is growing concern that chambers will have to be clear of internal material and require bare, or “dry walls”.

	SOLASE [7]	HYLIFE [8]	Cascade [9]	SOMBRERO [4]	KOYO [6]
Year Published	1977	1978	1983	1992	1993
Laser	CO <sub>2</sub>	SWL	SWL	KrF	DPSSL
Laser Energy, MJ	1	4.5	1.5	4	4
Rep Rate, Hz	20	1.5	5	6.7	3
Driver Eff., %	6.7	5	10	7.5	12
Illumination	Quasi-symmetric	2-sided	2-sided	Symmetric	Symmetric
Target Gain	150	400	200	118	150
First Wall Protection	Low Pressure Inert Gas	Thick Liquid Jets	Flowing Solid Particles	Low Pressure Inert Gas	Liquid Metal in Tubes
First Wall Neutron Loading, MW/m <sup>2</sup>	5	0.3	0.2	3.5	0.07
Breeding Material	Li <sub>2</sub> O	Li	LiAlO <sub>3</sub>	Li <sub>2</sub> O	PbLi
Structural Material	C Composite	Steel	SiC	C Composite	SiC
Thermal Eff., %	43	39	55	47	43
Net Power, MWe	965	1010	800	1000	710/unit (4)

The repetition rate of the target implosions is also a key factor in that it determines how fast the chamber must be cleared of debris and first wall materials before a new shot sequence can commence. If one has to depend on gravity to clear the chamber of small particles or droplets, then the rep rate will be limited to  $\approx 1$  Hz. Dynamic clearing of vaporized material (from both the target and first wall) will probably limit the rep rate to  $\approx 3-5$  Hz [11].

Both the neutron wall loading and structural materials will have an impact on the economic and safety performance of an IFE power plant. Currently, the useful lifetimes of first wall materials like C composites or SiC may be in the 1-3 MWy/m<sup>2</sup> range [12,13] whereas the lifetime for certain steels may be as much as  $\approx 10-20$  MWy/m<sup>2</sup> [14]. If the chamber is made too small (and thus the first wall loading too high), the first wall materials may experience premature failure or have to be replaced on such a frequent schedule as to negatively impact the availability of the reactor. If the chamber is made so big as to accommodate this radiation damage, it may affect the propagation of the beam or simply cost too much.

### Past Chamber Designs

Figures 2-5 show four examples of laser fusion reactor chamber designs. They represent the four ways designers have devised to protect the first walls from the fusion blast:

- Gas filled (Figure 2)
- Thick flowing liquid metals (Figure 3)
- Thick flowing granular solids (Figure 4)
- Liquids contained in porous tubes (Figure 5)

Two of the chamber designs, gas protected and liquid metals in porous tubes, have been used with direct drive target designs. The other two, thick flowing liquid metals and granular solids inside the chamber, cannot be used for symmetric illumination.

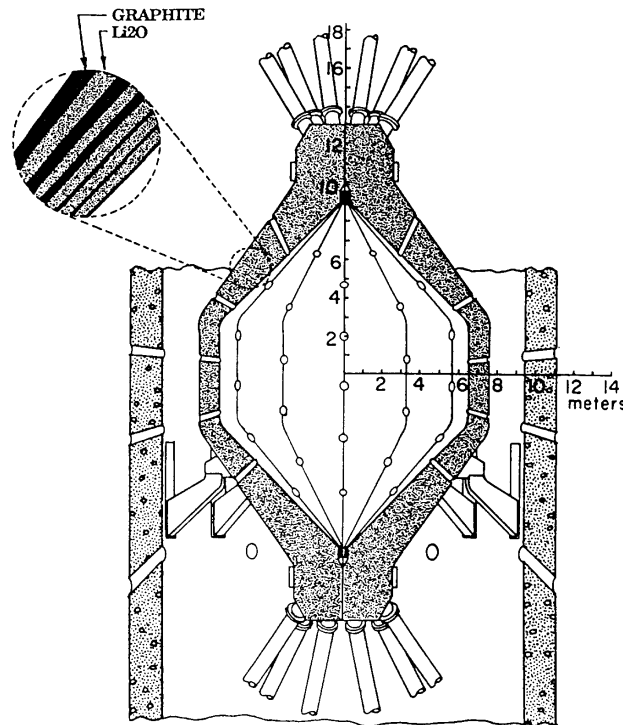


Figure 2. The SOMBRERO design [4] is an example of a dry wall IFE chamber.

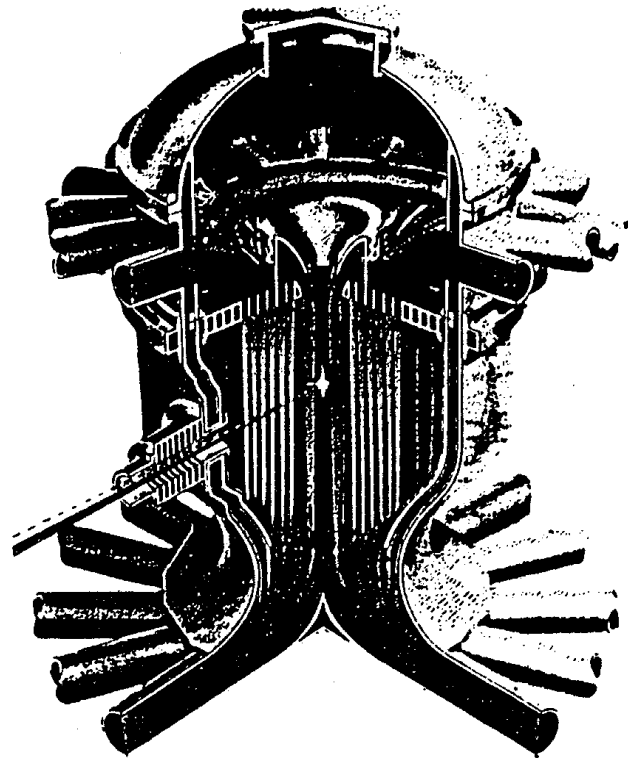


Figure 3. The HYLIFE design [8] is an example of a thick liquid metal protected IFE chamber.

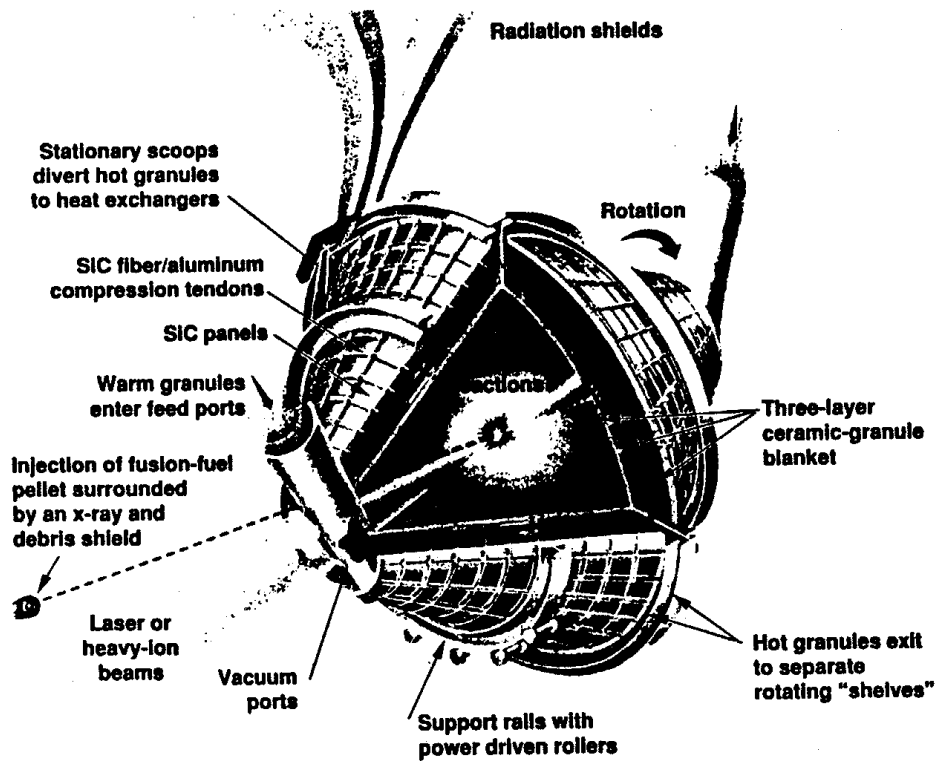


Figure 4. The Cascade design [9] is an example of a thick flowing particle bed protected IFE chamber.

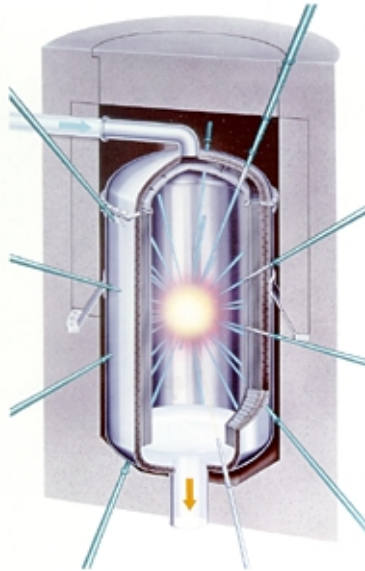


Figure 5. The KOYO design [6] is an example of the use of flowing liquid metals in tubes to protect the chamber first wall.

#### **Issues for Internal Liquid or Solid Protection**

The main reason for using flowing liquids or solids between the target and the first wall is to moderate and absorb the neutrons before they can damage the structural materials. One design for introducing thick (0.5 to 1 meter) flowing metals in the chamber is illustrated by the HYLIFE design [8]. There are several possible choices for the liquid: Li, PbLi, SnLi, or FliBe. A measure of how effective these flowing walls can be in extending the useful life of steel is shown in Figure 6 [10]. This figure reveals that as little as 30 cm of FliBe, or 40 cm of PbLi can extend the life of a steel first wall from 4 FPYs to 30 FPYs.

On the other hand, isochoric heating of free flowing liquids by the neutrons can cause the liquid jets to disassemble, forming droplets and mist. The clearing of those droplets and mist could take a second or more in a 10 m diameter chamber [11]. Unless very large gains can be achieved with indirect drive targets, this lower rep rate will reduce the power level in the chamber and thus raise the cost of electricity. Another critical issue is the reliable, rapid, and efficient reestablishment of stable liquid metal jets without blocking any of the incident beams.

A similar advantage for first wall protection accrues to the liquid metals contained in porous tubes (see Figure 5), first suggested for use in heavy ion, indirectly driven target chambers [15] and recently utilized in the KOYO design [6]. The advantage of this approach is that it inhibits the disassembly of the liquid stream and therefore should allow higher rep rates. The porous tubes also allow the flow configuration to be preserved and reduce the possibility of blocking the laser beam.

#### **Issues Associated with Gaseous Protection**

A major reason that a low-pressure inert gas was proposed for use in the SOLASE [7] reactor was to act as an “inverse thermal capacitor”. The low pressure of Xe ( $\approx 1$  torr) absorbs the large energy flux of x-rays and ions emitted in a few ns and then reradiates the energy to the wall over a few ms. This spreading out of the heat flux allows the first walls to avoid evaporation if they are no closer than  $\approx 4$ -5 meters from the target. The noncondensable gas is also easy to exhaust so that high rep rates can be achieved.

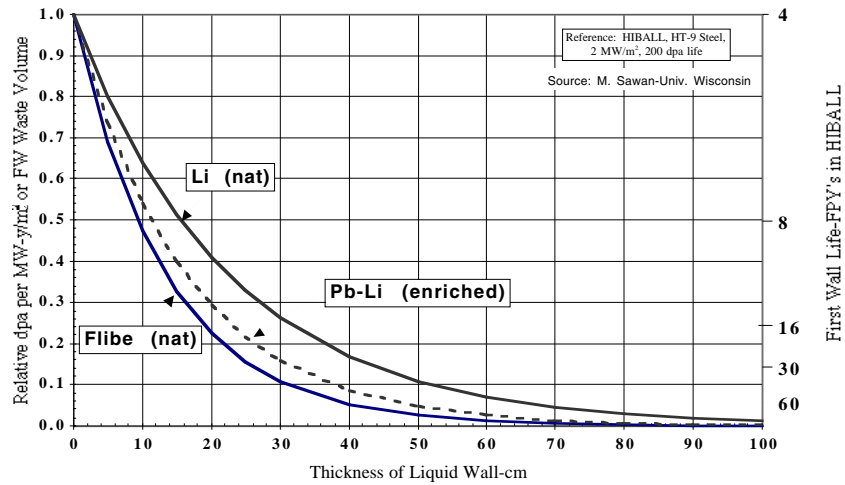


Figure 6. The use of thick liquid metal protection of the structural first wall can greatly extend its useful lifetime.

The major disadvantage of the gas protection scheme is that it does not stop the neutrons (as in the same manner as a MFE design allows the neutrons to hit the first wall). At too high of a pressure, the gas may also interfere with the focus of the laser beam. Fortunately, at pressures needed to protect the first wall from excessive heat fluxes, recent experiments at NRL [16] have shown that for KrF lasers, there may be little effect on the focusability of the laser beam.

### Critical Issues for Laser Fusion Structural Materials

Assuming that laser fusion power plants will use direct drive targets, and that free flowing liquid jets are not compatible with the illumination geometry required, then there will probably be little protection of the first structural materials. This means that radiation damage to the structure (currently expected to be C-C composites or SiC) is of great concern. Irradiation induced growth must be controlled and understood in order to achieve at least a 1-2 full power year (FPY) lifetime [4].

Another issue that has recently surfaced with respect to the use of high temperature ceramics is the trapping of tritium in irradiated material. Recent experimental data has shown that the tritium inventory in C is greatly increased [17-18]. The ceramics have been favored in IFE designs not only because of their ability to withstand high temperature and their low vapor pressures at high temperature, but also because of their low induced long-lived radioactivity [3, 4, and 14]. One must be sure that any solutions that increase the resistance to neutron radiation damage do not compromise the beneficial effects of low activation.

### Cost Implications of IFE Reactor Chamber Design

Analysis of recent IFE reactor studies reveals that the chambers typically contribute  $\approx$  8-9% to capital cost. Table 2 shows that the chamber costs do not dominate the COE from IFE. This does not mean that the cost of chambers can be ignored, but it does illustrate the greater flexibility one might have in using multiple cavities for a large power plant in order to realize the economy of scale.

Table 2. The Driver and Power Conversion Dominates the Capital Cost of IFE Power Plants					
	% of Total Capital in Category				
	Driver	Chambers	Buildings	Heat Transfer/ Turbine/Electric	Other
SOMBRERO [4] (lasers)	31	9	15	34	11
OSIRIS [4] (heavy ion)	37	8	9	34	12



## Conclusions

The past effort into the design of IFE reactor chambers has been largely responsible for our present understanding of the attributes of the early IFE designs. Since 80% of the IFE reactor studies were completed 15 years ago, a new effort must be mounted. New materials, analytical techniques, and internal first wall protection schemes must be examined.

The use of direct drive targets in laser driven reactors means that thick liquid wall and inhibited liquid metal flow concepts may not be appropriate. A more likely first wall protection scheme would involve the use of an inert gas such as Xe. The pressures required (<1 torr) are sufficiently low that laser breakdown does not appear to be a problem. However, it is still too early to know if the low-pressure gas will adversely influence the injection and tracking of the targets. Experiments in this area are sorely needed.

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