The INPORT Concept - An Improved Method to Protect ICF Reactor First Walls

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THE INPORT CONCEPT - AN IMPROVED METHOD TO PROTECT ICF REACTOR FIRST WALLS

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A method to protect the first metallic walls of ICF reactors from X-rays and target debris has been developed. The concept utilizes porous, flexible tubes of woven C or SiC fibers to contain liquid metals inside the vacuum chamber of an ICF system. These porous tubes allow for ablation and recondensation of liquid metal films. The tubes also moderate the neutron spectra and reduce the displacement and transmutation damage in metallic walls.

1. INTRODUCTION

A persistent technical problem in the Inertial Confinement Fusion (ICF) field has been the protection of the first load bearing walls from target debris, X-rays, and neutrons. Various schemes have been proposed in the past [1]: swirling liquid metal pools [2], wetted walls [3-5], magnetic protection [6], gaseous protection [7], dry wall ablative shields [8-11], and free falling sheets of liquid metals [12-15]. None of these schemes have been completely satisfactory, but the liquid metal protection scheme, HYLIFE [15], seems to be the best developed thus far.

One disadvantage with the HYLIFE scheme is the disassembly of the liquid metal columns after each shot and the need to reestablish the stream before the next target can be injected. This results in a small ΔT, high coolant recirculation rates, and large pumping powers, especially for the Pb-Li alloys. Ideally, one would like to develop a scheme which would slow down the flow of liquid metal so that it can absorb the energy of several shots before exiting the reactor.

Such a scheme was developed in late 1979 for the HIBALL [16] project. The basis of this new design is the use of woven C or SiC tubes which are flexible, sufficiently strong, compatible with Pb-Li alloys used in HIBALL, and porous enough to allow liquid to cover the surface while the bulk of the fluid flows down the center of the tube. This idea is called the INPORT concept, standing for the <u>In</u>hibited Flow - <u>Por</u>ous <u>T</u>ube Concept.

The object of this paper is to describe how such a concept is effective in prolonging the life of ICF cavities. In order to illustrate the beneficial features of the INPORT idea, we will demonstrate how effective it is in a specific reactor design (i.e., HIBALL) but it is clear that the ideas could be applied to laser fusion systems and perhaps even light ion beam fusion reactor designs.

2. GENERAL FEATURES OF INPORT CONCEPT

A schematic of how the INPORT concept works is shown in Figure 1. A woven, flexible tube of SiC allows the bulk of the coolant, in this case $Li_{17}Pb_{83}$, to flow from the top to the bottom of the reactor cavity (see Figure 2). The flow rate is adjusted by orifices at the top and bottom of the tubes. The loosely knit structure allows some of the liquid metal to leak out from the tube and wet the sides of the tube.

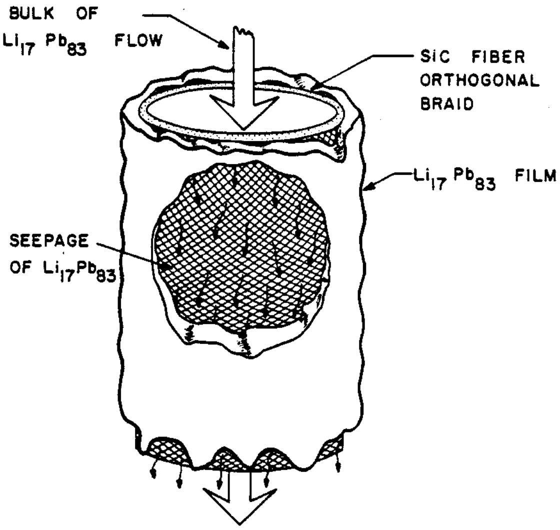

Figure 1. Schematic of INPORT Concept - Metallic coolant seeps through porous woven structure to protect outside of tube from target X-rays and ion debris

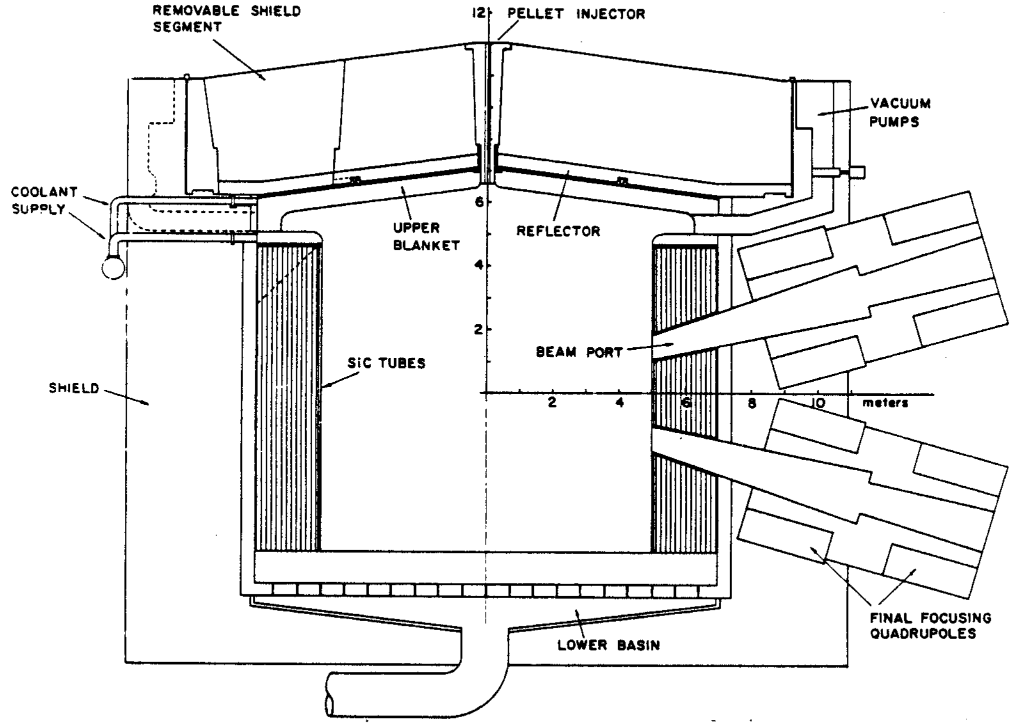

Figure 2. Cross Sectional View of HIBALL Reaction Chamber.

The thickness of the film (~ 1 mm) is enough to absorb the X-rays and debris from the target. The tubes are 10 meters long and arranged in two banks (Figure 3). The first one contains 3 cm diameter tubes to remove the high X-ray and ion debris heat flux (35 J/cm^2), and a second bank, in which each tube is 10 cm in diameter, will remove most of the kinetic energy of the neutrons and provide the tritium breeding (see Table 1). The thick region of Pb-Li and SiC also reduces the displacement and transmutation damage to the metallic components which will be illustrated later. In HIBALL [16], the 3 cm tubes are 5 m from the target, which has a yield of 400 MJ (Table 1). The pulse rate of the reactor is 5 Hz.

In order to adequately remove the 2000 MW of DT power from the chamber, the maximum $Li_{17}Pb_{83}$ flow velocity is 5 m/s in the 1230 small (3 cm diameter) tubes. The flow velocity in the 3070 outer tubes is slower, ranging from 0.8 m/s in the front to 0.1 m/s in the back row. The inlet temperature of the $Li_{17}Pb_{83}$ coolant is 330°C and the outlet is 500°C.

The amount of $Pb_{17}Li_{83}$ coolant evaporated per shot requires a complicated analysis and is explained in detail elsewhere [17]. These calculations properly account for heat

Table 1. Selective Operating Parameters of INPORT Units in HIBALL [16]

Target Yield x Freq. of Shots	400 MJ x 5 Hz
X-ray and Ion Debris Energy to First Tube Bank	35 J/cm^2
Tube Length	10 m
Tube Outer Radius	
(inner rows)	1.5 cm
(outer rows)	5 cm
Number of Tubes in HIBALL	
(inner rows)	1230
(outer rows)	3070
Coolant Velocity	
(inner rows)	5 m/s
(outer rows)	0.1 to 0.8 m/s
Coolant Inlet/Outlet Temperature	330/500°C
Amount of $Li_{17}Pb_{83}$ Evaporated Per Shot	13 kg
Condensation to < 10^{11}Pb atoms/cm^3	0.15 s

deposition in both the liquid and blowoff gas, as well as including reradiation of the hot Pb gas to the tubes. For the target and debris spectra of HIBALL, it was calculated that a total of 13 kg of $Li_{17}Pb_{83}$ is evaporated per shot.

This amount of material in the chamber results in an atom density of Pb and Li which is too high to allow propagation of the heavy ion beams. Consequently, the minimum time interval between shots is determined by the condensation of the gas to a lower density which for 80% of the beam to reach the target has been determined to be less than $\sim 10^{11}$ Pb_{atom}/cm^3. Again, detailed calculations [17] on the condensation rates reveal that ~150 ms is required to reach the conditions for adequate heavy ion beam propagation.

3. FABRICATION OF INPORT UNITS

The success of the INPORT concept depends to a large degree on the ease of fabrication of the porous units with a material which is compatible with the vacuum, coolant and radiation environment. The most logical method of forming the flexible tubes is by braiding, a commercial process which has been available since the late 1800's.

Braiding machines, such as that depicted in Figure 4, have been used to fabricate very complex shapes with a variety of materials of interest to this study. Figure 5 shows some examples of tubes, woven from fiberglass, which exhibit the flow characteristics desired in the INPORT concept. The tubes in Figure 5 are representative of epoxy stiffened tubes (No. 1), flexible covering over epoxy stiffened tubes (No. 2), or completely flexible tubes made from several plys of woven material (No. 10). Flow tests on these tubes demonstrated that the surface leakage is sufficient to protect the individual fibers from X-rays. Changes in the flow properties can be accomplished by changing the braid angle described through the factors given in Figure 4.

Tubes, similar to those in Figure 5, have been successfully made from graphite and SiC fibers. These materials are both thermally stable and sufficiently radiation damage resistant to be considered for INPORT units that are filled with $Li_{17}Pb_{83}$ eutectic alloy. However, the chemical stability of free carbon in the presence of Li is not sufficiently favorable to use graphite tubes and SiC was chosen for HIBALL. The SiC molecule is thermodynamically more stable than Li_2C_2 in the 300-500°C temperature range.

Typical properties of the SiC fibers used to make the test INPORT units are given in Table 2. Elevated temperature tests of 3 cm and 10 cm tubes as well as fatigue studies are now in progress.

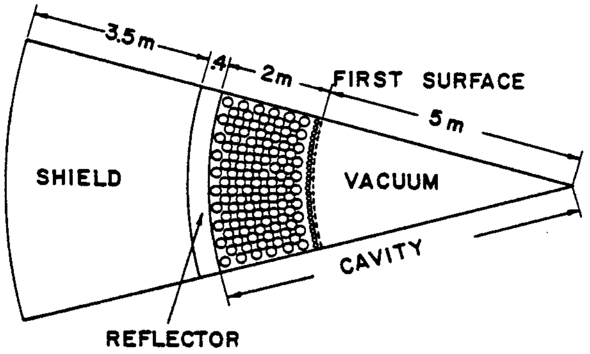

Figure 3. Cross Cut Section of HIBALL Reactor Revealing Two Banks of INPORT Tubes Between the Target and the Reflector.

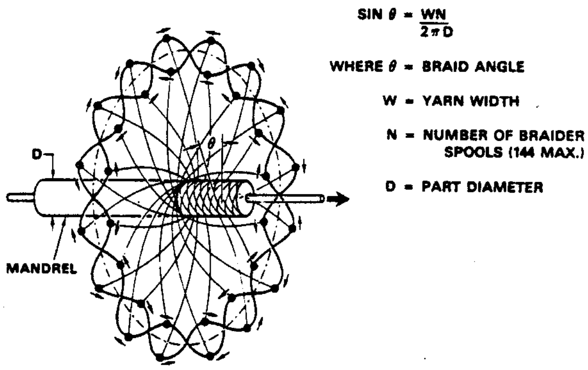

Figure 4. Schematic of Braiding Operation Used to Fabricate INPORT Units.

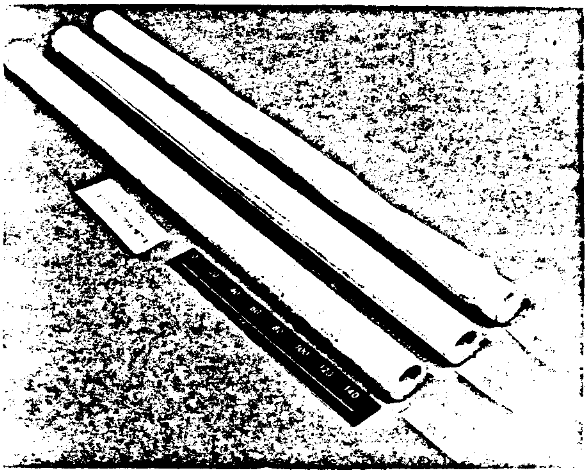

Figure 5. Examples of INPORT Units (see text for explanation).

Table 2

Filament Diameter	13 microns
# of Filaments/TOW	500
Density	2.5 g/cm^3
Tensile Strength*	250 kg/mm^2
Tensile Modulus	19,000 kg/mm^2

*Filaments retain 100% of their strength at 1000°C.

In summary, it has been demonstrated that INPORT units of the desired porosity and material can be fabricated. The next question is; Given the tubes can be made, how will their presence affect the nature of damage in the HIBALL cavity?

4. EFFECT OF INPORT UNITS ON RADIATION DAMAGE IN HIBALL

In this section we consider two effects, the damage produced in the SiC INPORT units themselves, and the effect of the Pb-Li filled INPORT units on the damage in the steel first walls.

Damage in SiC INPORT Tubes

In Figure 3 we observed that the packing density of the INPORT units was 33%, i.e., the "effective" thickness of the 2 m zone was only 66 cm. Neutronics calculations, using the appropriate SiC, Pb, and Li atom densities revealed that the displacement damage and helium production rates in the SiC vary as shown in Figures 6 and 7. The damage level of 118 dpa per full power year is equivalent to fast fission neutron fluences of ~1 x 10^{23} n/cm^2. At the back of the INPORT units the damage rate is only ~10 dpa/FPY (1 x 10^{22} n/cm^2 fission equivalent). Past studies by Price [18] have shown that the radiation induced expansion of alpha SiC saturates at ~10^{21} n/cm^2 or ~1 dpa. The level of expansion at saturation is inversely proportional to temperature as shown in Figure 8. In the temperature region typical of HIBALL, the linear expansion is no more than ~0.5% which yields a volume swelling of less than 1.5 to 2%.

Perhaps of more serious consequence in the SiC is the production of He by (n,α) reactions. Figure 7 shows that ~4000 appm He is produced per FPY. This amounts to less than 0.4% of the molecules being affected per FPY because of (n,α) reactions in C. However, it is clear that after a few FPY's, approximately 1% of the molecules will be destroyed and because of this high burnup rate, the lifetime will probably be limited to less than a few years in the tubes nearest to the target.

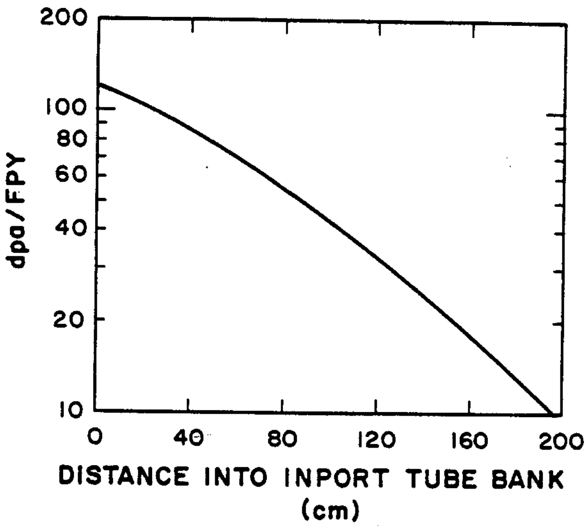

Figure 6. Variation of Displacement Damage in SiC INPORT Units.

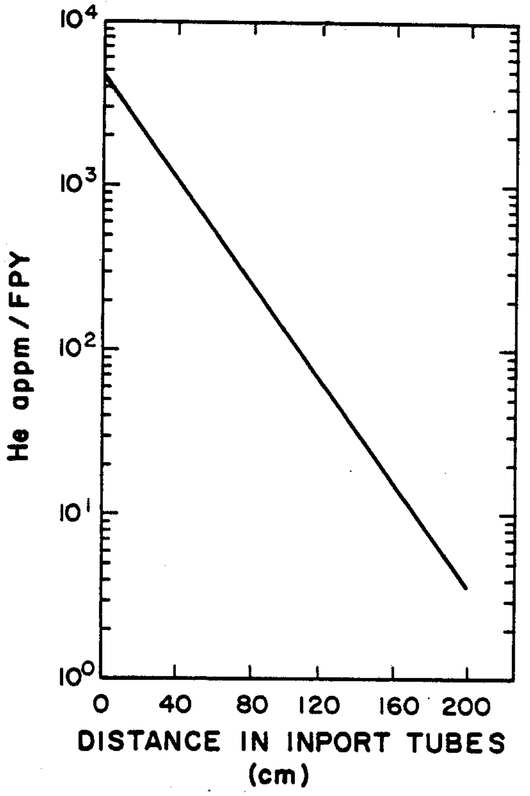

Figure 7. Variation of Helium Production in SiC INPORT Units.

Damage in the HT-9 Vacuum Wall

Figure 9 shows the effect of Pb-Li/SiC INPORT units on displacement, helium production, and the ratio of appm He/dpa in the HIBALL steel structure. We can see that without the INPORT units in front of the metallic wall, the damage level is 24 dpa/FPY. With 66 cm of Pb-Li/SiC, we find that the displacement damage is reduced to ~2.7 dpa/FPY.

An even more dramatic effect on the helium production is shown in Figure 9. In this case there is a ~1000 fold reduction in helium production; from ~200 appm He/FPY to ~0.2 appm He/FPY. Because of the relatively low temperature (300-500°C) it is felt that helium will not have much of an effect on determining the lifetime of the vacuum chamber.

If the lifetime of the HT-9 is limited by displacement damage at roughly 40 MW-y/m^2 (~400 dpa), the current DOE goal for fusion power plants, then the HIBALL metallic structure would have a useful life of over 100 FPY's. This is quite adequate for the present purposes and underlines the reason why there is so much enthusiasm for this concept.

5. CONCLUSIONS

Some of the more significant features of the INPORT concept are given below.

A. The INPORT concept can eliminate the direct exposure of metallic components to the target debris and X-rays in an ICF device.

B. The reduction of the flow rate in the INPORT units increases the ΔT in the coolant, thus reducing the pumping power of the system.

C. The porous nature of the INPORT units allows sufficient liquid to coat the tubes and absorb the X-ray and target debris energy.

D. Flexible INPORT tubes of SiC can be woven in a configuration compatible with an ICF cavity environment.

E. The neutron damage in SiC will probably cause some linear expansion to take place, but that should quickly saturate at $\lesssim$ 0.5% (~ 1 dpa).

F. The most probable life-limiting feature of SiC INPORT units is the high helium production rate of ~ 4000 appm/FPY.

H. The use of INPORT units containing an effective thickness of 66 cm of $Li_{17}Pb_{83}$/SiC materials will reduce the displacement damage by a factor of 10 and the helium production by a factor of 1000 from the unprotected case.

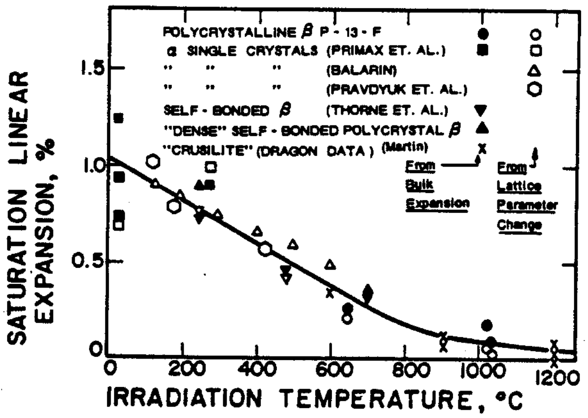

Figure 8. The Neutron Induced Expansion of SiC (after Price [18]).

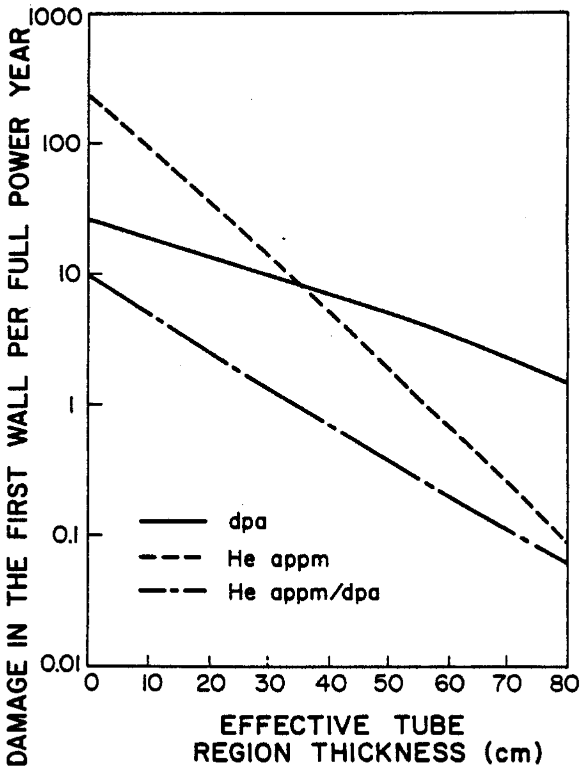

Figure 9. Effect of $Li_{17}Pb_{83}$/SiC INPORT Units on the Reduction of Radiation Damage in HT-9 Reflector Wall.

ACKNOWLEDGEMENT

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