A Novel First Wall Protection Scheme for Ion Beam ICF Reactors

E.A. Mogahed, P. Cousseau, R.L. Engelstad, R.R. Peterson,
H.Y. Khater, G.L. Kulcinski, J.J. MacFarlane, P. Wang,
M.E. Sawan, I.N. Sviatoslavsky, L.J. Wittenberg

September 1995

UWFDM-991

Presented at the 16th IEEE/NPSS Symposium on Fusion Engineering, 1–5 October 1995, Champaign IL

FUSION TECHNOLOGY INSTITUTE

UNIVERSITY OF WISCONSIN

MADISON WISCONSIN

Novel First Wall Protection Scheme for Ion Beam ICF Reactors

E. A. Mogahed, P. L. Cousseau, R. L. Engelstad, R. R. Peterson, H. Y. Khater, G. L. Kulcinski,
J. J. MacFarlane, P. Wang, M. E. Sawan, I. N. Sviatoslavsky, L. J. Wittenberg
Fusion Technology Institute
University of Wisconsin-Madison
1500 Engineering Drive, Madison, WI 53706

ABSTRACT AND INTRODUCTION

A novel first wall protection scheme for ion beam driven inertial confinement fusion reactors is presented. LIBRA-SP utilizes a self-pinched ion beam transport and is intended as a 1000 MWe power reactor. LIBRA-SP uses rigid HT-9 ferritic steel tubes called PERIT (perforated rigid tubes) units. These tubes are equipped with small nozzles on either side which spray vertical fans of liquid metal, overlapping each other such that the first two rows of tubes are completely shadowed from the target emanations. The target generated X rays accelerate the LiPb spray through the rapid vaporization of the surface facing the target. Simulations of the behavior of the spray with the BUCKY computer code show that the spray remains intact and is still at liquid density when it hits the PERIT units, producing a peak pressure on the PERITs of several GPa and a total impulsive loading of 72 Pa-s. The spray that is vaporized by the X rays blows into the center of the target chamber intercepting the target debris ions. The first row of tubes in the blanket carry the brunt of the radial impulsive load, which is applied at the reactor repetition rate. A code has been developed for determining the mechanical transient and steady state response of the tubes containing the liquid metal, driven by sequential pulses for specific boundary conditions. Maximum steady state deflections and bending stresses as a function of the rep-rate are calculated and used to optimize the length of the PERIT units for avoiding resonant conditions. The cylindrical portion of the chamber is covered by a blanket of rigid steel tubes at a packing fraction of 50%. Only the front two rows of tubes are equipped with the spray nozzles. These tubes are at a radius of 4 m, and the radius of the reflector, which is the vacuum boundary, is 5.2 m.

I. OVERALL DESIGN

In LIBRA-SP there are 24 ion beams altogether. Figure 1 is a cross sectional view of the reaction chamber. The vertical sides of the chamber contain a blanket zone consisting of many perforated rigid ferritic steel tubes with a packing fraction of about 50% through which the breeding/cooling material, liquid lead-lithium, flows. This blanket zone, besides breeding T_2 and converting neutron energy to thermal energy, also provides protection to the reflector/vacuum chamber so as to make it a lifetime component. The length of the first row tubes is 10.4 m, divided in two segments of 5.2 m each

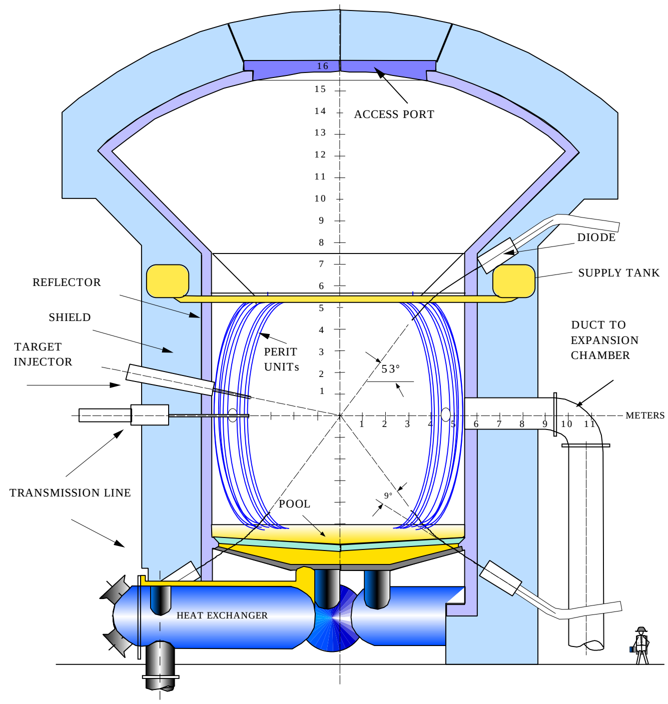

Fig. 1. Cross-sectional view of the reactor chamber.

between supports. The tubes are rigid for structural integrity and are perforated so they can maintain a wetted surface through the jet fan spray. There are two rows of PERIT units, the first consisting of 7.2 cm diameter and the second of 8.0 cm diameter tubes. At midplane the row's centerlines are 14 cm apart and the centerlines between tubes in each row are also 14 cm apart. The front tubes totally shadow the rear zone. There are 7 rows of HT-9 ferritic steel rear tubes, 15 cm in diameter, shown in Fig. 2. They transport the PbLi which moderates neutrons and breeds T_2. Behind the blanket is a 50 cm thick HT-9 reflector which is also the vacuum boundary. The whole chamber is surrounded by a steel reinforced concrete shield nominally 2.7 m in thickness. Figure 1 also shows vacuum tubes located behind the shield/blanket zone at the chamber midplane which lead to an expansion tank situated below the reaction chamber. Vapor flows into the expansion tank following a shot, exchanging heat with the PERIT units and cooling by isentropic expansion. Vacuum pumps attached to the expansion tank evacuate the noncondensable species in preparation for the next shot.

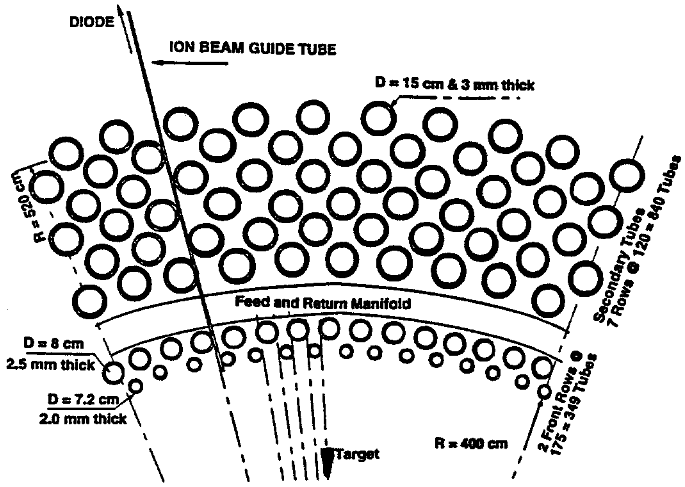

Fig. 2. The distribution of PERIT units and the shield/blanket zone.

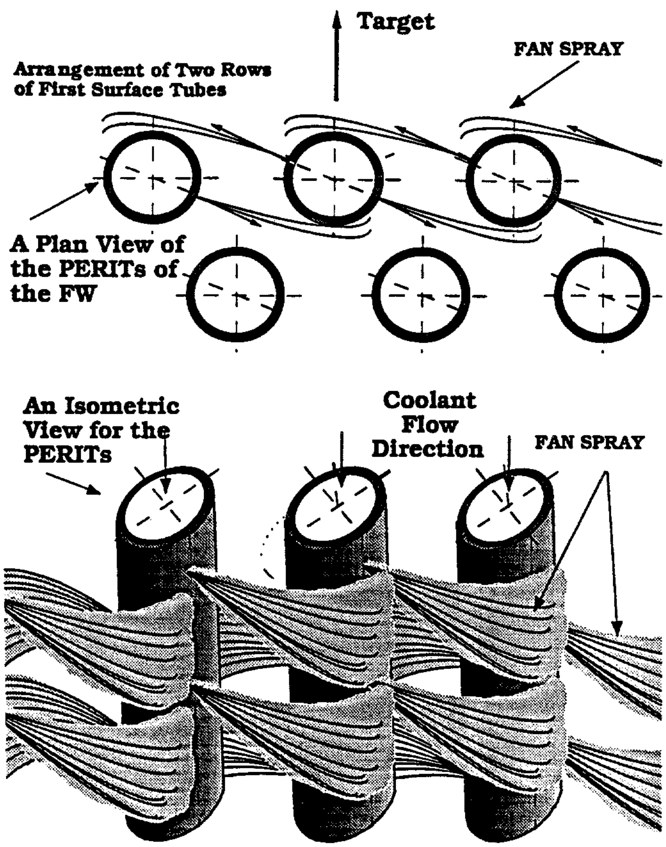

Fig. 3. First surface protection by fan sheet spray.

The chamber roof is unprotected. It is 16 m from the target, which makes it a lifetime component. Part of the roof and its shield are removable, providing access for chamber maintenance. Since the roof will be cooled, it also will condense vapor and have a wetted surface which will be vaporized after each shot. Another function of the mushroom shape is to protect the side walls (which are shadowed by the PERIT units) and to provide additional chamber volume for vapor expansion.

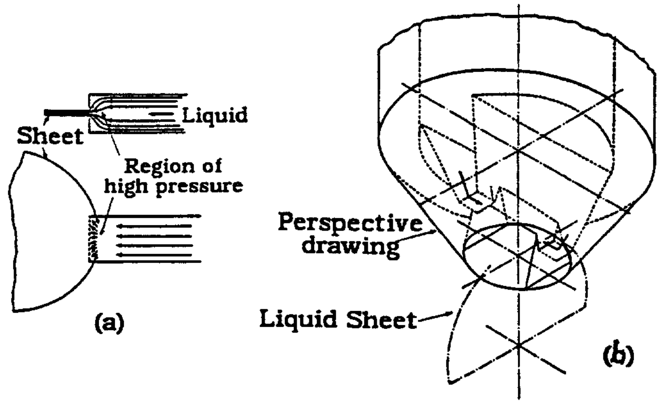

Fig. 4. Sketch of mechanism of flow through fan sheet nozzle.

The coolant feed pumps only supply the liquid metal to the open liquid tank at the top of each segment group. The liquid metal flows under gravity down the coolant tubes and through the perforations. Figure 3 shows a schematic of the PERIT units with the fan sheet sprays. The PbLi coolant enters the reactor at 370°C, exits at an average temperature of 500°C and collects in the bottom pool. The pool drains through a perforated plate into a sump leading to the intermediate heat exchangers (IHX) located in the base of the chamber. In the IHX the PbLi exchanges heat with liquid PbLi, which is pumped to a steam generator. A fraction of the PbLi flow is diverted to a T_2 removal system.

II. FIRST SURFACE PROTECTION

A. Recent Work and Discussion

1) *Formation of liquid sheets.* In this work, our attention will be concentrated on flat liquid sheets. Taylor [1] explains the principles of liquid sheet formation. In practice, in the fan sheet nozzle, two streams of liquid are made to impinge behind an orifice by specially designed approach passages and a sheet is formed in a plane perpendicular to the plane of the streams. The principle is illustrated in Fig. 4(a) which shows liquid flowing through a rectangular orifice formed at the end of the rectangular tube. A flat sheet is produced as the liquid freely spreads through the orifice limited only by the side walls. A commercial nozzle is shown in Fig. 4(b). It is designed on this principle, made of ceramic material and contains a rectangular orifice which is produced by the interpenetration of two rectangular slots.

In the absence of surface tension, the edges of the sheet would travel in straight lines from the orifice so that a sector of a circle would be formed. However, as a result of surface tension, the edges contract and a curved boundary is produced as the sheet develops beyond the orifice. Liquid at the edge moves along the curved boundary, and later becomes disturbed and disintegrates [1]. The breakdown of the edges is restrained by viscosity. At higher injection velocities the contraction is less pronounced, and the placid sheet eventually becomes ruffled and experiences violent oscillations due to a flag-like instability caused by the reaction of the surrounding gas with the sheet. In our case where the surrounding gas is at very low pressure these flag-like instabilities are less likely to occur.

2) Analysis of flow in sheets. In order to examine the nature of the fluid stream lines in a fan sheet, investigators [1,2] have used photographs of jets containing aluminum particles. Measurements from successive photographs with different conditions indicate that the stream velocity is constant along the sheet and its absolute value depends only on the differential injection pressure.

G. I. Taylor [1] and N. Dombrowski et al. [2] analyzed this problem and the latter reached an approximate expression for the trajectory and obtained an expression for the sheet thickness (see Ref. 4 for detailed analysis). These calculations are used to design the nozzles needed to produce satisfactory liquid metal sheets for LIBRA-SP. To obtain full coverage for the PERITs, every consecutive sheet must overlap. The required overlap gives the distance between each consecutive nozzle to be 8 cm.

From the structural dynamics (fatigue) point of view, it is better to have the perforations as close as possible to the bending plane (less stress concentration). Then, the direction of the jet is chosen to make the sheet 1.0 mm away from the surface of the next PERIT. Exactly on the opposite side of the PERIT there is another system of perforations but staggered 4.0 cm in the vertical direction to complete the coverage of the cavity first surface. The mechanical advantage of having both perforations on the opposite sides is that the lateral jet reaction is canceled.

III. MECHANICAL RESPONSE

A. Interaction of Target Emanations with Spray

The deposition of target X rays and debris ions in the spray causes an explosive expansion of the region of the spray facing the target. This blows a small amount of vapor into the middle of the chamber, drives a shock through the spray and accelerates the bulk of the spray toward the PERITs. The BUCKY [3] computer code has been used to study these phenomena in the LIBRA-SP target chamber [4].

The results of a BUCKY simulation of the reaction of the spray to the target is summarized in Table I. The PbLi spray is initially 40 μm thick at 600°C. In this simulation, it can be seen that the spray mostly remains intact and will coast at a constant speed until it strikes the PERITs. The simulation shows that the spray collides with the PERITs at 0.8 μs, so the spray is moving at about 1.8×10^4 cm/s. At the time of collision, the pressure on the PERITs quickly rises to about 11 GPa after which it begins to disperse. A total impulsive pressure of 71 Pa-s is applied to the PERITs. A shock which is initially driven through the spray by the rapid deposition of target energy reaches the back of the spray at about 0.07 μs. About 1.15 mg/cm^2 of the spray is blown into the middle of the target chamber [4].

Table I
Summary of BUCKY Simulation of Spray Behavior

Initial spray thickness	40 μm
Spray velocity	1.8×10^4 cm/s
Shock velocity	5.7×10^4 cm/s
Peak pressure on PERITs	11 GPa
Impulsive pressure on PERITs	71 Pa-s
Mass blown into chamber	1.15 mg/cm^2

B. Mechanical Response of the PERIT Units

It is expected that the first two rows of PERIT units will be subjected to the radial impulse load from the blast wave. The primary response of the tubes will be a radial displacement (or planar displacement); however, it has been shown that the tubes could begin to "whirl" under certain operating conditions [5,6]. If three-dimensional motion takes place, it is assumed that the maximum displacement would not be greater than the maximum planar displacement. Characterizing the planar motion and the resulting stresses in the PERIT units is essential for a credible design.

The general equation of motion describing the mechanical response of a PERIT unit under sequential impulse loading can be found in [4]. A modal solution of the equation of motion for arbitrary boundary conditions is also given. In the above derivation the following assumptions were made. The pressure load is assumed to be uniformly distributed over the length of the tube and is applied at the rep-rate of the reactor. In the previous section, the magnitude of the impulse load was calculated at 71 Pa-s. The results scale linearly, so the displacements and stresses can be easily determined for any impulse magnitude. Since the flow velocity of the PbLi is small, the effects of the moving liquid within the tube can be neglected and the fluid considered stationary. Stationary fluid in a tube adds mass to the system without changing the flexural rigidity of the tube. Rayleigh damping was used to model internal structural damping; external viscous damping was neglected. The damping ratio of the fundamental natural frequency was set at 0.5%. For this study two different end conditions were examined; pinned-pinned and clamped-clamped. Because of the generality of the modal solution, other more complicated boundary conditions can be studied by using their associated orthogonal shape functions. A finite element model of a PERIT unit under sequential impulse loading was also constructed using the commercially available program ANSYS®. The finite element model confirms the results from the modal solution.

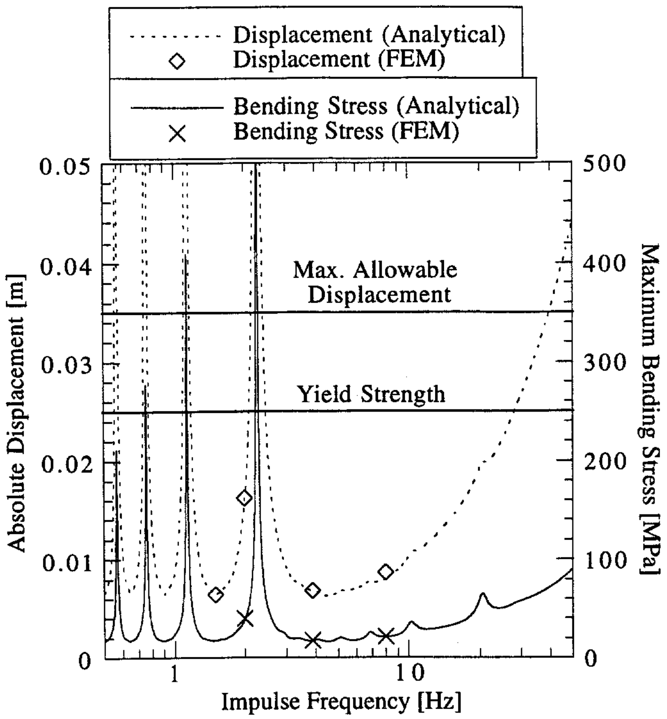

Fig. 5. Maximum steady state midspan displacement and bending stress of a pinned-pinned PERIT unit.

For the proposed LIBRA-SP cavity, a number of the PERIT design parameters have been set by power requirements and heat transfer requirements, as well as the use of HT-9 as the tube material and PbLi as the liquid metal. The length of the tubes remained as a design parameter to be optimized. Parametric studies were performed to determine the necessary length to preclude resonant conditions and minimize the radial displacements and bending stresses. Figure 5 shows the midspan displacement amplitude as a function of the impulse frequency (or rep-rate) for a pinned-pinned tube with a length of 5.3 m. A maximum allowable displacement of 3.5 cm, to prevent tube interference, has been noted on the figure. For a rep-rate of 3.88 Hz, the absolute displacement of the tube is well below the allowable deflection. Figure 5 also shows the corresponding midspan bending stresses with the yield strength of the material [7] indicated. This figure illustrates the frequencies or rep-rates associated with resonant conditions, i.e., the peaks in the response curves. The large peak in the center of the figure is the fundamental frequency of the system and the peaks to the left are overtones of the fundamental frequency. These peaks would effectively shift as the length of the tube changes. Therefore, it is imperative to design the free span of the tube at approximately 5.3 m in order to shift the reactor's operating rep-rate, 3.88 Hz, from the resonant peaks.

IV. SUMMARY AND CONCLUSIONS

A new scheme for first wall protection in ion beam driven inertial confinement fusion reactors is presented. The scheme utilizes rigid HT-9 ferritic steel tubes equipped with small nozzles which spray vertical fans of liquid PbLi, overlapping each other such that full coverage of the front rows of tubes is obtained, protecting them from the target emanation. The balance of the blanket and shield zone is also filled with rigid HT-9 tubes which are not equipped with nozzles. The PbLi flows through the tubes under gravity, collects in a bottom pool, then drains through a perforated plate to a sump leading to intermediate heat exchangers.

Making the tubes rigid solves a major problem of the flexible woven tubes used in earlier designs, namely that of maintaining a constant tension needed to control deflection. At the same time, it addresses the issue of controlled seepage through woven tubes which can change over time. In that respect, it represents a major improvement in the method of first wall protection for LIBRA-type ion driven inertial confinement reactors.

ACKNOWLEDGMENT

Support for this work was provided by the U. S. Department of Energy through Sandia National Laboratory and Forschungszentrum Karlsruhe, Karlsruhe.

REFERENCES

[1] G. I. Taylor, "Formation of Thin Flat Sheets of Water," The Scientific Papers of Sir Geoffrey Ingram Taylor, Edited by G. K. Batchelor, Trinity College, Cambridge, UK, Vol. IV, Paper #33, pp. 378-396, 1971.

[2] N. Dombrowski, D. Hasson and D. E. Ward, "Some Aspects of Liquid Flow Through Fan Spray Nozzles," Chemical Engineering Science, Pergamon Press Ltd., London, Vol. 12, pp. 35-50, 1960.

[3] J. J. MacFarlane et al., "BUCKY-1, A 1-D Radiation Hydrodynamics Code for Simulating Inertial Confinement Fusion High Energy Density Plasmas," University of Wisconsin Fusion Technology Institute Report UWFDM-984, August 1995.

[4] B. Badger et al., "LIBRA-SP - A Light Ion Fusion Reactor Design Study Utilizing a Self-Pinched Mode of Ion Propagation, Report for the Period Ending June 30, 1995," University of Wisconsin Fusion Technology Institute Report UWFDM-982, June 1995.

[5] R. L. Engelstad, "Vibration and Stability of Vertical Tubes Conveying Fluid Subjected to Planar Excitation," Ph.D. Thesis, University of Wisconsin-Madison, 1988.

[6] Y.- M. Lee, "Nonlinear Vibration and Stability of a Beam Subjected to Planar Excitations," Ph. D. Thesis, University of Wisconsin-Madison, 1994.

[7] SANDVIK HT9 "Martensitic Chromium-molybdenum steel," S-1720-ENG. SANDVIK Steel Catalog, May 1981