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UWFDM-446

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Summary

The heavy ion beam ICF reactor HIBALL incorporates an annular array of vertical tubes between the cavity per se and the first structural wall. These tubular components (INPORT units) are fabricated from porous woven silicon carbide. Liquid LiPb flows within the units and through the porous walls to form a protective exterior surface film. X-rays vaporize a portion of this layer resulting in an impulsive pressure on the tubes. This paper is concerned with the mechanical response of the SiC INPORT units from this dynamic loading.

Introduction

A persistent problem in the development of inertial confinement fusion (ICF) reactors is protection for cavity structural walls from target debris, X-rays and neutrons. For this purpose a novel design has been proposed for the heavy ion beam fusion reactor HIBALL, a conceptual design jointly developed by the University of Wisconsin Fusion Engineering Program and the Kernforschungszentrum Karlsruhe, FRG[1]. As shown in Figure 1, the general configuration of the reactor chamber is cylindrical with the cavity first wall masked by an annular tube bank through which liquid $Li_{17}Pb_{83}$ flows. Individual tubes are made of woven silicon carbide fibers and are both pliable and porous. These have been named INPORT units, the acronym originating from Inhibited Flow/Porous Tube. The primary flow of LiPb is within the INPORT unit but the wall porosity results in the development of a thin exterior film (approximately 1mm thick) as shown in Figure 2. This layer protects the INPORT by absorbing target debris and X-rays. Film vaporization from this energy deposition produces a reactive impulse on the tube. The work which follows is an assessment of the mechanical response of the INPORT units to such dynamic pressure.

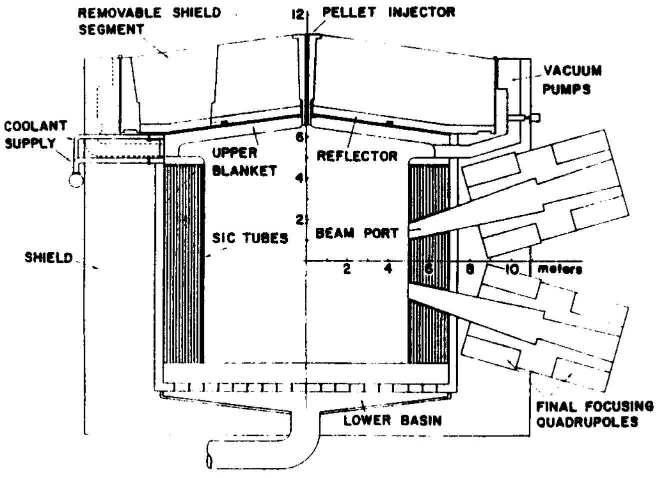

Figure 1. HIBALL Chamber Design

TABLE I

Principal HIBALL Parameters

DT Power Level	8000 MW
Net Electrical Output	3768 MWe
Accelerator Type	RF - Linac
Beam Ions	Bi^{+2} @ 10GeV
Firing Rate/Chamber	5 Hz
Number of Chambers	4
Chamber Wall Material	HT-9
Breeder and Coolant	$Li_{17}Pb_{83}$

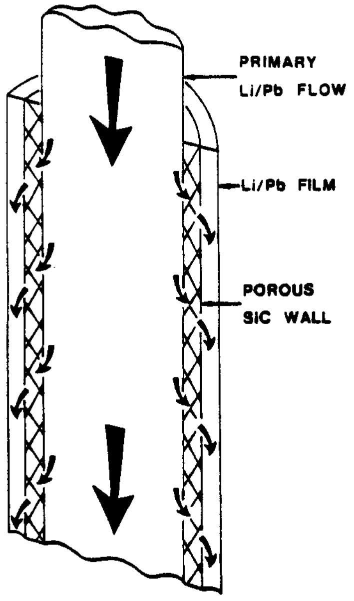

Figure 2. Sectioned INPORT Unit

Impulse Determination

It is necessary to estimate the magnitude of the impulsive loading exerted on the INPORT units. On a conservative basis, the bulk kinetic energy of the vaporized fluid can be equated to the thermal energy of the gas.

$$(3/2)(M_{gas}/m_{ion})k_B\ T_{gas} \doteq (1/2)\ M_{gas}V^2$$

The left side of this equation represents the gas thermal energy which is equal to deposited X-ray energy less the energies of ionization and vaporization. The gas bulk velocity is denoted by V and m_{ion} represents the average mass of ions in the gas. For 87.6 MJ of X-ray energy and 13.3 kg of vaporized LiPb, T_{gas} is 1.2eV. The reactive impulse, ΔI, is $M_{gas}V$.

$$\Delta I = M_{gas}(3k_B\ T_{gas}/m_{ion})^{1/2} = 1.89\text{x}10^9 \text{ dyne - sec.}$$

The corresponding impulsive pressure is

$$\Delta P = 600 \text{ dyne - sec/cm}^2$$

This evaluation is conservative since it is assumed that all vaporized atoms are initially moving towards the cavity center with their thermal velocity. Consequently the impulsive loading is overestimated.

INPORT Characteristics

The units comprising the first two rows of the annular tube bank have a diameter and thickness of 3 cm and 0.8 mm, respectively. Only these first two rows receive the one-sided impulsive pressure, axially distributed as shown in Figure 3. All units are 10 m long and have top ends connected to upper blanket modules which provide support and are the source of LiPb. The lower ends are either free (one point suspension) or are mechanically restrained from moving (two point suspension). Both stiffened and unstiffened silicon carbide tubes have been considered for the INPORT units. In the former case the woven tubes are rigidized with a SiC binder or matrix. The members resist transverse loading by flexural action, not unlike structural beams. Preliminary studies have shown that resonance, large deflections and excessive flexural stresses are potential problems for this design unless supplementary structural support is provided. With these considerations and cost comparisons, unstiffened tubes are preferable in this application. Such flexible INPORT units react to lateral loading with tensile force development alone, i.e., having negligible shear and bending resistance. In the work which follows, dissipation is accounted for by including viscous damping in the system.

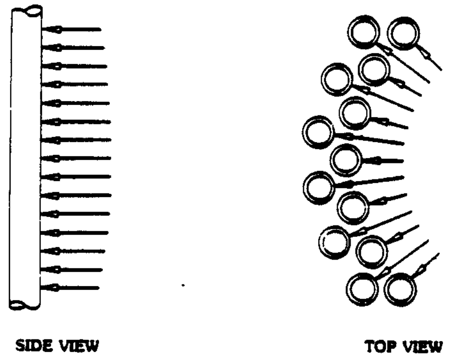

Figure 3. Impulse Characterization

INPORT Response - One Point Suspension

The analysis is based upon modal superposition using small deflection theory or more precisely, small slope theory, with the tension gradient in the axial direction equal to the weight per unit length. Calculations include the weight of the LiPb, the SiC and the outer surface film. Analytical details can be found in UWFDM 450[1]. Numerical results were obtained from a computer program based upon this analysis. In all cases the impulse was considered uniformly distributed along the length. Natural vibration frequencies are necessary for these calculations and resonance considerations. Representative values are listed in Table II.

Deflection profiles for undamped motion following a single shot are shown in Figure 4. The quantitative time history of Figure 5 corresponds to this case also. The maximum midpoint and tip deflections are approximately 16 and 55 cm, respectively. The program was extended to determine INPORT unit response under repetitive impulses at 5 Hz. Damping was included with the magnitude expressed as a percentage of the so-called critical value, i.e., the damping coefficient which would produce non-oscillatory response.

TABLE II

INPORT Natural Frequencies (Hz)

Mode Number	One Point Suspension	Two Point Suspension
1	0.1895	0.3778
2	0.4351	0.7557
3	0.6821	1.1335
4	0.9294	1.5113
5	1.1768	1.8892

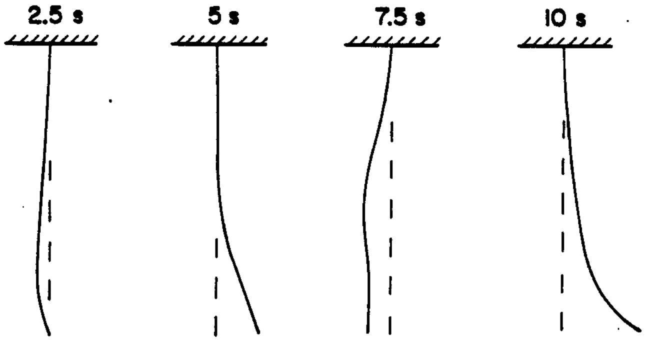

Figure 4. Deflected Shapes at Various Times After Impulse

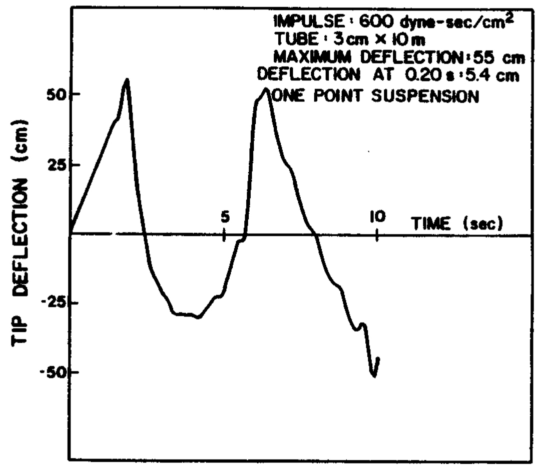

Figure 5. Single Shot INPORT Response

The damping levels used here are much higher than for metallic reactor components but the INPORT units have a significant natural damping capacity from the soft woven construction and the ever present LiPb in liquid form. Figure 6 corresponds to start-up, with the initial velocity and displacement zero. At the end of 0.20 sec the velocity and displacement functions are determined and used as starting conditions with another uniform impulsive pressure. The process is repeated and carried out for fifty shots. (The time scale shown corresponds to the first thirty-five shots.) Initially there is substantial overshoot for moderate damping with all cases eventually stabilizing to the displaced configuration corresponding to the equivalent static load.

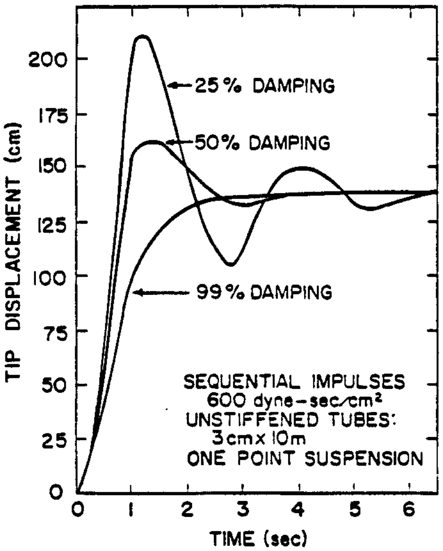

Figure 6. INPORT Response at Start-Up

INPORT Response - Two Point Suspension

In order to reduce transverse motion, consideration was given to a design which constrained both the upper and lower ends of the INPORT unit. Time histories were determined for midspan displacements for various levels of damping. Figure 7 is a typical result for a single impulse. Under sequential impulses at a repetition rate of 5 Hz, start-up simulation again showed overshoot for low damping levels with steady state amplitudes reached rather quickly as shown in Figure 8. On a relative basis these mean amplitudes are moderate, typically less than 2% of the length.

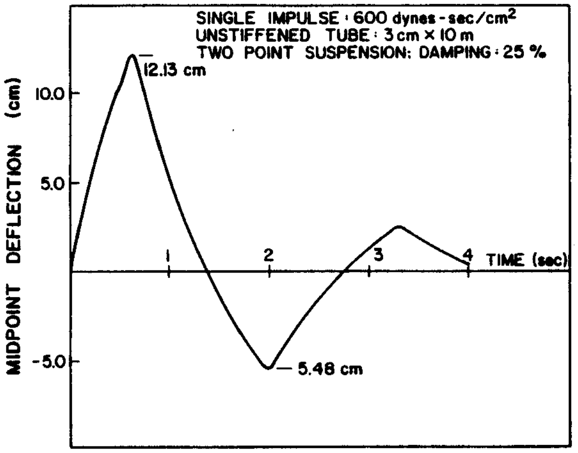

Figure 7. Single Shot INPORT Response

Finally the response was determined following shutdown. The free transient motion shown in Figure 9 follows fifty shots. The displacement history is very smooth even though it is made up of contributions from many modal components. The results confirm expectations that no unusual characteristics develop for this scenario.

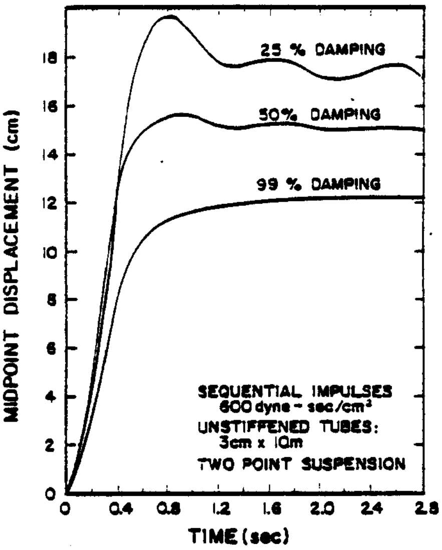

Figure 8. INPORT Response at Start-Up

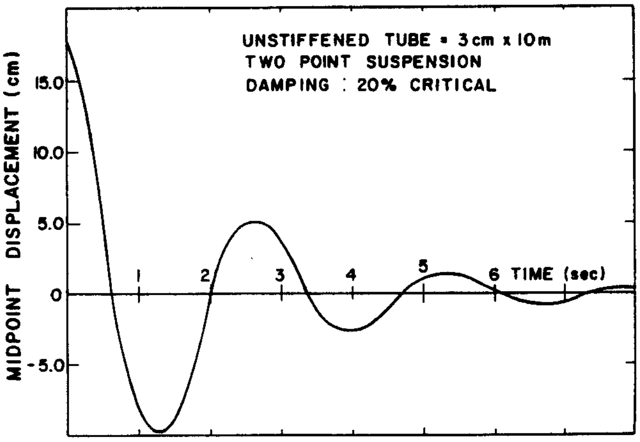

Figure 9. INPORT Response Following Shutdown

Conclusions

The analysis of the mechanical response of INPORT units has shown that the vibration and deflection characteristics are generally very compatible with the design of the heavy ion beam reactor HIBALL. Repetitive pulsing of tubes supported at one end produces sizable displacements for a wide range of damping values. This disadvantage could be accommodated in future designs with appropriate space allowances for such response. Similar pulsing of INPORT units supported at both ends results in deflections of a much smaller amplitude, typically less than 2% of the length. The modelling also indicates that reactor shutdown produces no undesirable INPORT motion.

Thus, on a mechanical basis, it appears that the INPORT concept is sound and a potentially promising solution to the problem of ICF first wall protection.

Acknowledgment

The authors gratefully acknowledge the support provided by the Federal Republic of Germany through Kernforschungszentrum Karlsruhe (KfK). The HIBALL study is part of a basic research program established by the German Federal Ministry of Research and Technology; work performed under agreement with Fusion Power Associates, Gaithersburg MD.

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1. "HIBALL - A Conceptual Heavy Ion Beam Driven Fusion Reactor Study," UWFDM-450; KfK-3202, June 1981, Fusion Engineering Program, University of Wisconsin, Madison.