FPA Contribution to FRG Heavy Ion Fusion Project
Annual Report

R.R. Peterson, L. Pong, A. Hassanein, D.K. Sze, I.N. Sviatoslavsky, K.E. Plute, M.E. Sawan

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FUSION POWER ASSOCIATES

2 Professional Drive, Suite 248
Gaithersburg, Maryland 20879
(301) 258-0545

1500 Engineering Drive
Madison, Wisconsin 53706
(608) 263-2308

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Foreward

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Contents

Gas Dynamics of $Li_{17}Pb_{83}$ Vapor in HIBALL

In the recently published HIBALL, heavy ion beam fusion reactor conceptual design,[1] the structural walls of the target chamber vessel are protected from the pulsed energy of the target explosion by a system of porous SiC INPORT tubes[2] through which flows liquid $Li_{17}Pb_{83}$. These INPORT tubes are themselves protected from the damaging target generated x-rays and ions by a film of $Li_{17}Pb_{83}$ on their surfaces which absorb the x-rays and ions. A portion of this film is vaporized during the absorption of the x-rays and it flows into the center of the target chamber. When the ion beams are directed into the target chamber, the density of the vapor must be at or below 4×10^{10} cm^{-3} for enough of the ion energy to reach the fusion target to cause ignition. This required density is several orders of magnitude below the maximum density of the vapor. For this reason, the repetition rate of the cavity may be critically dependent upon the amount of time the vapor takes to recondense. The gas dynamics of this $Li_{17}Pb_{83}$ vapor as well as the deposition of the x-rays and ions in the film and the heat transfer in the film have been studied and a condensation time for the cavity has been determined.[3]

The history of the $Li_{17}Pb_{83}$ vapor may be traced through 7 stages.

1. The film is vaporized by the x-rays.
2. The vapor begins moving into the target chamber and after about 10^{-4} sec, it absorbs the ions and raises its temperature to above 1 eV.
3. The vapor continues to flow towards the center of the chamber but begins radiating energy onto the INPORT tubes.
4. Additional $Li_{17}Pb_{83}$ is evaporated off of the tubes by this flux of radiant heat.

5. The increased amount of vaporized mass increases the opacity of the gas, decreasing the flux of radiant heat.
6. The vapor reaches the center of the chamber and converts its kinetic energy into heat.
7. The vapor condenses back onto the tubes.

The analysis of this scenario has been achieved with several coupled computer codes. The x-ray spectrum was obtained from a target burn simulation.[1] Deposition of the x-rays and creation of the vapor was modeled by an x-ray stopping code and the gas flow and radiation transfer were modeled with a radiation hydrodynamics code.[3] The condensation and evaporation were analyzed with a separate code but a recently developed form of the hydrodynamics code includes these effects in a self-consistent way.

The density of the vapor as a function of time has been calculated with this analysis. It has been found that the vapor density reaches the desired value approximately 0.2 sec after the target explosion, allowing a 5 Hz repetition rate. There still exist some uncertainties in these calculations and work is presently underway to improve their accuracy.

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1. B. Badger et al., "HIBALL - A Conceptual Heavy Ion Beam Driven Fusion Reactor Study," KfK 3202/1 - UWFDM-450 (December 1981).

2. G.L. Kulcinski et al., "The INPORT Concept - An Improved Method to Protect ICF Reactor First Walls," University of Wisconsin Fusion Engineering Program Report UWFDM-426 (August 1981).

3. R.R. Peterson et al., "Gas Dynamics in Liquid Metal ICF Reactor First Surfaces," University of Wisconsin Fusion Engineering Program Report UWFDM-443 (October 1981).

INPORT Concept

One of the most difficult problems in ICF (Inertial Confinement Fusion) is that of protecting the first wall of the cavity against target debris, X-rays, neutrons and shock waves. Various schemes have been proposed such as swirling liquid metal pools,[1], wetted walls,[2] magnetic protection,[3] gaseous protection,[4] dry wall ablative shields,[5] and free falling liquid metal streams.[6] None of these schemes have been completely satisfactory, but the free falling stream of liquid metal, employed in HYLIFE[7], seems to be the best developed thus far.

There are two major disadvantages to the free falling liquid metal stream. Since the residence time of the liquid metal in the cavity is so short, it takes several passes through the cavity before it heats up sufficiently for effective use in a power cycle, thus requiring a high recirculation rate and a high pumping power. Furthermore, because each shot completely disassembles the streams, the repetition rate is determined by the time it takes to settle out the mist and reestablish the streams.

A desire to retain the salient features of the free falling liquid metal protection scheme while eliminating its disadvantages has led to the INPORT (Inhibited Flow Porous Tube) concept, developed for HIBALL in late 1979. In this scheme, shown schematically in Fig. 1, the liquid metal flows through flexible braided porous SiC tubes suspended within the cavity. The SiC material is extremely strong at high temperatures and is compatible with the $Li_{17}Pb_{83}$ breeding material proposed for use in HIBALL. The flow can be retarded, thus increasing its residence time in the cavity leading to an adequate temperature rise after a single pass and resulting in lower pumping power. The braided SiC fabric which surrounds and guides the liquid metal,

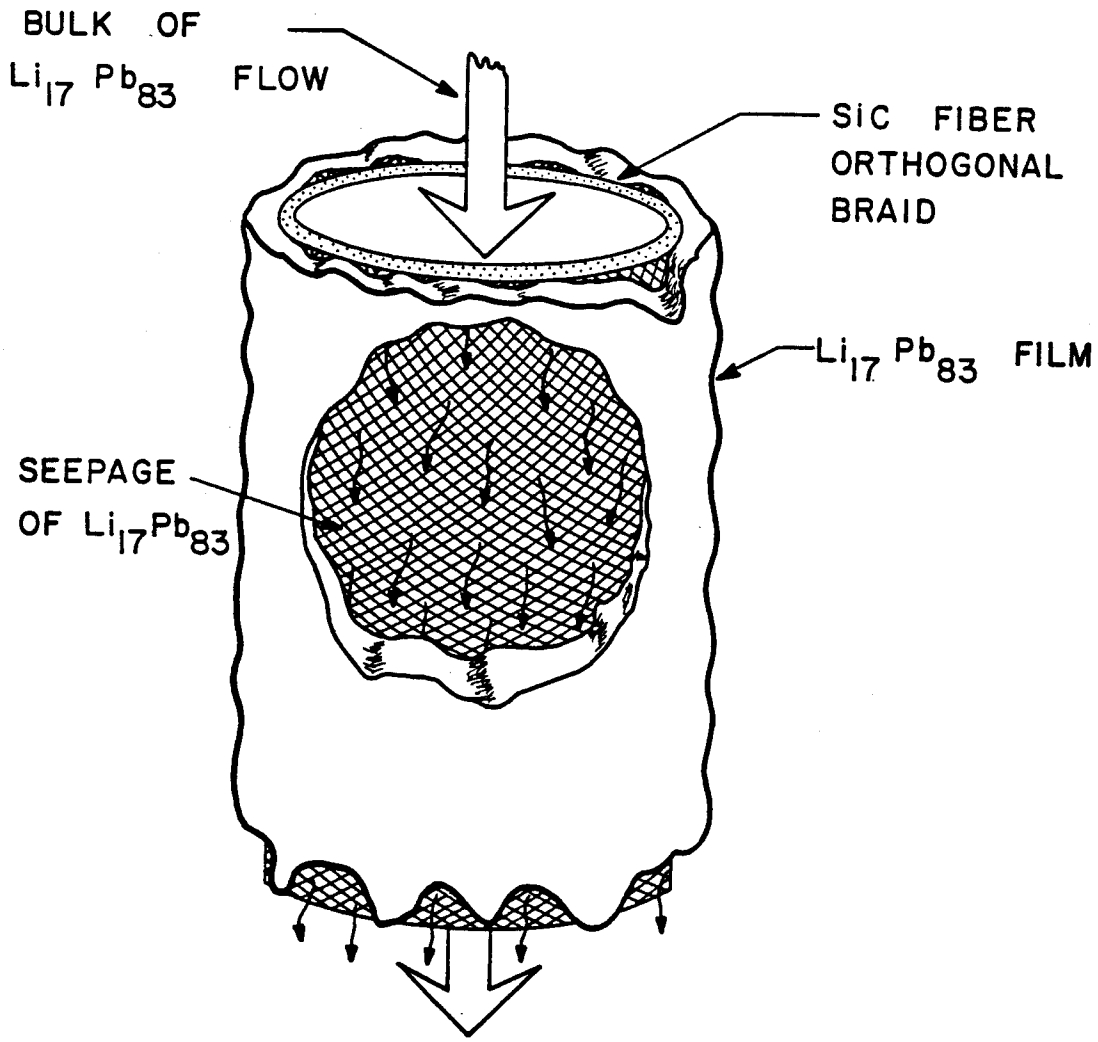
BULK OF
$Li_{17}Pb_{83}$ FLOW
SiC FIBER
ORTHOGONAL
BRAID
$Li_{17}Pb_{83}$ FILM
SEEPAGE
OF $Li_{17}Pb_{83}$

Figure 1

prevents its disassembly after a shot. The repetition rate limiting factor is not the time needed to settle the mist and reestablish the streams, but rather the time needed to condense the vapors in the cavity, which is substantially shorter. Because the tubes are porous, there will always be a wetted surface presented to the X-rays and target debris. No solid material is ablated, rather a small fraction of the wetted surface is evaporated, only to recondense upon the large surface area of the tubes in a relatively short time. By ensuring a sufficiently thick effective breeding material zone, the first structural wall of the cavity can be protected for the lifetime of the reactor. Thus, the only replaceable components within the cavity are the INPORT tubes, which are designed for relatively easy changeout.

Although the INPORT concept appears to solve most of the immediate problems of ICF first wall protection, it raises some questions that must be answered. Among these questions are:

- How can this concept protect all the surfaces in the cavity?
- What is the response of the tubes to repeated impulses?
- How can the flow in the tubes be regulated?
- What is the stability of the wetted surfaces?

Protecting the roof of the cavity is, perhaps, the most difficult aspect of this scheme. In HIBALL it was proposed to cover the roof with wedge shaped modules which have the same type of SiC braided fabric covering the surface facing the inside of the cavity. The wedges would be removable individually for changeout. Breeding material is allowed to flow radially inward on the upper half of the module, then turn and flow radially outward on the bottom half. The surface facing the X-rays and ions will be wetted as in the tubes.

The stability of the external wetted surface is in question and remains to be investigated.

Providing protection for the beam ports leads itself to several solutions with the INPORT concept. For HIBALL we have proposed a scheme in which the tubes connect into a manifold which routes the flow around the beam tube and then reconnects into tubes below. The manifold itself will be made of SiC and will afford the same protection as the tubes.

Since the bottom of the cavity is a pool of liquid metal, the only problem here is to provide some shock absorbing damping. A perforated plate on the bottom of the pool serves this function, dissipating energy as the liquid is forced through the perforation.

The response of the tubes to repeated shocks has been analyzed in several support configurations. It was found that a two point support, one on top and the other fixing the tubes on the bottom seems to work very well. Assuming a 20% damping in the tubes, which seems reasonable for such a system, the maximum steady state displacement at midplane for a 5 Hz repetition rate is ~ 15 cm. The design can easily accomodate such a condition. The response of the roof modules to repeated impulses is presently being investigated.

Flow in the INPORT tubes can be regulated with restriction on the bottom. The seepage through the fabric depends on the void fraction in the braid and the breeding material pressure. Since there will be a pressure gradient due to the static head in each tube, the void fraction in the braid will have to be graded from top to bottom in order to regulate the amount of seepage. This is particularly true of the first several rows of tubes which must remain wetted at all times. Grading the void fraction in the braid does not present any undue difficulty in manufacturing of the tubes.

The wetted surface stability does not appear to be a problem for the tubes, but is very serious for the upper module surfaces. The stability of the wetted surface depends on the slope of the roof, the permeability of the fabric and on certain physical properties of $Li_{17}Pb_{83}$. This problem will be addressed analytically to the extent that such data is available.

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Summary of the Tritium Inventory in HIBALL

HIBALL is a heavy ion beam reactor consisting of four reactor chambers which produce a total DT power of 8000 MW. The reactor cavities are fueled with multilayered targets containing 4.0 mg of DT at a rate of 5 per second per cavity. A one day fuel supply consists of 2.8 kg D and 4.1 kg T. The fraction of fuel burned is 0.29, thus 1.9 kg D/d and 2.9 kg T/d are handled by the exhaust system. In addition, 2.8 kg/d of D_2 used to propel the target and 1.5 kg/d of tritium bred in the $Li_{17}Pb_{83}$ blanket will enter the exhaust processing system.

The chamber exhaust is pumped by compound cryopumps with on-line times of 2 hours and a tritium inventory of 0.37 kg. The pumps are regenerated so that helium is released first, then the hydrogen isotopes are released and sent to the fuel cleanup unit. The purpose of the fuel cleanup unit (T_{INV} = 0.041 kg) is to remove impurities from the hydrogen isotopes before sending them to the cryogenic distillation units. The distillation system which consists of 4 columns (T_{INV} = 0.083 kg) removes hydrogen impurities, provides a pure D_2 stream for the injection system and produces pure DT for target production.

In the reactor chambers the first structural wall is protected by rows of woven SiC tubes containing the liquid metal alloy $Li_{17}Pb_{83}$ which serves as both the coolant and breeding material. Tritium is bred at a rate of 4.4×10^{-6} kg/sec (Breeding Ratio = 1.25) and extracted from the reactor chamber by vacuum pumping between shots at pressures less than or equal to the vapor pressure of tritium above the eutectic. The very low tritium solubility in the alloy of 0.051 wppm/torr$^{1/2}$[1] results in an inventory of 0.010 kg T in the $Li_{17}Pb_{83}$ (1.9×10^7 kg $Li_{17}Pb_{83}$ in 4 chambers and reflectors) at a tritium

partial pressure of 10^{-4} torr. The inventory in the SiC tubes (1.6×10^4 kg SiC in 4 chambers) at 500°C is unknown, but has been approximated as 0.012 kg.

The liquid metal is circulated into the heat exchange cycle. The high tritium pressure above the eutectic, 10^{-4} torr, causes a tritium containment problem in the steam cycle. The permeation of tritium through clean HT-9 in the steam generator would result in a loss of 43 g T_2/d to the steam cycle. Therefore, the steam generator is designed with double walled tubes purged with an oxygen atmosphere as in the WITAMIR[2] design. This provides a very effective barrier limiting losses to less than the 10 Ci/d design goal.

In HIBALL, production methods for the manufacture of targets have not been specified and therefore it is not possible to estimate the tritium required for target production. Parametric studies of target factories have shown that the tritium inventory may be in the range of tens of kilograms depending on factors such as the time and efficiency of the production steps.[3] For HIBALL, a one day fuel supply of tritium is assumed as storage (4.1 kg) and an order of magnitude estimate of 10 kg T is the assumed inventory associated with the target factory. The total tritium inventory in HIBALL is summarized in Table 1.

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Table 1. HIBALL Tritium Inventory

Fuel Cycle (kg):		
Cryopumps	0.37	
Fuel Cleanup	0.041	
Isotropic Separation	0.083	
Subtotal		0.49
Blanket (kg):		
$Li_{17}Pb_{83}$ (cavity and reflector)	0.010	
SiC tubes	0.012	
Subtotal		0.025
Total Reactor Inventory (kg):		0.52
Storage (1 day fuel supply) (kg):		4.1
Target Factory (kg):		~ 10

Shielding Analysis of Focusing Magnets

Fusion reactors are required to accommodate a variety of penetrations.[1,2] The HIBALL heavy ion beam fusion reactor utilizes 20 ion beam line penetrations. Each final focusing system consists of eight quadrupole magnets. Adequate penetration shielding is required to protect these magnets from excessive radiation damage.

A three-dimensional neutronics and photonics analysis was performed to assess the shielding effectiveness of different penetration shield shapes. The Monte Carlo code MORSE[3] and a coupled 25 neutron-21 gamma group cross section library[4] were used. The design criteria used are:

(1) A 50% radiation induced resistivity increase in the copper stabilizer which corresponds to 1.4×10^{-4} dpa (displacements per atom).

(2) A radiation dose of 5×10^{9} Rad in the epoxy insulation.

(3) A peak nuclear heating of 10^{-4} W/cm^3 in the magnet.

Because of symmetry, only 1/40 of the reactor was modeled with reflecting albedo boundaries. Figure 1 gives a vertical cross section of the focusing magnets and shield. The shield consists of 63 v/o 316 Ss, 15 v/o Pb, 17 v/o B_4C and 5 v/o H_2O.

Because of the $1/R^2$ geometrical attenuation, and to reduce the computing time, only the last two quadrupoles Q_7 and Q_8 were modeled. In order to get statistically adequate estimates for the flux in the focusing magnets with a reasonable number of histories, an angular source biasing technique was used. Twenty thousand histories were used in the calculations.

The inner surface of the shield in the quadrupole sections is tapered such that it does not see direct line-of-sight source neutrons. This was found to be more advantageous than using a flat shield surface. Further

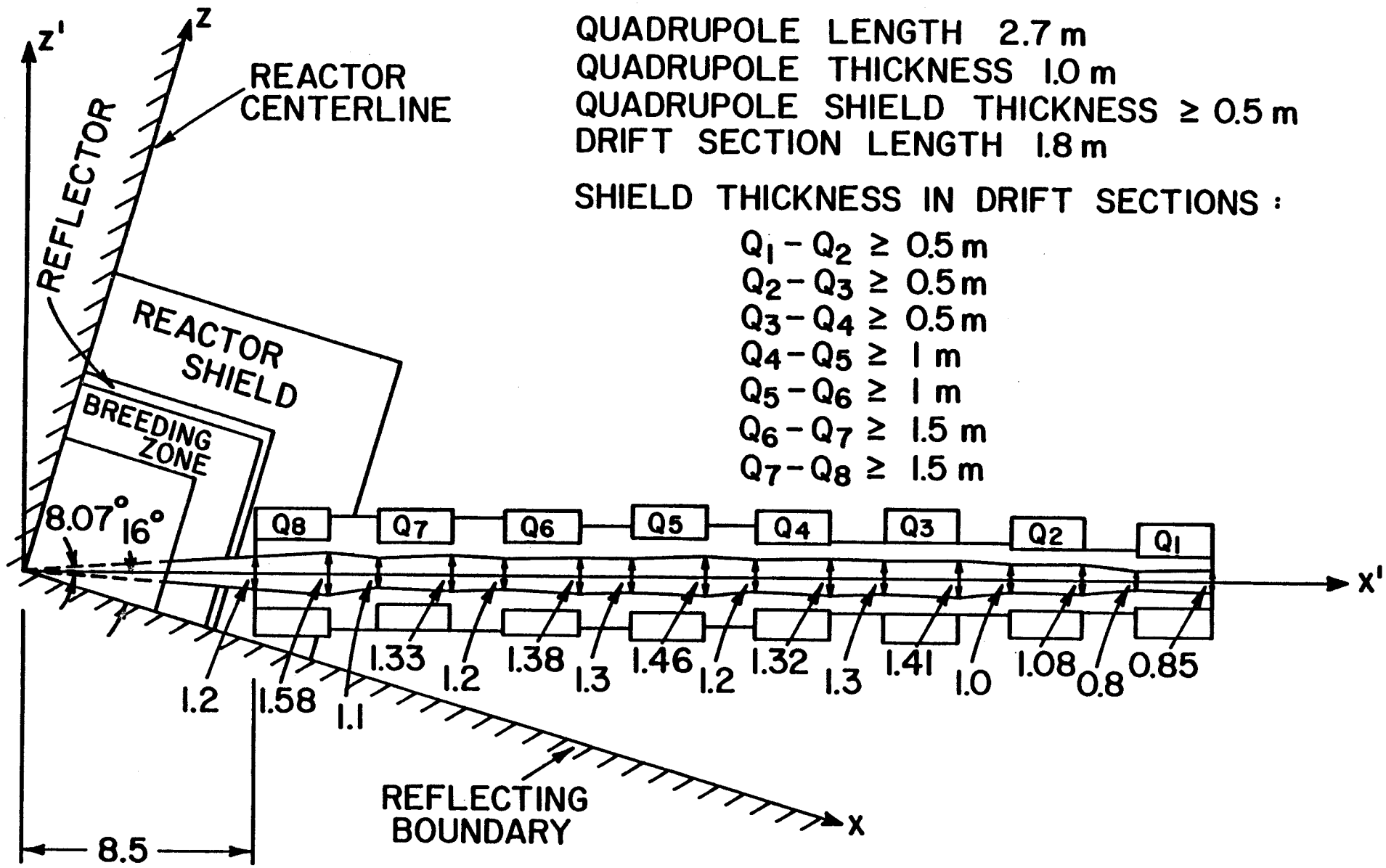

Figure 1 Vertical cross section for focussing magnets and shield.

improvement was obtained by modifying the shape of the shield in the drift sections as shown in Fig. 2. The inner surface of the shield in the drift section is tapered at both ends such that all source neutrons impinge on a vertical neutron dump in the shield. This results in increasing the attenuation distance for neutrons impinging on the shield. In option C, the source neutron dump is moved closer to Q_8. This is motivated by the fact that scattering is forward peaked at high energies.

Table 1 gives the peak dpa rate, the peak radiation dose and the peak power density in the magnets for the different geometrical options considered. It is clear that the tapered shield with option C is the most effective shield design. It is concluded that a magnet shield with option C satisfies the design criteria on radiation dose in the insulator and nuclear heating in the magnet with the possibility of eliminating the need for magnet annealing during an estimated lifetime of 20 full power years (FPY).

Radiation streaming was followed up the beam line penetration to the exit of the periodic transport located 60.37 m from the target. 2×10^{14} neutrons per second stream into the periodic transport carrying 373 watts. Gamma streaming corresponds to 7.6×10^{12} photons/sec carrying 1.8 watts. These can be easily dumped in a separate neutron dump.

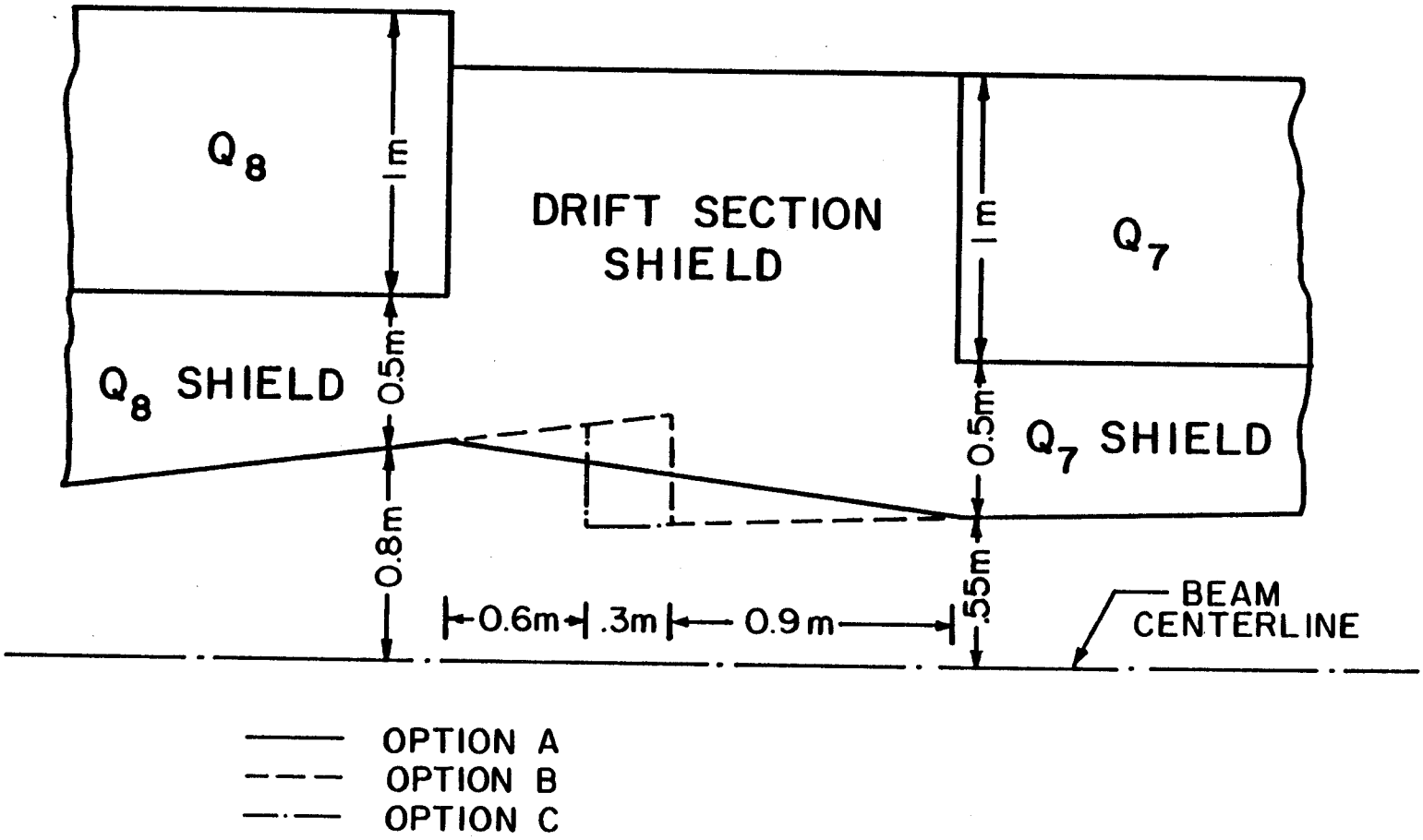

Figure 2 Options for tapering drift section shield.

Table 1. Effect of Penetration Shield Shape on Peak Values of DPA, Radiation Dose, and Nuclear Heating in the Focusing Magnets

	Flat Shield	Tapered Shield in Quadrupole Section		
		Option A	Option B	Option C
Peak dpa/FPY in Cu Stabilizer	1.056×10^{-3}	1.151×10^{-4}	1.600×10^{-5}	4.480×10^{-6}
Peak Radiation Dose in Insulation (Rad/FPY)	3.467×10^{9}	2.552×10^{8}	2.526×10^{7}	7.20×10^{6}
Peak Power Density (W/cm^3)	4.380×10^{-3}	2.44×10^{-4}	3.554×10^{-6}	5.350×10^{-7}

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