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HYLIFE-II Reactor Chamber Design Refinements

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ABSTRACT

Mechanical design features of the reactor chamber for the HYLIFE-II inertial confinement fusion power plant are presented. A combination of oscillating and steady, molten salt streams (Li_2BeF_4) are used for shielding and blast protection of the chamber walls. The system is designed for a 6 Hz repetition rate. Beam path clearing, between shots, is accomplished with the oscillating flow. The mechanism for generating the oscillating streams is described. A design configuration of the vessel wall allows adequate cooling and provides extra shielding to reduce thermal stresses to tolerable levels. The bottom portion of the reactor chamber is designed to minimize splash back of the high velocity (> 12 m/s) salt streams and also recover up to half of the dynamic head. Cost estimates for a 1 GWe and 2 GWe reactor chamber are presented.

INTRODUCTION

HYLIFE-II is a design study of a 1 GWe inertial confinement fusion power plant.[1] A molten salt called Flibe (Li_2BeF_4) is used as a shield for neutrons and x rays and for heat transfer to the steam cycle. Flibe also serves to reduce blast effects on the vessel wall and as a medium for breeding tritium (used in the targets). The temperature of most of the vessel structure and the Flibe will be at 650^{o}C. Construction material for the 6 m internal diameter vessel, Fig. 1, is 304 stainless steel.

Targets containing capsules loaded with nuclear fuel (D and T) are injected to the vessel centerline, then caused to implode by 12 heavy ion beams. The planned repetition rate for target detonations is 6 Hz. Between each shot the Flibe protective blanket must be regenerated and Flibe droplets in the path of heavy ion beams must be removed.

The subject of this updated paper is the mechanical design of the reactor chamber system. Three new sections have been added to the prior work [2]: beamline shutters, isochoric heating and cost estimation. The target detonation rate has gone from 8 to 6 Hz.

FLIBE FLOW CIRCUITS

Flibe shielding circuits inside the vessel vacuum chamber include oscillating flow, and steady flow. The remaining inside circuits are for spray nozzles and a shielding tray. Flibe spray inside the vessel increases the liquid surface area to aid in vapor condensation after each shot. The shielding tray provides an additional 50 cm of Flibe shielding to protect the oscillating flow deflector drive shafts from excessive heating and thermal stress. Two more circuits are contained in the vessel wall. They consist of a cooling circuit and a shielding circuit.

The vessel first structural wall (FSW) and other internal metal components require about 50 cm of Flibe shielding in order to obtain a 30 year lifetime, due to neutron damage. The shielding also provides blast protection and reduces neutron heating of the FSW. Oscillating flow is used to sweep out Flibe droplets from the previous shot and to create a pocket for the new shot. The pocket is bounded on two sides by the oscillating streams and closed at each end by steady streams. Reductions in Flibe flowrate were obtained by reduction in the pocket size from the previous report.[2] Twelve heavy ion beamline paths and a potential target injection path, at one end of the pocket are shielded by a series of vertical and horizontal streams as shown in Figure 2. Both the oscillating flow streams and the fixed flow streams at the other end of the pocket are made up of separate curved streams of Flibe. Line of sight shielding in any direction is assured by the stream curvature, and space between the streams allows venting of shot induced vapor. Rapid venting is necessary in order to reduce induced bulk liquid velocity toward the FSW, caused by the pressure of the unvented vapor.

VESSEL WALL CONFIGURATION

The reactor vessel wall is necessarily complex in order to satisfy a number of requirements. The composite wall is a vacuum barrier and must also prevent tritium leakage to the atmosphere. In addition the wall is subjected to cyclic pressure loads and needs be cooled to carry away neutron heating thermal loads.

The FSW is made from 10 cm diameter tubes with a 3.0 mm wall thickness. The tubes are separated by 2.5 cm spacer bars, 3.0 mm thick, see Figure 3. This wall configuration lacks adequate hoop strength, so it is supported from the next shell by perforated rings spaced 30 cm apart. Shells No. 2 and 3 supply the required hoop strength.

Neutron heating of the tube metal is a maximum of 23.9 W/cm^3.[3] This results in wall heating of 2.9 W/cm^2 and requires turbulent flow inside the tube for cooling. A velocity of 1 m/sec results in a Reynolds No. of 28000, in the Flibe, which is well into the turbulent zone. Thermal stress in the tube is only 2.05 MPa. Spacers between the tube are cooled by conduction to the tube walls, a Flibe spray on the outside, and low velocity (0.26 m/s) Flibe on the inside.

This low velocity Flibe is 50 cm thick and provides additional shielding between the FSW and the second shell. Since the main function of this thick Flibe layer is neutron shielding, and not heat transfer, it does not require turbulent flow. Flibe pumping costs are reduced by having the shielding flow velocity lower than the cooling flow velocity. Neutron heating of shell No. 2 is reduced to 0.52 W/cm^3 by the extra shielding. This reduction in internal heating was necessary to reduce thermal stress in the relatively thick (2.5 cm) shell No. 2. With Flibe cooling on the outside surface, the maximum thermal stress is 18.1 MPa.

Shell No. 3 is 2.5 cm thick also and is separated from shell No. 2 by a 2.5 cm gap. Flibe flowing in this annular space at 1 m/s velocity will cool both shells. The internal neutron heating rate of 0.30 W/cm^3 in shell No. 3 results in a maximum thermal stress of 10.4 MPa.

A gap of 10.2 cm separates shell No. 3 and shell No. 4. This gap is filled with a permeable insulation to allow flow of an inert purge gas. The purge gas will remove any tritium that has diffused through shell No. 3. Shell No. 4 is 1.6 mm thick and is supported from shell No. 3 by support rings spaced 46 cm apart.

ISOCHORIC HEATING

Cyclic stress in the tubes of the FSW was investigated at the expected 18.6 W/cm^3 neutron heating rate. Confined Flibe in the tubes is instantaneously heated by neutrons each time a target capsule is detonated. The instantaneous heating raises the stainless steel and Flibe temperature and pressure. Resulting "hoop stress" in the tube wall, as the tube and Flibe expand, must be limited to a low value (estimated at 45.5 MPa by extrapolation from 10^6 cycles to 5x109 cycles at 650°C [4]) to avoid fatigue failure during the power plant 30-year lifetime.

Pressure in the Flibe from isochoric heating is determined from $P=AE_n$, where "A" is the Grüneisen parameter and "E_n" is the volumetric energy density. Application of this formula gave a pressure of 3.04 MPa in our case. The temperature rise per pulse is 0.68°C for Flibe and 0.77°C for stainless steel. These instantaneous temperature elevations cause both materials to be in the compressed state with stored potential energy. This energy is then equated with the potential energy of the elastic expansion of the tube wall. Determination of the maximum extension of the wall allows calculation of its stress.

Application of the above method of calculation resulted in a design change of the tube wall thickness from 1.2 to 3.0 mm. Cyclic hoop stress of the wall was calculated at 28.1 MPa, thus a 30-year lifetime of the FSW is practical.

OSCILLATING FLOW

Oscillating flow in two opposite Flibe streams, subsequent to a shot, establishes a new pocket for the next shot. Pressurized Flibe is piped to two fixed nozzles inside the vessel where downward velocity of 12 m/s is established, see Figures 1 & 4. Streams from the nozzles enter an oscillating deflector system that is mechanically driven from outside the vessel. There is a small gap between the nozzle and the deflector. No seal is needed at this location as the static pressure has been reduced to zero at the nozzle exit. Deflectors are 2 m in length from the shaft centerline and are rotated ± 1.55°. Shaft centerlines are 1.2 m apart. Streams emerge from the opposed deflectors with sine wave motion and merge to form the pocket, Figure 1. As a new pocket is formed the previous one grows larger.

Pressure from Flibe vaporization at shot time causes additional pocket expansion and breakup. The calculated envelope of Flibe particles with a 7 m/s shot induced motion of the pocket wall is shown in Figure 1. The 7 m/s Flibe velocity is at the upper range of velocities calculated (1.7 to 6.7 m/s), and the average velocity may only be 2.0 m/s.[5]

OSCILLATING FLOW MECHANISM

Flow deflectors are shaft driven from outside the reactor chamber. A rotary seal system will need to be developed to prevent air from leaking in and tritium from leaking out, Figure 5.

A Labyrinth seal inside the vessel will protect the first seal from Flibe liquid, but not Flibe vapor. Thus the first seal may need to run at a temperature above the freezing point of Flibe. Space between the first and second seals will be vacuum pumped to capture any tritium that leaks through. An inert gas at slightly above atmospheric pressure will occupy the space between the second and third seals. This will prevent oxygen from entering the differential vacuum pumping system. Proppesed rubbing surfaces for the seals are the standard graphite and ceramic.

Each drive shaft is supported by two main bearings, one outside and one inside the vacuum chamber. Oil (or grease) lubricated radial and thrust bearings are used outside the vacuum chamber. A Flibe lubricated hydrostatic bearing is proposed for use inside the chamber. A graphite bushing could be used with a metal shaft. A layer of pressurized Flibe will prevent contact of the surfaces during operation. The large diameter (0.61 m) thick (7.1 cm) wall hollow drive shafts needed a total of 100 cm of Flibe shielding to reduce neutron heating to an acceptable level (0.43 W/cm^3). Thermal stress at this rate of heating, with Flibe cooling of the inside and outside shaft surfaces, is 33.1 MPa. The 100 cm of Flibe shielding is a total of 50 cm from the shielding streams and 50 cm from the shielding tray, Figure 1.

Both the deflector assembly inside the vessel and the crank outside are counter weighted for dynamic balance. The cranks are oscillated by a shaft with crank throws 180° apart. Horizontally opposed connecting rods connect the crankshaft to the deflector cranks, see Figure 6.

The forces required to oscillate the flow deflectors are horizontally opposed and will consequently cancel out in the bearing block assembly. Only ± 1.55° of travel of the Flibe deflectors are required. With careful balancing of the two oscillating assemblies, vibration transmitted to the vessel can be minimized. Design calculations indicate that the oscillating flow mechanism can be designed with stresses below the endurance limit.[4]

HEAD RECOVERY SYSTEM

The head recovery system has two main functions. The first one is to prevent splash and upward deflection of rapidly (> 12 m/s) falling Flibe streams. Partial recovery of the dynamic head, prior to the pump inlets, is the second goal. The design selected to accomplish both functions is shown in Figures 1 and 2. Downward moving Flibe, below the shot point elevation, will encounter a central cone, the vessel wall, or the turning vanes directly.

In all cases the flow is directed into the turning vanes where the direction is changed to near horizontal. After a small void zone, flow will join (and maintain) a rotating volume of liquid, see Figure 4. Liquid then exits the annular volume at four locations and enters diffusers where velocity decreases and static head increases. On the average the liquid travels about a quarter of a turn before entering the diffuser. Each diffuser feeds three Flibe pumps, see Figure 7.

Efficiency of the head recovery section will need to be determined experimentally. Following are estimates used to determine the head recovery for use in the pump power calculations.

Efficiency	Process
80%	Losses due to adverse deflections and velocity mismatches prior to turning vanes.
86%	Losses in non tangential exit of liquid from turning vanes.
86%	Losses in non-tangential meshing of streams with the rotating liquid surface.
85%	Loss in reservoir and diffuser due to friction and velocity mismatches.

Thus, the estimate of overall efficiency of head recovery is: $(0.8)(0.86)^2(0.85) = .503$ or 50%.

BEAMLINE SHUTTERS

The 12 heavy ion beam tubes need protection from Flibe liquid propelled by blast effects. It would also be desirable to prevent all of the shot-generated Flibe vapor from entering the beam tubes but some amount is expected to get through.

The shutter design configuration is illustrated in Figure 8 and Figure 9. Two side by side 5.2 m diameter disks are rotated in vacuum at 360 RPM. They are driven by external electric motor drives. Rotary vacuum seals on the drive shafts prevent air from entering the reactor chamber. Twelve 0.14 m diameter holes in each disk are coincident with the beam tubes at shot time.

The large side by side disks are needed to obtain a fast (0.001 s) closing time without opening again until the next shot. Coaxial counter-rotating disks, centered on the beam lines, when rotated fast enough to obtain a 0.001 s closing time reopen several times before the next shot. The side by side disks when rotated in the same direction will block liquid particles when each disk has rotated half a hole. The 22.5° offset of the shaft center lines was required in order to prevent partial reopening of the beam line as the holes in the disks crossed each other and the beam line tubes. Operating clearance is needed for disk rotation, so they can impede vapor flow but not seal against it. The 0.001 s closing time will stop liquid particles from the nearest Flibe streams having velocities up to 1000 m/s.

A port can be provided at the center of the 12 beam line array for target injection. The target velocity is expected to be about 100 m/s.[6] A slot could be provided in each disk in line with the injection trajectory when the target passes through.

POWER CONSUMPTION

Operating the HYLIFE-II reactor vessel consumes a considerable amount of power. The main power requirement is for pumping Flibe. Another power requirement is to drive the oscillating flow deflectors. The deflectors add a time varying horizontal component to the Flibe velocity. This horizontal kinetic energy is dissipated and must therefore be supplied by a drive motor. If the motor were 90% efficient and the mechanical drive system 80% efficient then 112 KW of electrical power would be used for the deflectors.

Pumping power for the Flibe pumps was based on a differential head across the pumps of 17.4 meters. The outlet pump head of 25.4 m is a total of 7.4 m of velocity head at the nozzles, 10.5 m of lift and 7.5 m,[7] of pipe friction and minor losses. The head recovery section of the vessel is estimated to recover 8 m of head at the pump inlet. Table I is a summary of the Flibe pumping flow rates and power. A pump efficiency of 80% (electrical to fluid) was used to calculate the drive power (22.7 MWe total) needed. Most (90%) of the power used is for high speed (12 m/s) shielding flow inside of the vacuum chamber.

COST ESTIMATES

Cost estimates have been prepared for Account Number 22.1 and include the reactor, bypass ducts, pumps and motors. Results are shown in Table II for HYLIFE-II (2500 MW thermal, vessel radius = 3.0m) and in Table III for the

Enhanced HYLIFE-II (5000 MW thermal, vessel radius = 4.25m). The basic method used was to calculate the weight of fabricated components and multiply by the Coal Standard of about 62 $/kg for 304 stainless steel piping (assumed equivalent in cost to PCA steel, [8]). Components that would require more labor to fabricate were assigned higher cost per unit weight. Parts or sub-assemblies that would be purchased were estimated directly.

Twelve 4.44 m^3/s Flibe pumps are used for HYLIFE-II and twenty pumps of the same size are required for the Enhanced HYLIFE-II. For both power plants the bypass pumps and motors represent the largest cost entry. The method of pump cost estimation used in this report is probably not very accurate, and needs to be improved as more information becomes available.

Ruby Code [7] cost equation for primary coolant pumps and motors:

$C_{pcpm}=1.35(Pth/(Ti-To))^{0.74}$ millions of 1988 $'s

For 2500 MWt, a delta T of 66°C, division by 1.5 to correct from nuclear to coal standard and multiplication by 1.145 to obtain 1993 $'s,

C_{pcpm} = 15.173 ...millions of 1993 $'s for HYLIFE-II

Total flow rate of all pumps = 4.444(12.0) = 53.3 m^3/s
(9.68 pumps are used for bypass flow and 2.32 are used for flow to the Balance of Plant (BOP) circuits)

Flow rate of primary BOP coolant = 4.444(2.32) = 10.31 m^3/s

Cost estimation per pump and motor for 4.444 m^3/s = C:
(The cost is determined by multiplying C_{pcpm} by the ratio of flowrates raised to the 0.74 power (economy of scale used in the Ruby equation), then dividing by 12.0 to obtain the cost per pump and motor)

$C = (15.173(53.33/10.31)^{0.74})/12.0$ = $4.27 million (1993) dollars for HYLIFE-II.

For the Enhanced HYLIFE-II the process is repeated.

For 5000 MWt, a delta T of 66°C, division by 1.5 to correct from nuclear to coal standard and multiplication by 1.145 to obtain 1993 $'s,

C_{pcpm} = 25.341 ...millions of 1993 $'s for Enhanced HYLIFE-II

Total flow rate of all pumps = 4.44(20.0) = 88.88 m^3/s
(15.36 pumps are used for bypass flow and 4.64 are used for flow to the Balance of Plant (BOP) circuits)

Flow rate of primary BOP coolant = 4.44(4.64) = 20.62 m^3/s

Cost estimation per pump and motor for 4.444 m^3/s = C: (The cost is determined by multiplying C_{pcpm} by the ratio of flowrates raised to the 0.74 power, then dividing by 20.0 to obtain the cost per pump and motor)

$C = (25.341(88.88/20.62)^{0.74})/20.0$ = $3.74 million (1993) dollars for the Enhanced HYLIFE-II.

SUMMARY

The HYLIFE-II inertial confinement fusion power plant mechanical design has been refined and expanded. Molten salt (Flibe, Li_2BeF_4) is used for shielding, blast protection, energy transfer and cooling. The configuration of salt streams inside the vacuum vessel has been revised in order to reduce flow rate and provide a minimum thickness of 0.5 m in all directions from the shot point to various metal surfaces. A total reduction of 63% in Flibe flow rate was obtained in the change of detonation rate from 8 to 6 Hz and net reductions in shielding flow inside the reactor chamber.

A high speed shutter design, to protect the heavy ion beam lines from shot-generated Flibe liquid debris, has been added. Two side by side 5.2 m diameter disks are rotated in the same direction, in vacuum at 360 RPM. Twelve 0.14 m holes, centered at a 1.7 m radius from the center of rotation, are coincident with the beam paths at shot time. A closing time of 0.001 s is obtained with each disk closing half a hole. This closing time will stop liquid particles from the nearest Flibe streams having velocities up to 1000 m/s.

A cost estimate for construction of the reactor vessel system is included. The estimates are for the base 1 GWe and enhanced 2 GWe power plants and are based on the Coal Standard and 1993 dollars. The estimate total for the reactor, associated ducts, Flibe pumps and motors is $81.2 million dollars (Base HYLIFE-II) and 127.7 million dollars (Enhanced HYLIFE-II).

ACKNOWLEDGMENTS

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FIGURE CAPTIONS

TABLE CAPTIONS

Table I. Flibe Pumping Parameters

FLOW CIRCUIT	FLOW RATE (m^3/s)	PUMP POWER (MW)
Internal fixed nozzle	11.52	4.91
Internal oscillating flow	19.44	8.29
Beam shielding, vertical flow	5.52	2.35
Beam shielding, horizontal flow	11.64	4.96
Shell 1, tubes	1.10	0.47
Between shells 1 & 2	1.90	0.81
Between shells 2 & 3	0.40	0.17
Spray nozzles	1.21	0.52
Shielding tray	0.60	0.26
TOTAL	53.33	22.74

Table II. HYLIFE-II Reactor Cost Estimate

Cost estimate: HYLIFE-II Reactor, Bypass Ducts, Pumps and Motors
(Account number: 22.1, Coal Standard, 1993 Dollars)

PART NAME	TYPE OF CONSTRUCTION	WEIGHT (kg)	COST $/kg or unit	# REQ'D	COST ($)
Cyl. at bottom of cone	Rolled and welded	2240	62	1	138880
Bottom plate	Welded	21790	62	1	1350980
HR top plate	Welded	8720	62	1	540640
Diff. pipe, 2.2m	Rolled and welded	10629	88	4	3741760
Diff. pipe, 1.25m	Rolled and welded	1348	88	12	1425600
Bottom cone	Rolled and welded	16880	62	1	1046560
Turning vane	Rolled	467	62	50	1447700
Tapered ves. wall	Welded tubes and SPR's	5470	104	1	568880
Tapered ves. wall	Rolled and welded	42950	88	1	3779600
Straight ves. wall	Welded tubes and SPR's	5500	104	1	572000
Straight ves. wall	Rolled and welded	56230	88	1	4948240
Upper shell and dome	Rolled and welded	42220	88	1	3715360
Shielding tray	Rolled and welded	2800	62	1	173600
Defl. dr. shaft	Forged and machined	4925	104	2	1024400
Deflectors	Formed and welded	2320	88	2	408320
Counter weights	Welded heavy plate	1040	62	4	257920
Shaft seals	Special order		8000	6	48000
Ext. bearings	Roller bearings		10000	4	40000
Ext. brg. housing	Formed and machined	6480	104	2	1347840
Int. brg. housing	Formed and machined	1010	104	2	210080
Int. brg. bushing	Machined graphite	80	104	2	16640
Osc. shaft cranks	Forged steel	3200	32	2	204800
Connecting rods	Forged steel	630	62	4	156240
Drive crank assy.	Forged steel	2390	88	1	210320
Gr. reduct. assy.	Gears, etc., housing		160000	1	160000
Drive motor	Elec, 3PH, 150 hp		1500	1	1500
Int. Flibe ducts	304 ST STL	11260	62	1	698120
Vacuum ports	Welded	320	88	2	56320
BLP Flibe ducts	Welded 304 ST STL	22520	88	1	1981760
Reactor total					**30272060**
BP pumps and motors	Flibe service		4270000	9.7	41419000
BP Flibe ducts	Rolled and welded	26950	88	4	9486400
Reactor, Flibe pumps and motors, and ducts: Total = 81,177,460					

Table III. Enhanced HYLIFE-II Reactor Cost Estimate

Cost estimate: Enhanced HYLIFE-II Reactor, Bypass Ducts, Pumps and Motors
(Account number: 22.1, Coal Standard, 1993 Dollars)

PART NAME	TYPE OF CONSTRUCTION	WEIGHT (kg)	COST $/kg or unit	# REQ'D	COST ($)
Cyl. at bottom of cone	Rolled and welded	5230	62	1	324260
Bottom plate	Welded	43580	62	1	2701960
HR top plate	Welded	17440	62	1	1081280
Diff. pipe, 2.2m	Rolled and welded	17220	88	4	6061440
Diff. pipe, 1.25m	Rolled and welded	2180	88	12	2302080
Bottom cone	Rolled and welded	39330	62	1	2438460
Turning vane	Rolled	660	62	50	2046000
Tapered ves. wall	Welded tubes and SPR's	9020	104	1	938080
Tapered ves. wall	Rolled and welded	100070	88	1	8806160
Straight ves. wall	Welded tubes and SPR's	9070	104	1	943280
Straight ves. wall	Rolled and welded	131020	88	1	11529760
Upper shell and dome	Rolled and welded	84440	88	1	7430720
Shielding tray	Rolled and welded	5600	62	1	347200
Defl. dr. shaft	Forged and machined	6700	104	2	1393600
Deflectors	Formed and welded	2320	88	2	408320
Counter weights	Welded heavy plate	1040	62	4	257920
Shaft seals	Special order		8000	6	48000
Ext. bearings	Roller bearings		10000	4	40000
Ext. brg. housing	Formed and machined	6480	104	2	1347840
Int. brg. housing	Formed and machined	1010	104	2	210080
Int. brg. bushing	Machined graphite	80	104	2	16640
Osc. shaft cranks	Forged steel	4350	32	2	278400
Connecting rods	Forged steel	860	62	4	213280
Drive crank assy.	Forged steel	3250	88	1	286000
Gr. reduct. assy.	Gears, etc., housing		160000	1	160000
Drive motor	Elec, 3PH, 150 hp		2000	1	2000
Int. Flibe ducts	304 ST STL	15990	62	1	991380
Vacuum ports	Welded	640	88	2	112640
BLP Flibe ducts	Welded 304 ST STL	22520	88	1	1981760
Total					54698540
BP pumps and motors	Flibe service		3740000	9.7	
BP Flibe ducts	Rolled and welded	43660		4	
Reactor, Flibe pumps and motors, and ducts: Total = 127,662,860					

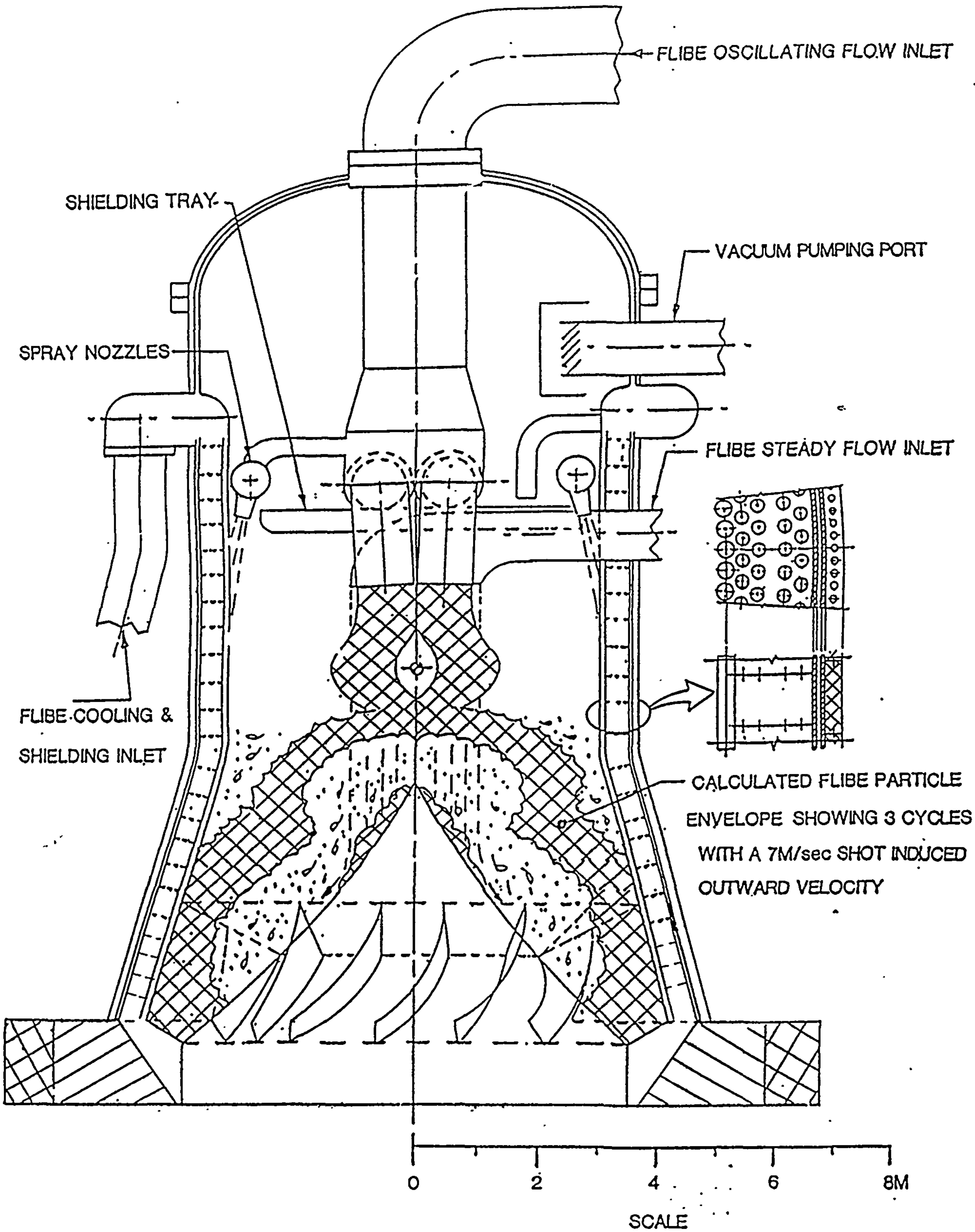

FIGURE 1. HYLIFE II REACTOR VESSEL

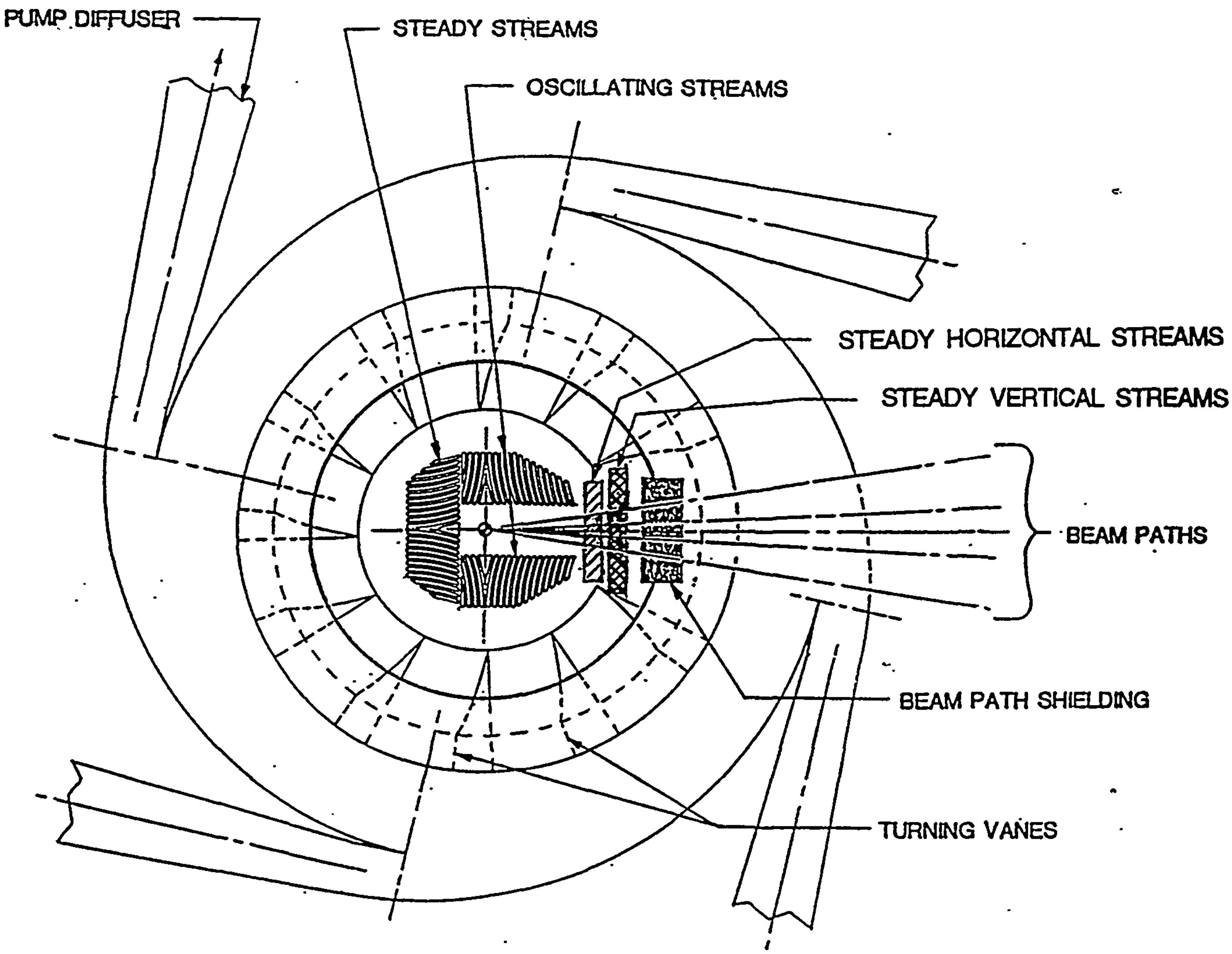

FIGURE 2. SHOT POINT PLAN VIEW

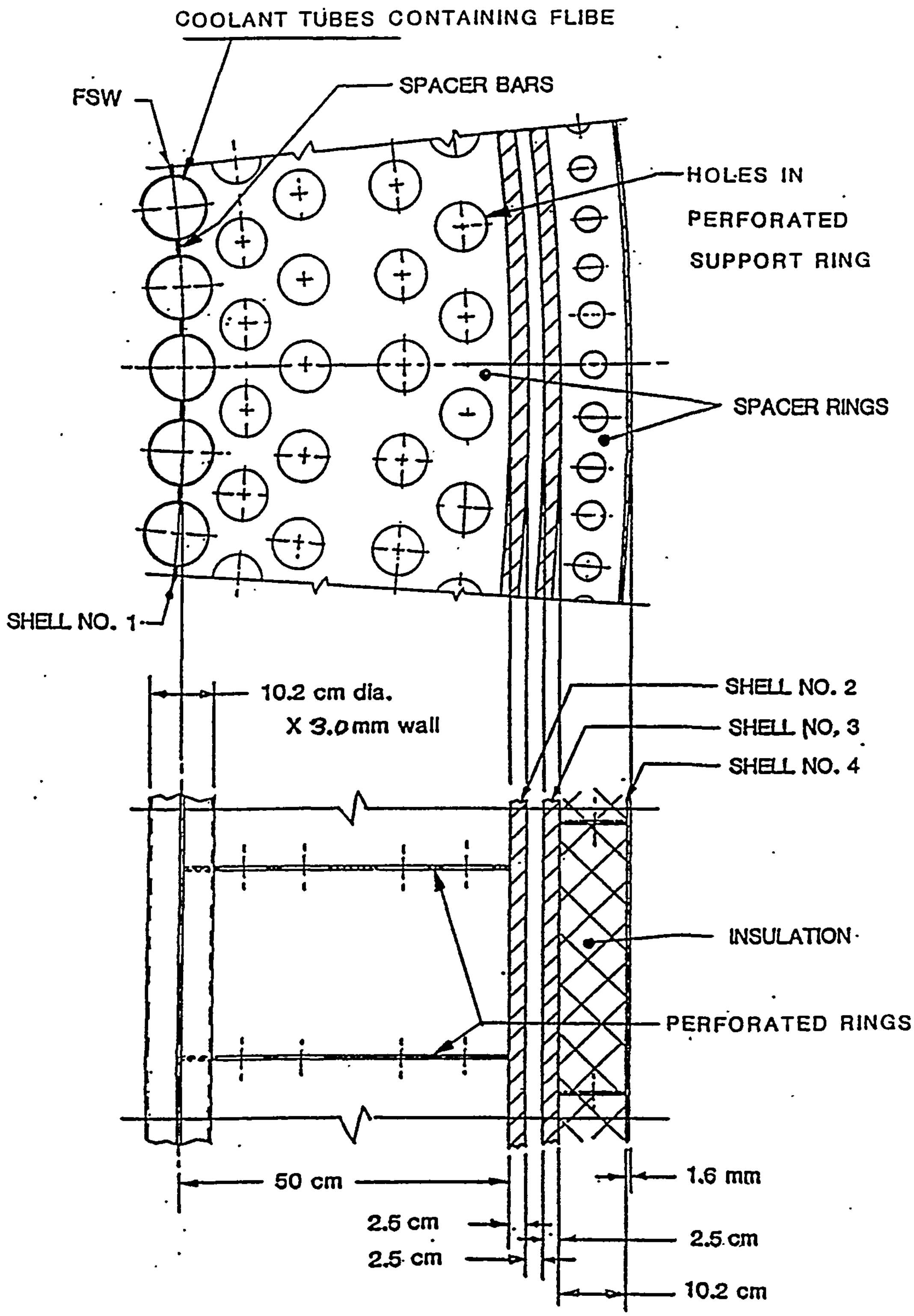

FIGURE 3 VESSEL WALL CONSTRUCTION

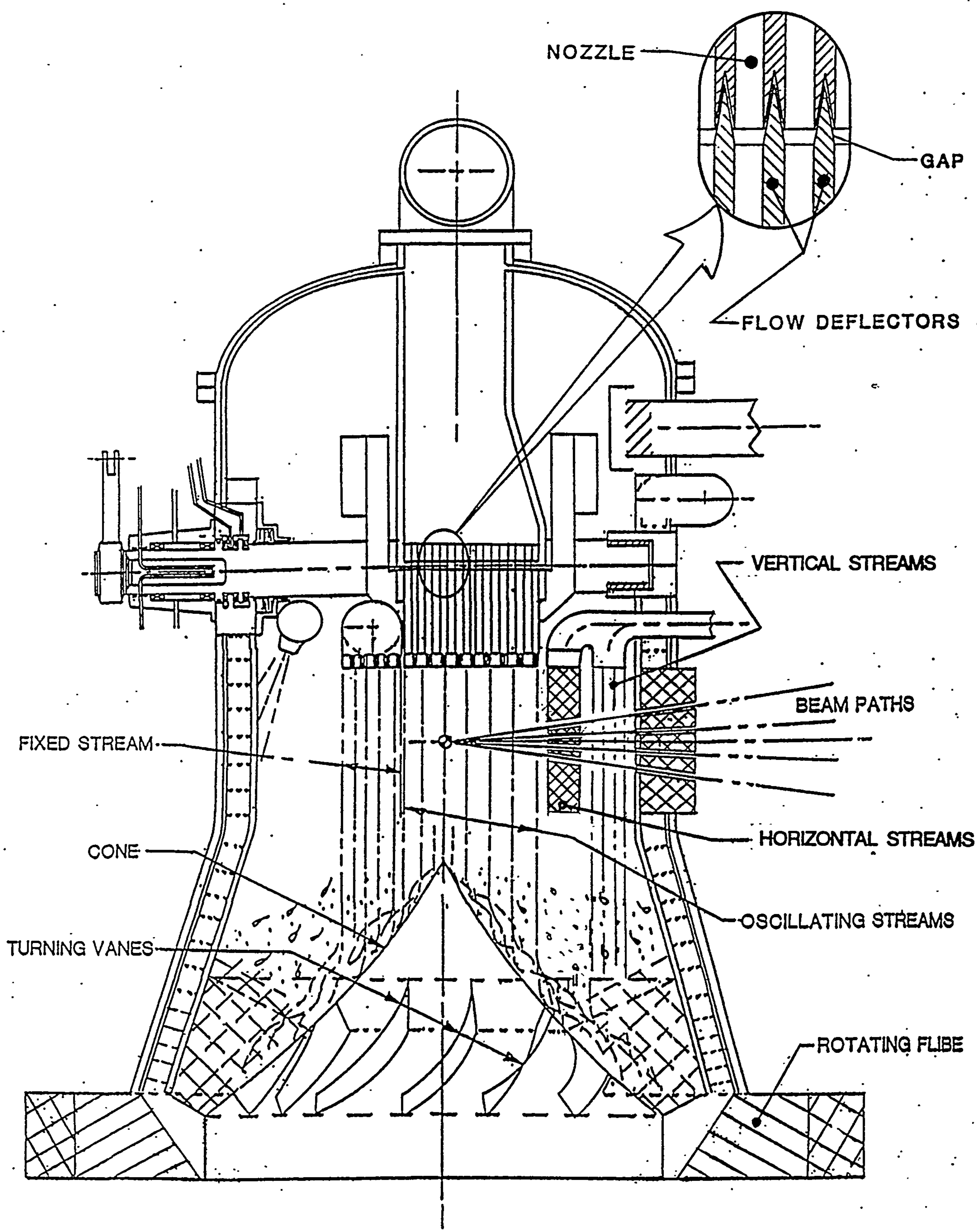

FIGURE 4. FLIBE SHIELDING STREAMS

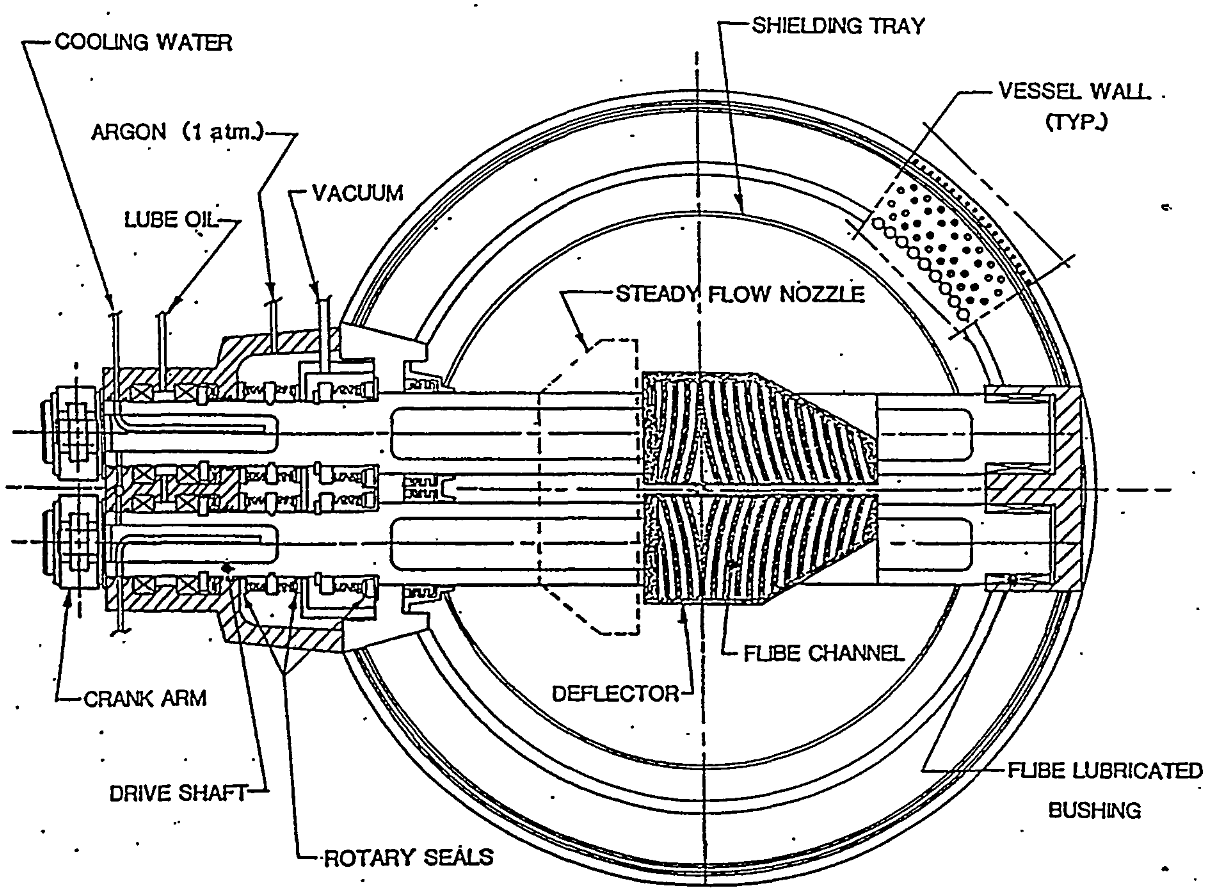

FIGURE 5. FLIBE DEFLECTOR DRIVE SHAFTS

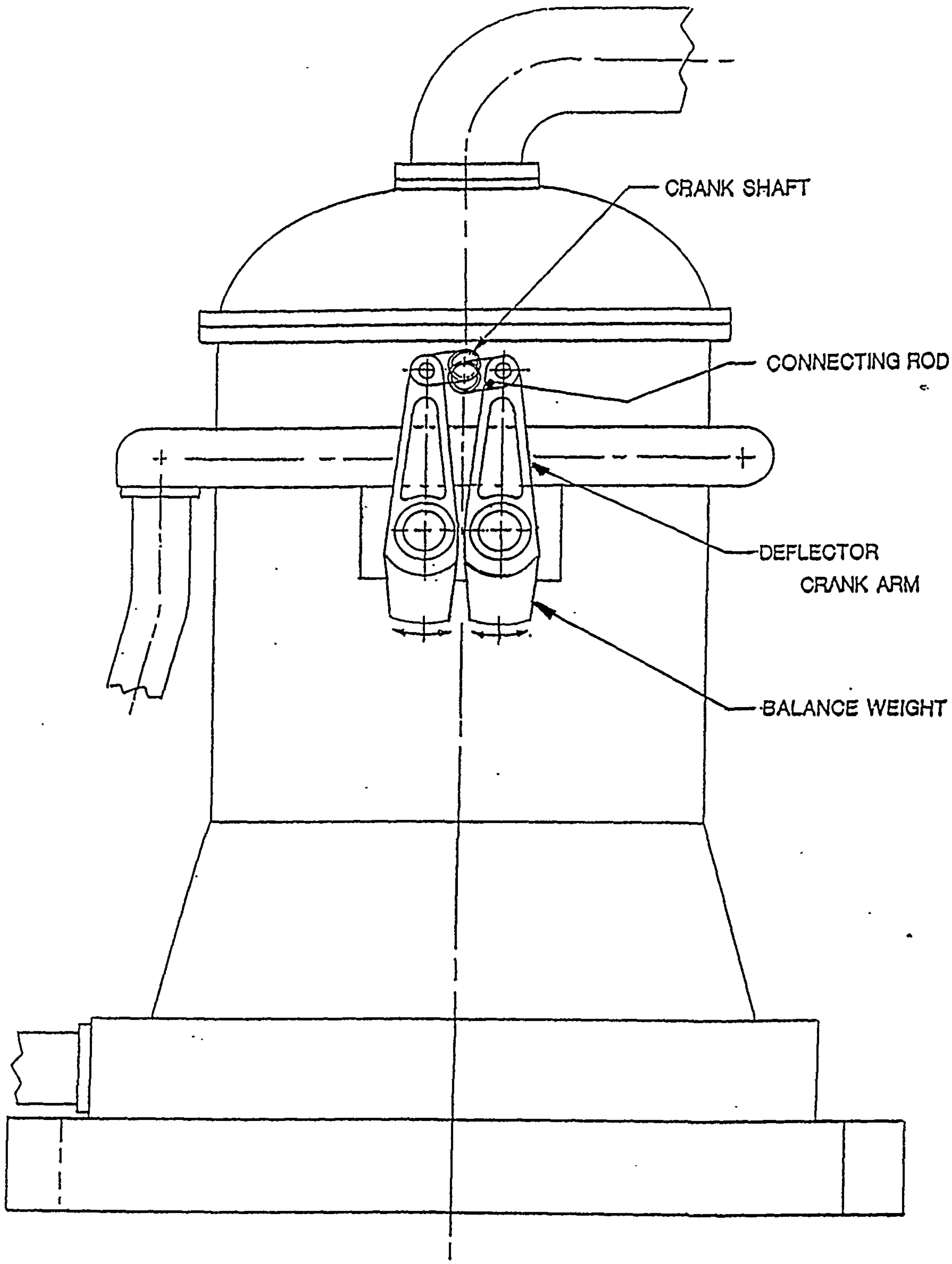

FIGURE 6. DEFLECTOR DRIVE SYSTEM

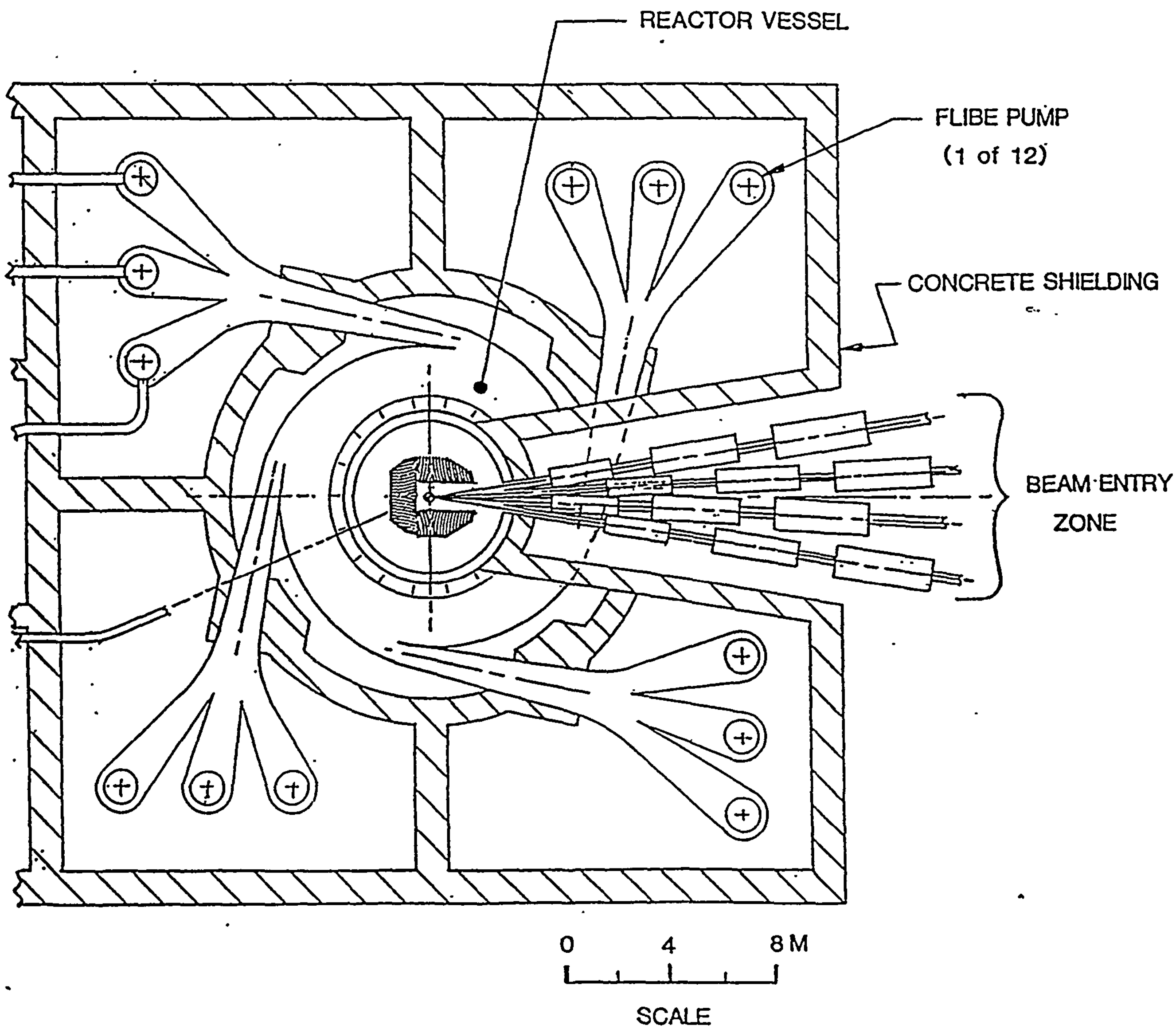

FIGURE 7. REACTOR BUILDING – PLAN VIEW

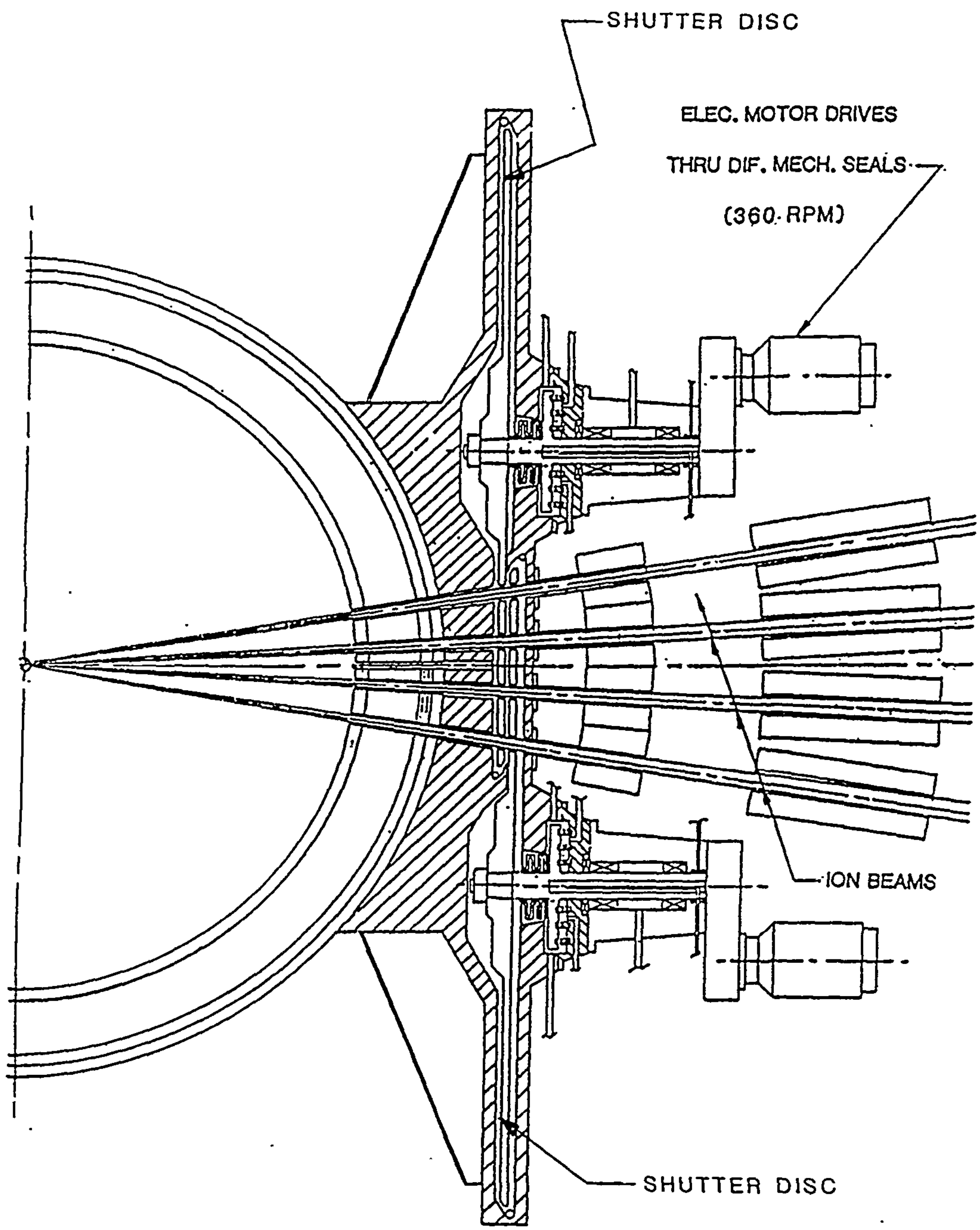

Fig. 8 BEAMLINE SHUTTERS

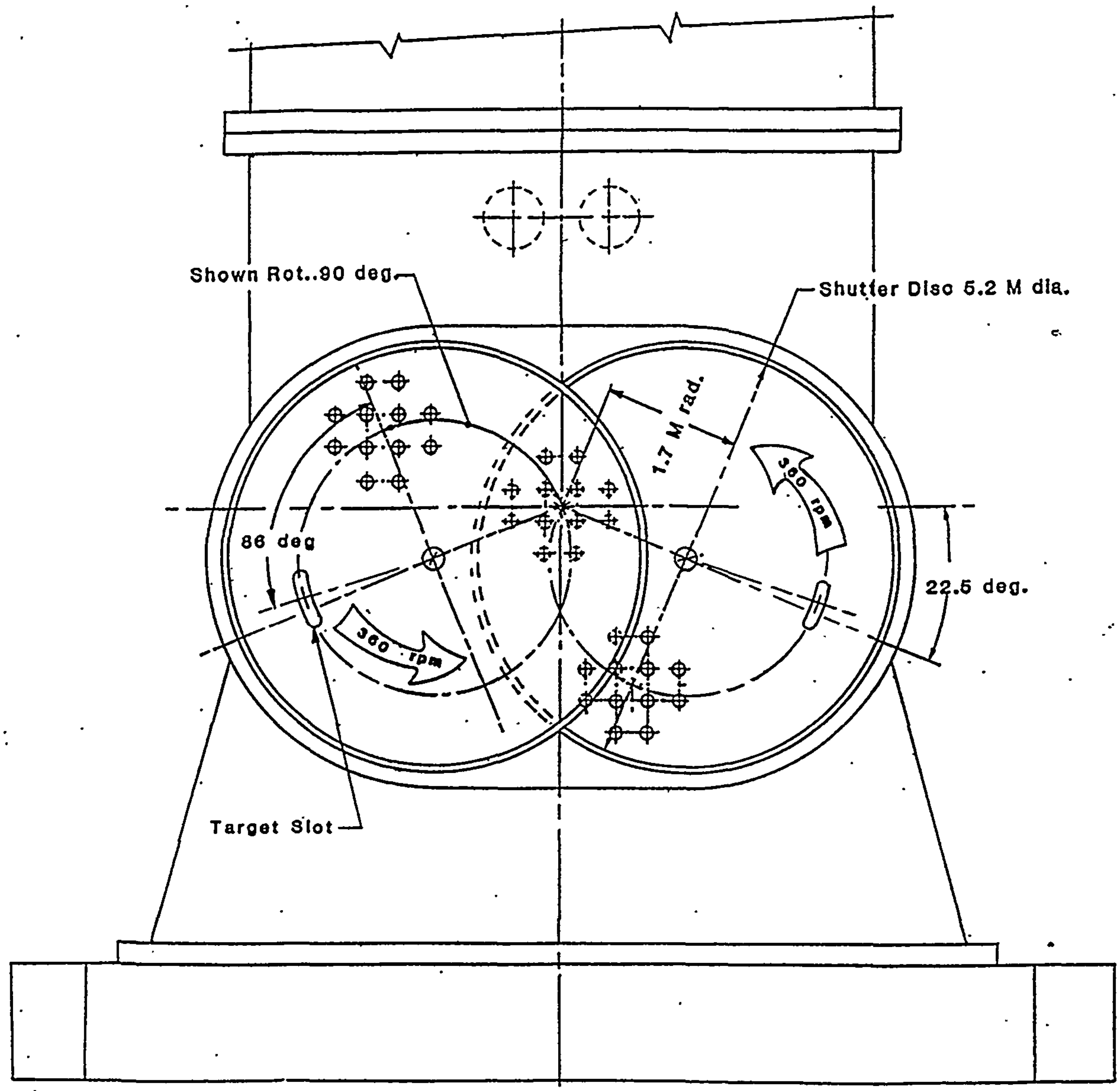

Fig. 9 SHUTTER DISCS