6.3.2 Plant Maintenance Approach - The approach used to define plant maintenance takes into account two key factors. These factors are (a) maintenance prediction and planning systems which use artificial intelligence (AI) methods and (b) the continuing improvement of automation technology. Both scheduled and unscheduled maintenance were considered plant maintenance requirements. Maintenance needs were analyzed and the hazards in the plant were considered. The maintenance analyses were included in the reactor and plant design process. This resulted in a number of operational and availability advantages for the plant design considered in this study. Total remote maintenance was chosen for critical areas which results in no human exposure to radionuclides.

6.3.2.1 Maintenance Requirements - The major reactor and plant systems and components requiring maintenance were first determined during the study. These were selected based upon previous maintenance experience and consultation with the Prometheus team members regarding their respective system designs. The maintenance analysis effort then concentrated on critical areas which would have the most impact on the overall plant availability and maintenance costs. Table 6.3.2-1 lists the major maintenance items for the Prometheus power plants. The remaining plant items are addressed with a general allowance factor.

Maintenance Environment - There are many new and unique requirements which are associated with the IFE reactor plant designs. The reactor vessel operates with an internal pressure of a few mtorr for Prometheus-L and 100 mtorr for Prometheus-H. The low pressure regions extend into the laser beamlines out to the vacuum window at the Reactor Building wall for Prometheus-L. For Prometheus-H, the complete length of the heavy ion beam lines is at an even lower pressure (10^{-5} to 10^{-9} torr). During reactor operation, radiation levels of 1.8×10^7 rads per hour are expected inside the reactor hall, principally from neutrons out the back of the shield. X-ray and gamma-ray emissions will be present at a lower level. The shields are designed to limit the neutron flux level at the back of the shield to 2×10^6 n/cm$^2\cdot$sec during operation which equates to a biological dose of 2.5 mrem/hr 24 hours after shutdown (2.5 mrads/hr for equipment). The reactor hall (the region outside the bulk shielding walls and inside the reactor building walls) environment will be inerted with CO_2 in order to minimize activation of the hall atmosphere. Only remote maintenance would be performed during reactor operation. After shutdown, hands-on maintenance could be accomplished for specific needs with remote maintenance being the preferred option.

If the beamlines are removed for maintenance, there would be the potential hazard of lead vapor from the first wall coolant. The potential for tritium leakage also exists but specific detritiation systems are provided in the reactor building for this purpose.

The laser building will be inerted with CO_2 as a design requirement. The building will have low level gamma radiation during operation. The operating KrF laser gas would also present a maintenance hazard. The LINAC tunnel complex by comparison will have low level gamma radiation which will build up as a background dose during the life of plant.

Various other hazard sources such as lasers, high voltage power lines, and alpha emitters (e.g., uranium in the tritium storage getters) will exist. These are to be expected not only in the reactor building, target factory, driver buildings, and hot cell facility, but also associated with the transfer routes between these buildings. The hot cells and lead cleanup facilities will have comparatively high levels of radioactive contaminants.

Table 6.3.2-1 Major Maintenance Items

Major Items Common To Both Reactor Types

- First Wall Panels
- Blanket Modules
- Reactor Vacuum Pumps
- Blanket Tritium Extraction Pumps
- Reactor Computer Control System
- First Wall Lead Cooling Pump
- First Wall Coolant Heat Exchanger (lead to steam)
- Lead Drain Pump
- Lead Decontamination System
- Helium Extraction Pump
- Helium Decontamination System
- Tritium Extraction Loop
- Blanket Helium Coolant Pumps
- Blanket Coolant Heat Exchanger (helium to steam)
- Heat Exchangers
- Helium Low and High Pressure Reheaters
- Steam Turbines
- Alternators/Generators
- Transformers
- Target Factory

Laser Option Specific Items

- Target Injector (electromagnetic injection)
- Laser Amplifiers
- Gas Circulation Blowers
- Laser Gas Heat Exchanger
- Laser Optics Vacuum Backing Pumps
- Final Optical Elements

Heavy Ion Option Specific Items

- Target Injector (pneumatic injection)
- Heavy Ion Accelerator Modules
- Ion Beam Vacuum Backing Pumps
- Magnets

6.3.2.2 <u>Fault Diagnosis and Maintenance Scheduling</u> - Fault diagnosis and maintenance scheduling technology are evolving quickly. These capabilities are expected to be extensively used during the deployment of the fusion reactor power plants. Artificial intelligence-based tools will continue to be improved for both fault diagnosis and maintenance scheduling.
Built-in-test (BIT) systems for fault diagnosis are becoming more powerful with the capability to minimize the repair site diagnostic skills. The repair time is minimized by rapid selection of correct replacement parts and notification of the appropriate repair specialis. Built-in-test systems use both top-down and bottoms-up system models with a combination of driver software and firmware incorporated. Faults are analyzed by the driver software traversing a system failure modes model and selecting test results from the diagnostic firmware to define the failed part. Fault dependencies can be determined to predict future malfunctions or failures. The U.S. Navy has positive experience with BIT systems such as those used in the ANSAR8 surveillance system.

Scheduling systems have been used for many years in manufacturing. With the advent of low overhead computerized systems, applications in maintenance scheduling and coordination are being developed and used. Such systems allow optimization of maintenance personnel and equipment, thus minimizing plant downtime and the required spares inventory.

6.3.2.3 <u>Maintenance Options</u> - There are three general options for the maintenance of the fusion reactor plants.

- <u>Hands-On Maintenance</u> - This includes regular contact maintenance or contact maintenance in a controlled area with a partial or full change of clothing which may include a ventilated or "bubble suit".
- <u>Semi-Remote Maintenance</u> - Maintenance is accomplished using long handled-tools or from behind temporary shielding.
- <u>Fully-Remote Maintenance</u> - Maintenance is carried out with totally remote devices such as manipulators or robotic devices. The operator is removed from the work place.

The type of maintenance procedure adopted is determined by the degree of protection required, the hazards, and the type and intensity of radiation present. There is usually a time penalty associated with the semi-remote or fully-remote options. However, if the operation is highly repetitive, task automation may be employed to improve maintenance times.

6.3.2.4 <u>Maintenance Approach Choices</u> - The maintenance approach for a major power plant is optimized to maximize the plant availability. This is best achieved by use of planned maintenance actions on key systems in order to prevent expensive, unplanned plant outages.

Scheduled Maintenance - Scheduled maintenance consists of preventative maintenance actions both on a regular basis and during planned plant outages. Maintenance prediction and planning systems using AI techniques are used to schedule maintenance tasks for minimal downtime. These prediction and planning systems are used in conjugation with sensor input to identify parts with early wearout or potential failure tendencies. Identification of these parts allows replacement during the planned maintenance periods. Due to the lack of statistical data on this approach, the reliability, availability, and maintainability (RAM) analysis reported in Section 6.3.3 did not consider these potential benefits in availability.

Unscheduled Maintenance - Unscheduled maintenance consists of downtime due to unforeseen failures or premature wearout. Unscheduled maintenance is very costly and time consuming. Frequently only repair of one element is accomplished and no other parallel maintenance activities can be accomplished. Failure of components can happen at any time and under any load conditions, frequently at full load conditions. Other systems can be damaged as a result of the initiating failure. Replacement parts may not be available for immediate installation thus causing further delays. Unscheduled maintenance should be minimized to the greatest extent possible with scheduled maintenance.

6.3.2.5 Reactor Maintenance - The Reactor Equipment is the most important system relative to the availability parameter. The Reactor Equipment was chosen for the most extensive analysis in the study. Of the two Prometheus concepts, the laser-option reactor vessel was examined in more detail due to the more difficult access. Site layouts of the two reactor designs are shown in Figure 6.3.2-1. This figure illustrates the Reactor Building and the Hot Cells where maintenance will be performed on the removed radioactive components such as the wall and blanket modules. At the center of the laser Reactor Building, the 60 laser beamlines are shown. These beamlines, which are equally spaced around the complete sphere, proved to have the more difficult maintenance. Figure 6.3.2-2 is a cross-section through the laser-option Reactor and Driver Building which illustrates two of the laser drivers and four of the beamlines which penetrate the reactor chamber. Also shown are the plumbing and steam generators for the helium and lead primary coolant systems. Figure 6.3.2-3 illustrates the comparable heavy ion-driven Reactor Building with the diametrically opposed beam bundles.

The reactor designs for both reactor concepts are well suited for repair and replacement with the adopted vertical maintenance scheme. The top of the reactor vessel is removable with all internal parts lifted upwards. The only required bottom access is to the lead coolant outlet pipe and contaminated lead outlet pipe.

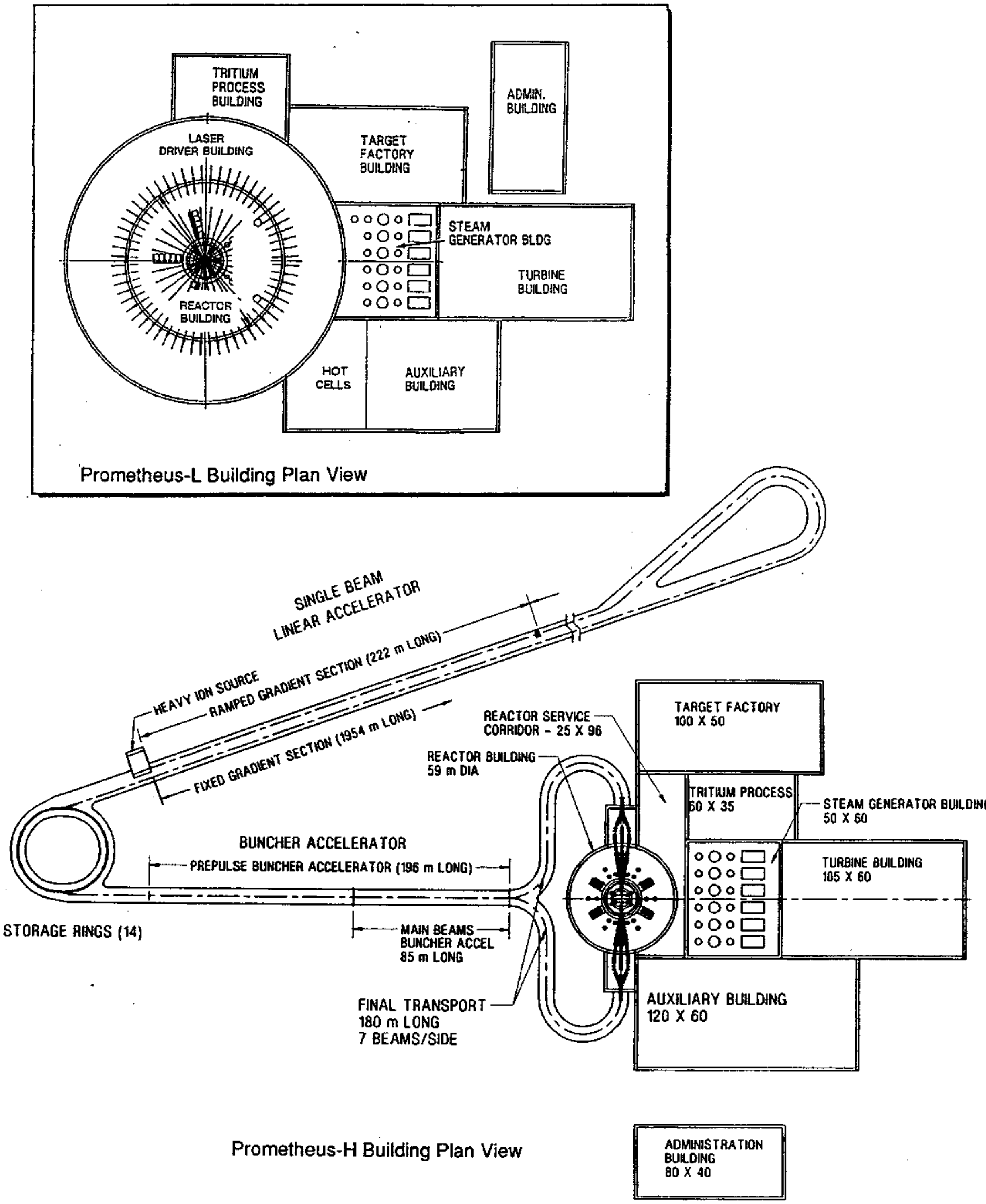


Figure 6.3.2-1 Plant Site Plans for Two Reactor Design Options

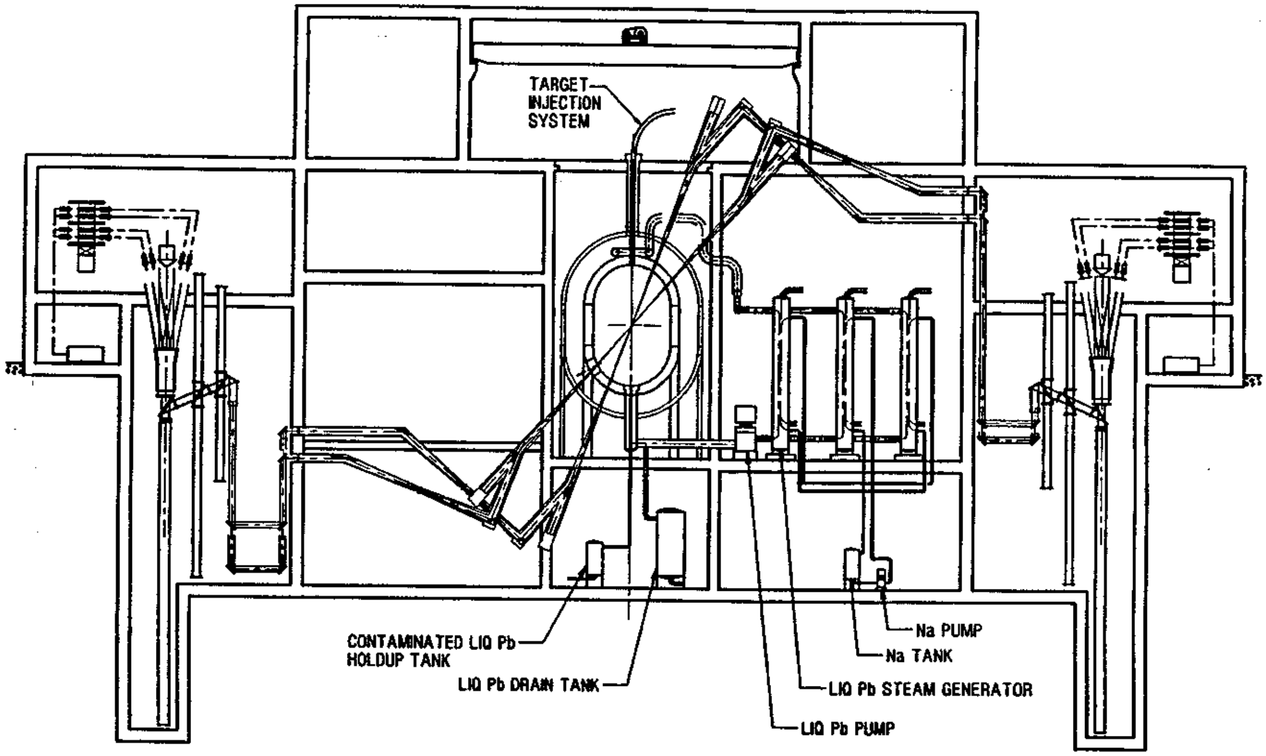


Figure 6.3.2-2 Reactor and Laser Building Layout Shown with the Primary Coolant Systems and a Portion of the Laser Beam Lines

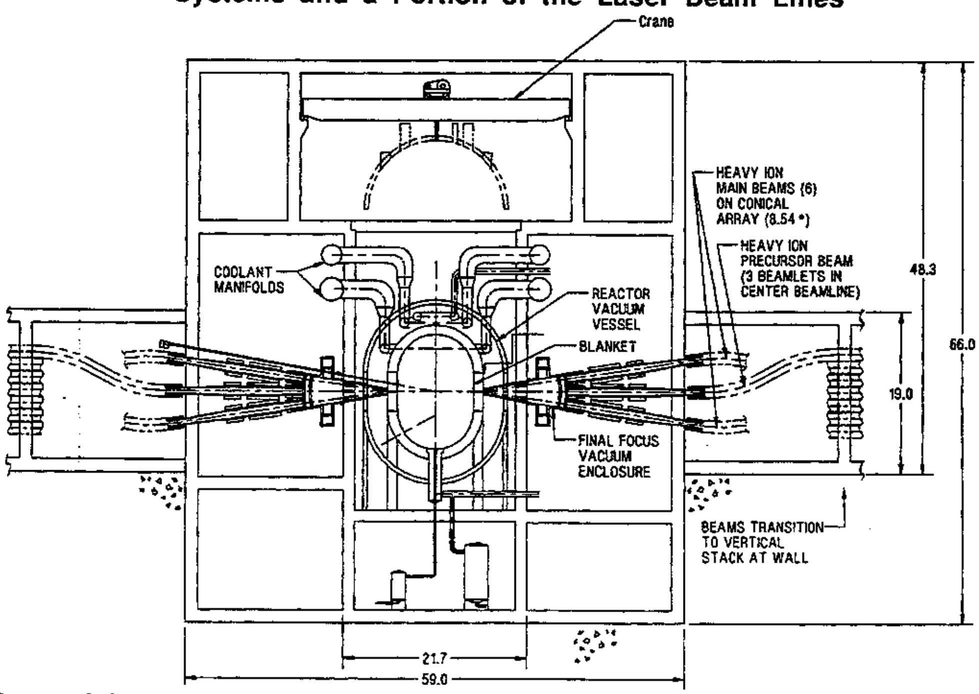


Figure 6.3.2-3 Heavy Ion-Driven Reactor has Two Beam Bundles Located on Opposite Sides of the Reactor Vessel

Figure 6.3.2-4 is a cross-section of the reactor which illustrates the major equipment components. The primary helium coolant inlet and outlet ducts enter from the top of the vessel. These ducts connect to coolant manifolds which in turn connect with the blanket modules. Lead coolant has separate inlet and outlet plumbing. Large vacuum ducting must also be disconnected to remove the blanket modules. To facilitate maintenance, the reactor vessel is subdivided into five equally-spaced sectors as shown in Figure 6.3.2-5. Each maintenance sector has independent supports and plumbing systems. Moreover, the blanket modules are divided into six separate vertical levels, each supplied by separate manifolds. More detail on the laser-driven reactor vessel with the beamlines in place is shown in Figure 6.3.2-6. The vacuum pumps are located outside the right-circular cylindrical bulk shield. Only the first wall, blanket, vacuum vessel, coolant piping, beamlines, and target injector are inside the shield boundary. The laser beams are projected to the center of the cavity for clarity.

A trimetric view of the heavy ion beam-driven reactor is shown in Figure 6.3.2-7. This vessel is slightly smaller with the radius of the first wall being 4.5 meters. The most discernible difference is the relative lack of penetrations in the heavy ion case. Only one of the ion beamline sets is shown in this view. The ion beams converge at the back face of the blanket. Only a two-centimeter diameter hole is required through the blanket and wall. The only sizable openings in the first wall are the vacuum pump ports. All other maintenance features of the two reactor chamber options are identical.

Reactor Assembly and Disassembly - Because the laser and the heavy ion-driven reactor have similar maintenance requirements and design concepts, the reactor vessel assembly and disassembly procedures have many common features. The procedures for the laser option will be discussed as the nominal case because it is the more demanding.

Many of the assembly and disassembly operations are conducted from the interior of the vessel with access from above. Typical of these activities is the removal of first wall panels every 5-10 years. External access to the reactor vessel is also required. Figure 6.3.2-2 illustrates the cylindrical bulk shield wall surrounding the reactor vessel. A circular shield cover will be removed vertically to provide overhead access. This will allow access to the coolant ducts and laser beamlines. The target injection system will also be accessible. Maintenance will be accomplished with long-reach manipulators from above and mobile devices from below or along the shield wall. Local contamination control boundaries will be erected to prevent the spread of contamination from worksites.

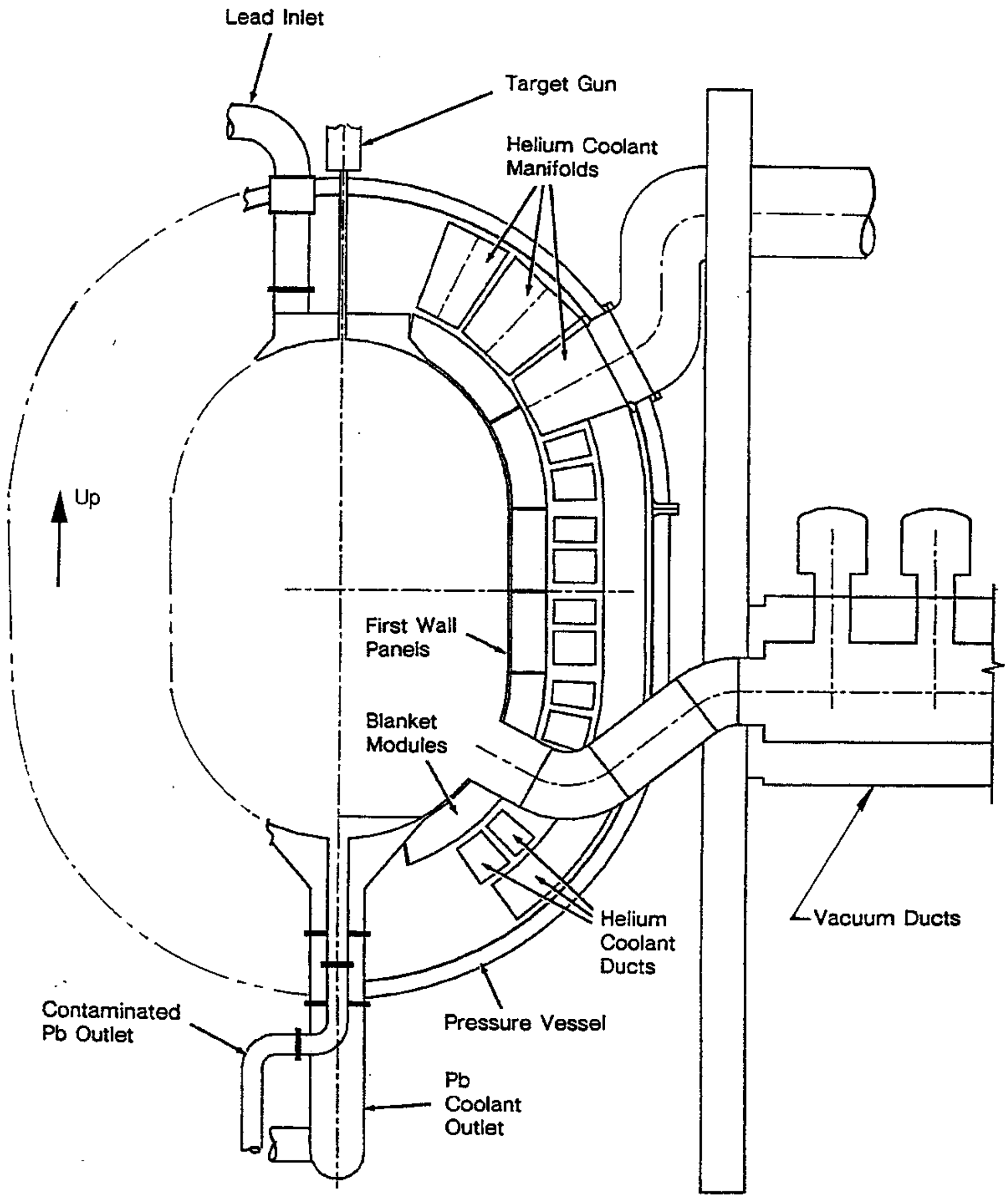


Figure 6.3.2-4 Reactor Vessel Cross Section with Major System Components Shown

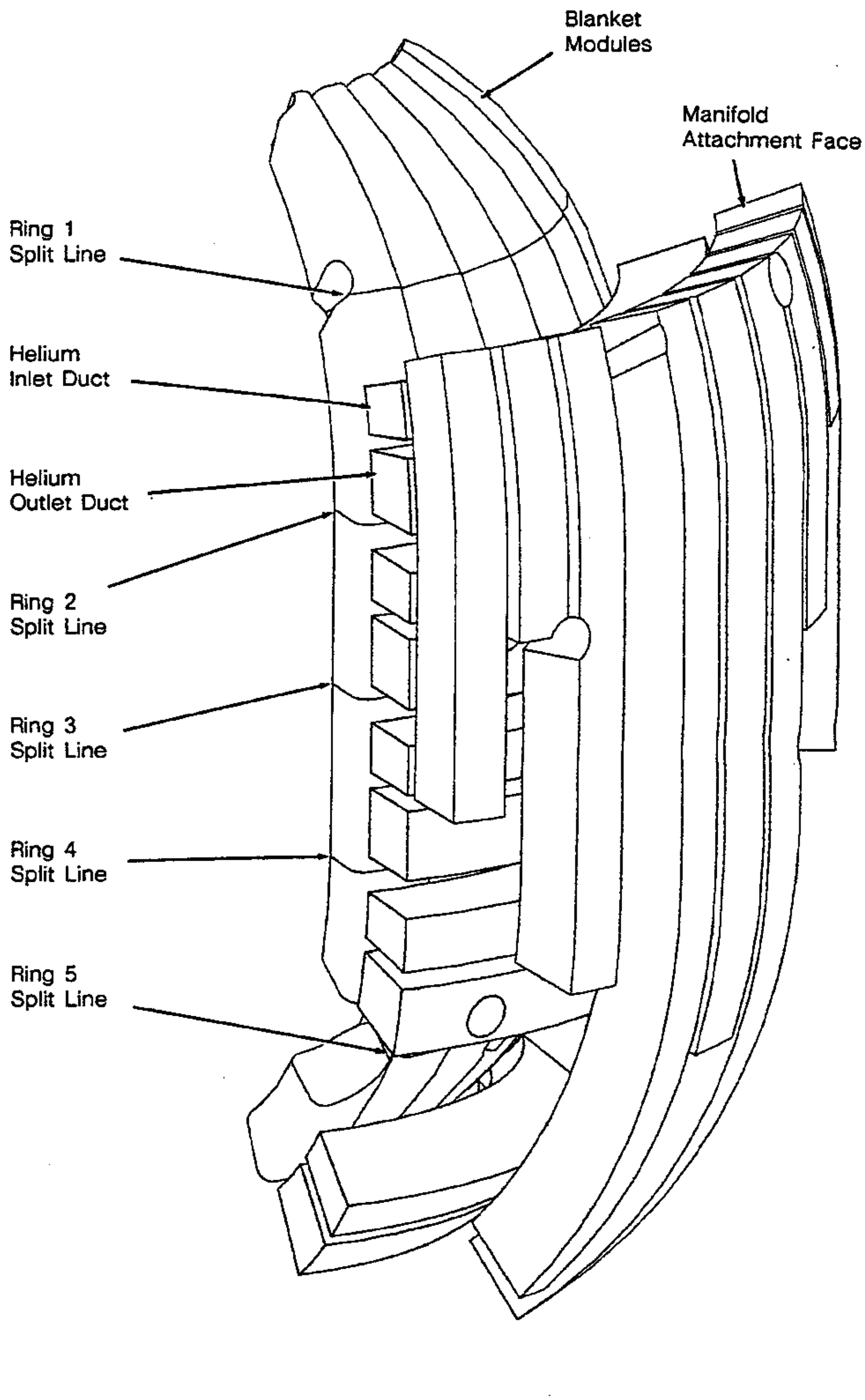


Figure 6.3.2-5 A Blanket Module Sector with Associated Coolant Ducts

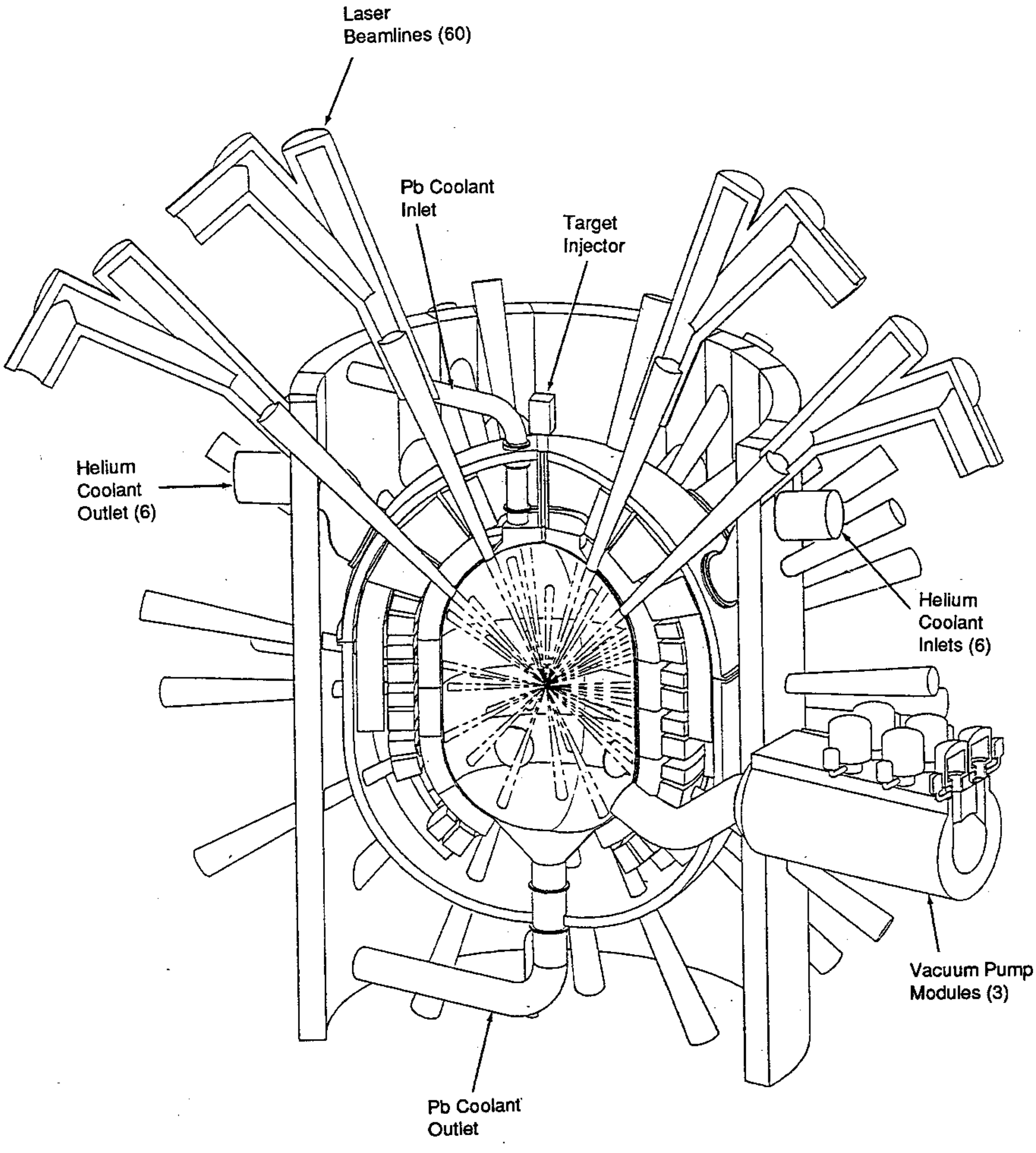


Figure 6.3.2-6 General Arrangement of the Major Laser-Driven Reactor Equipment

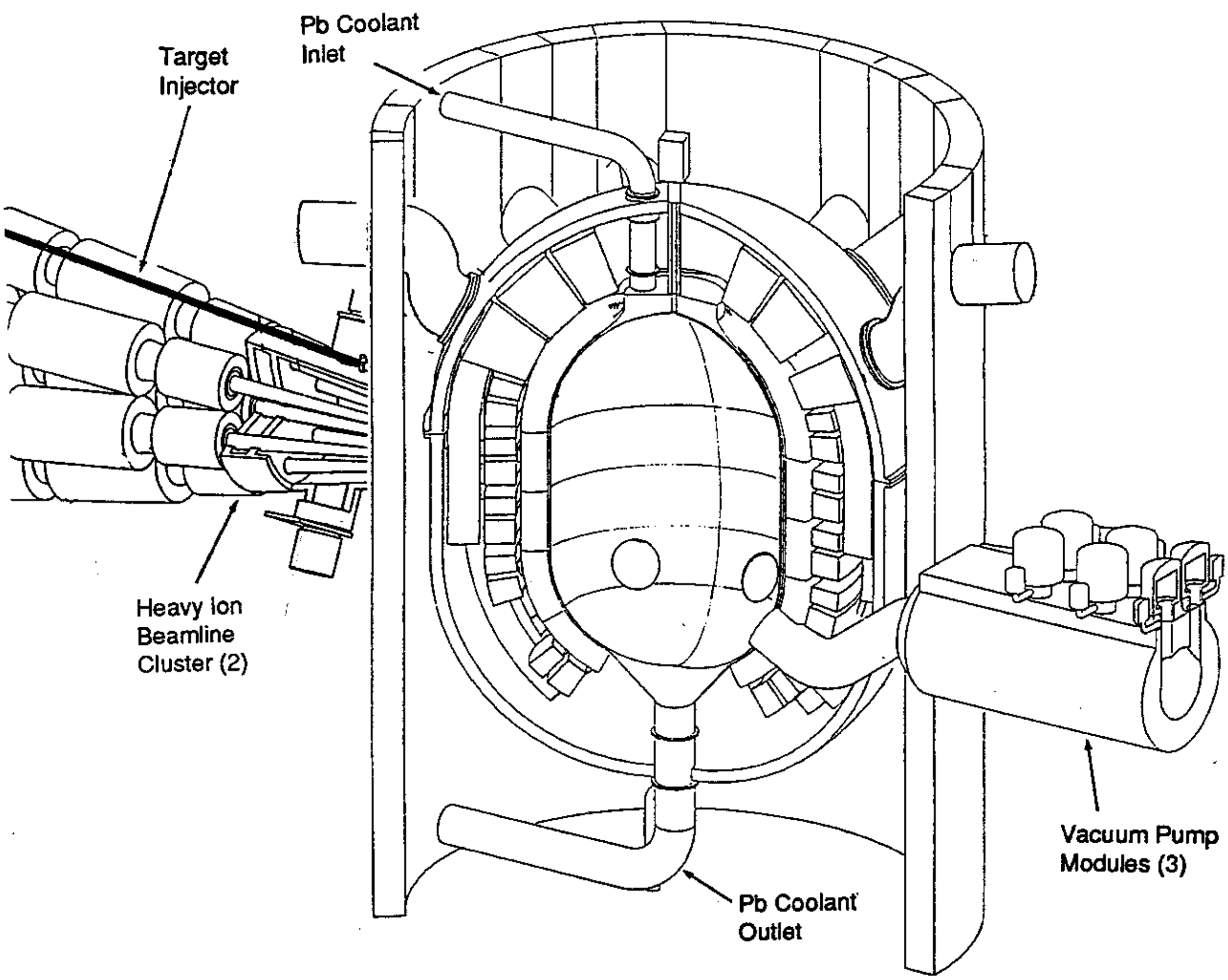


Figure 6.3.2-7 General Arrangement of the Major Heavy Ion-Driven Reactor Equipment

The general procedure for disassembly will be as follows:

(a) The lead coolant system is drained and the first wall is flushed of the lead coolant.
(b) The shield slabs in the floor of the upper access chamber, as shown in Figure 6.3.2-2, are removed to gain access to the reactor vessel. Figure 6.3.2-8 is a view looking downwards at the reactor vessel. The building floors are not shown for clarity. The remote maintenance equipment will then be installed and moved into position.
(c) Sections of the coolant plumbing (see Figures 6.3.2-9 and 6.3.2-10) will be removed to provide clear access to the top of the vessel.
(d) Sections of the laser beamline ducting are disconnected and removed.

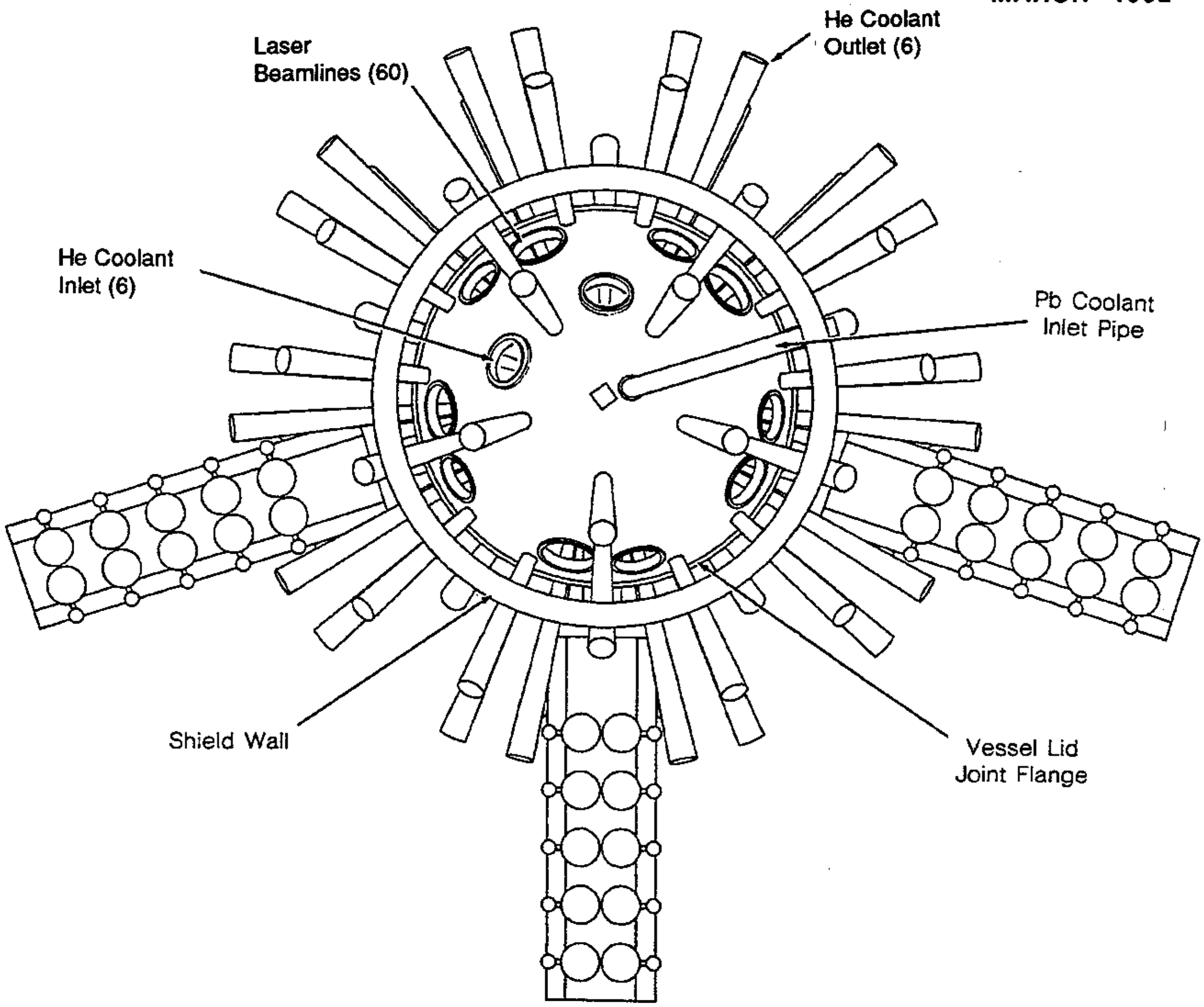


Figure 6.3.2-8 Access to Reactor Vessel with Upper Bulk Shielding and Helium Coolant Ducting Removed

(e) The target injection system is removed from the top of the reactor vessel. This procedure is further described in a following paragraph.

(f) The top of the reactor vessel is unbolted at the flange joint and any seal welds cut. Figure 6.3.2-11 illustrates a remote manipulator working on the attachment flange.

(g) Reactor vessel top is removed and placed in the upper access tunnel as shown in Figure 6.3.2-3 (heavy ion option).

(h) Helium manifolds are disconnected from the large helium inlet and outlet piping. Figure 6.3.2-12 shows the reactor vessel with the upper helium manifold removed and the manifold-to-duct attachment joint visible. Figure 6.3.2-13 shows the vessel with the helium manifold lifted clear.

(i) The first (top) blanket ring is removed after its support attach points are released, revealing the first wall dome as shown in Figure 6.3.2-14.

(j) The second blanket ring is removed after its support attach points are released. This enables removal of the first wall dome as shown in Figure 6.3.2-15.

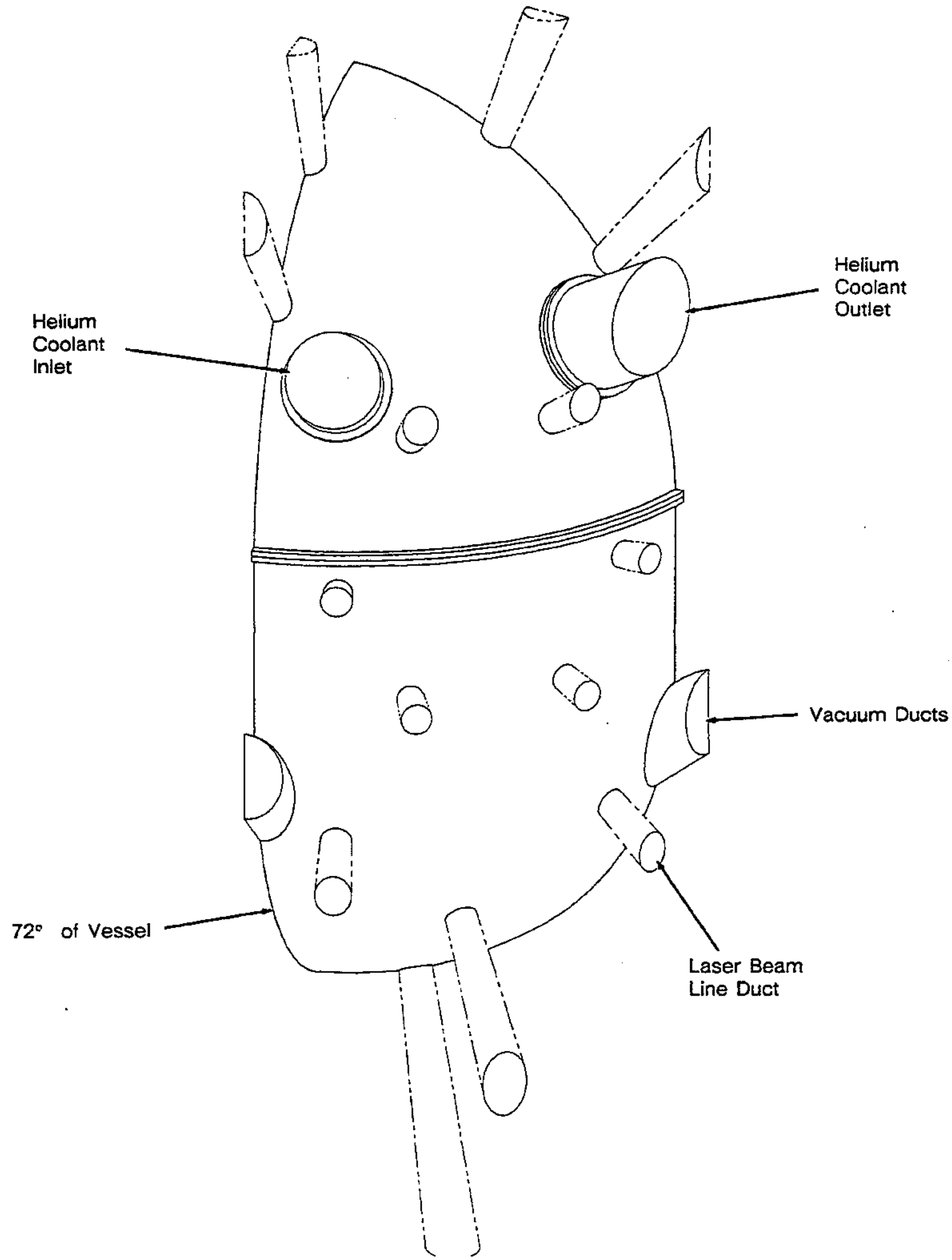


Figure 6.3.2-9 Segment of Reactor Vessel with Coolant Ducting

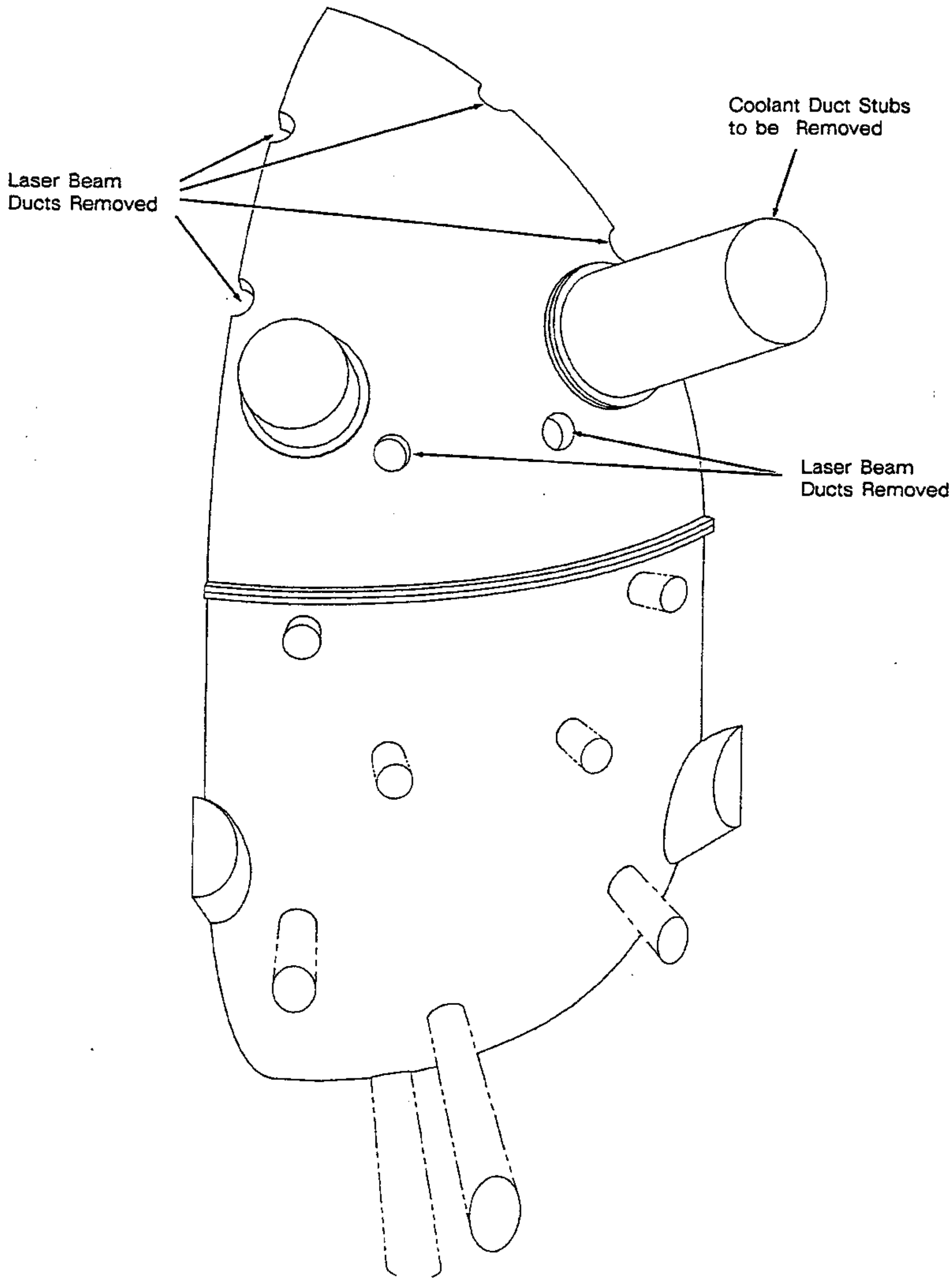


Figure 6.3.2-10 Segment of Reactor Vessel Showing Some Laser Ducts Removed

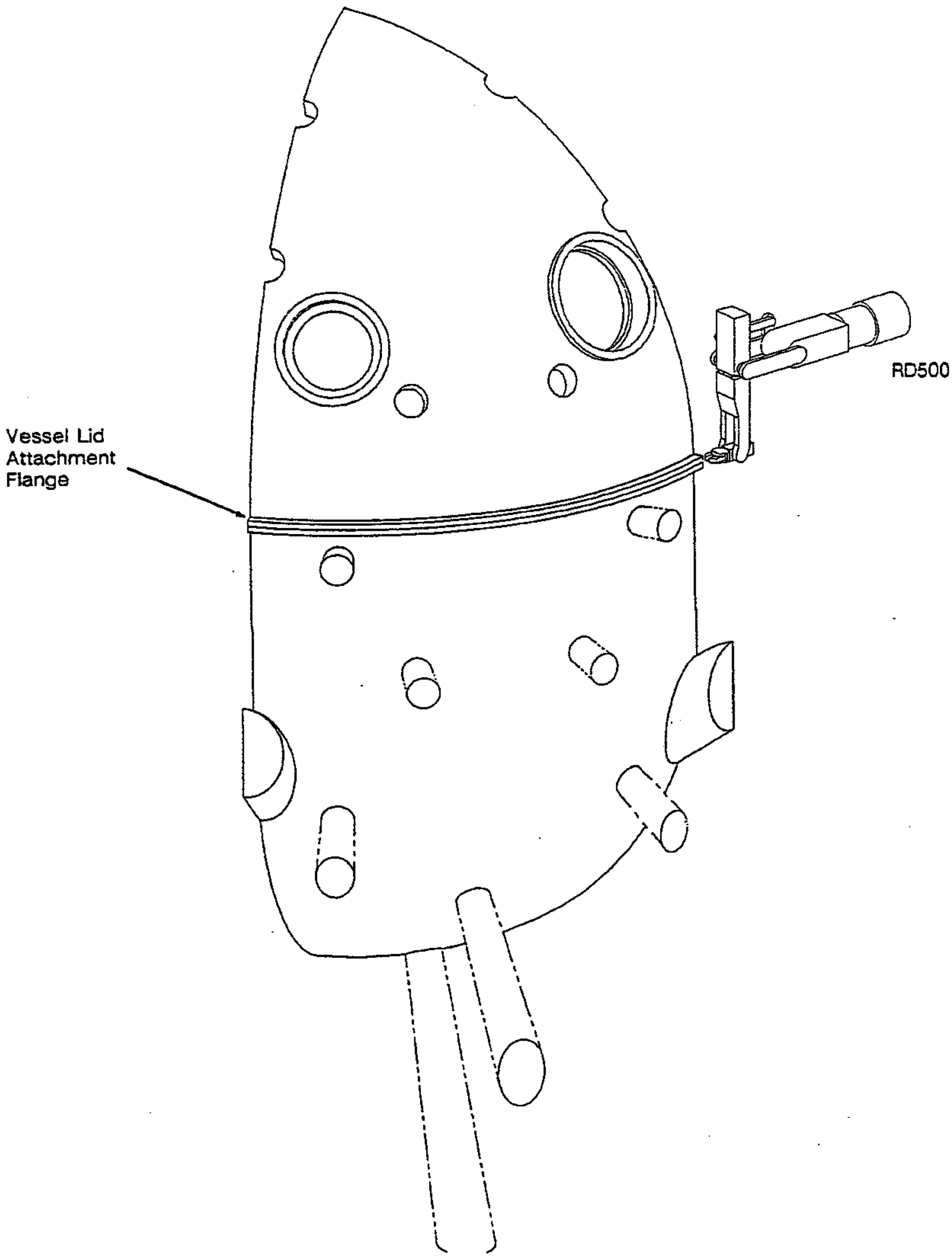


Figure 6.3.2-11 Remote Manipulator Working on Vessel Lid Attachment Flange

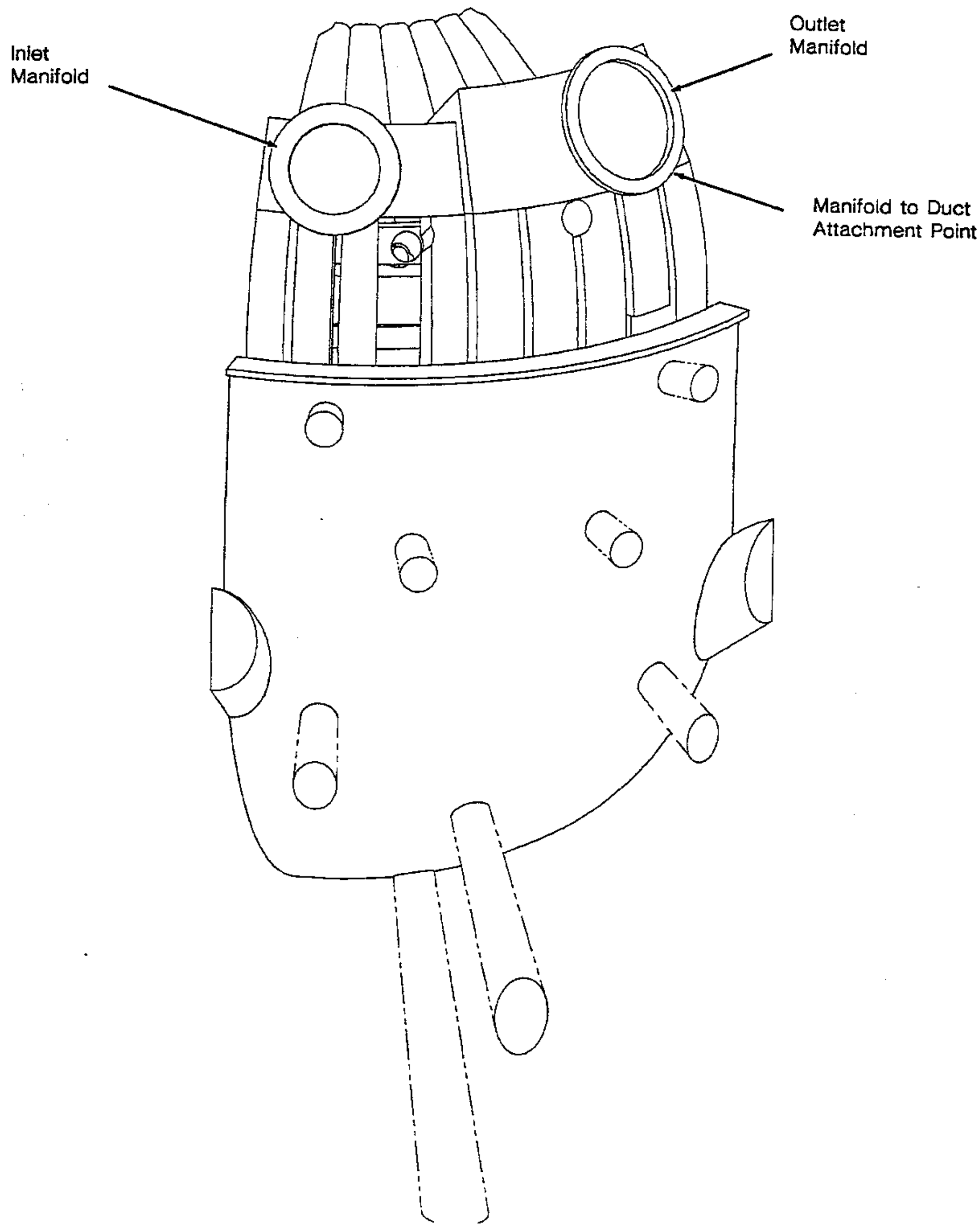


Figure 6.3.2-12 Reactor Vessel with Lid and Top Ring Manifold Removed

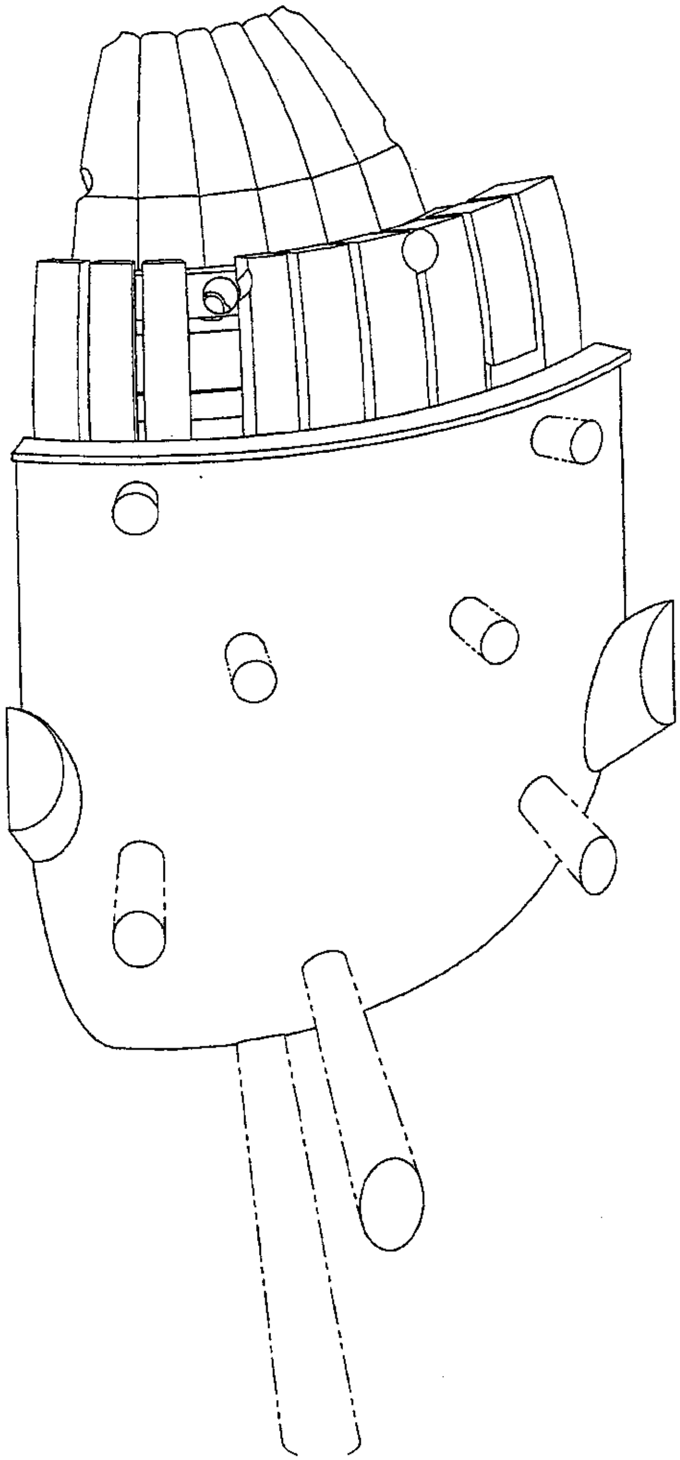


Figure 6.3.2-13 Reactor Vessel with Manifolds Removed

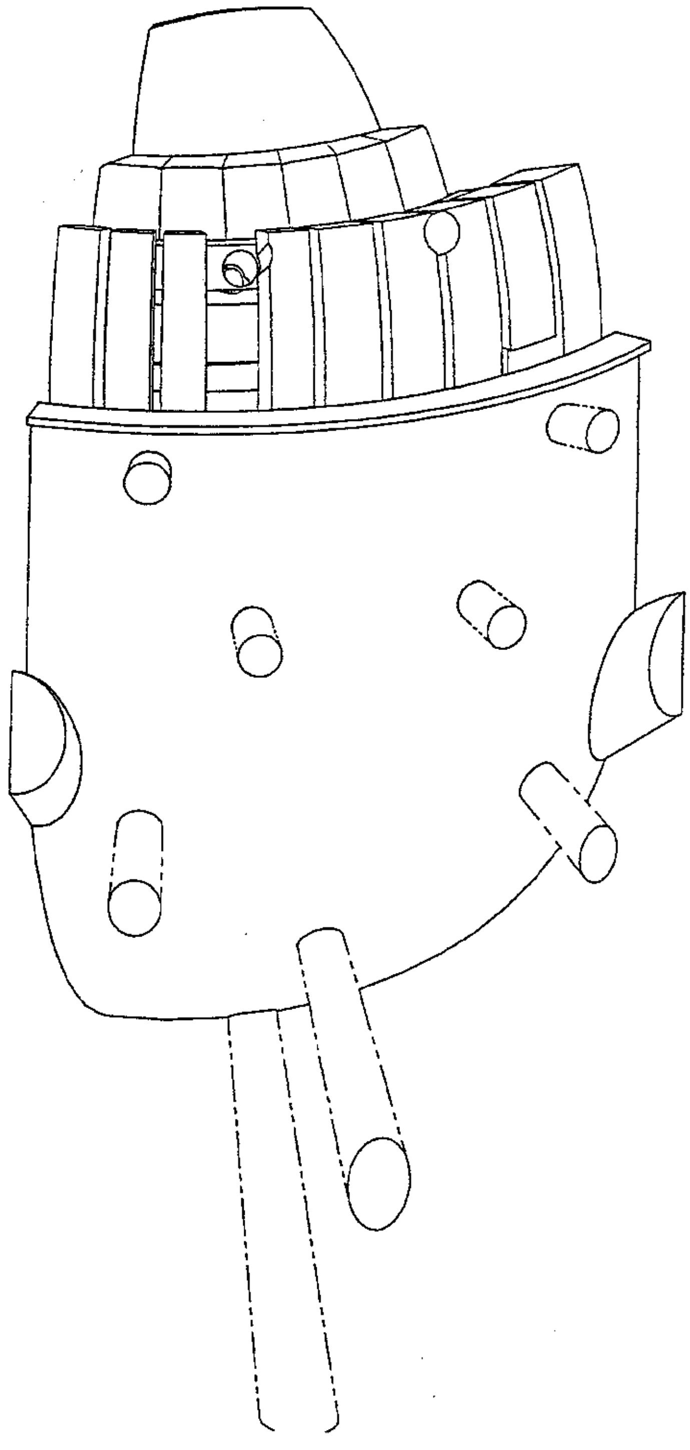


Figure 6.3.2-14 Reactor Vessel with Upper Blanket Ring Removed

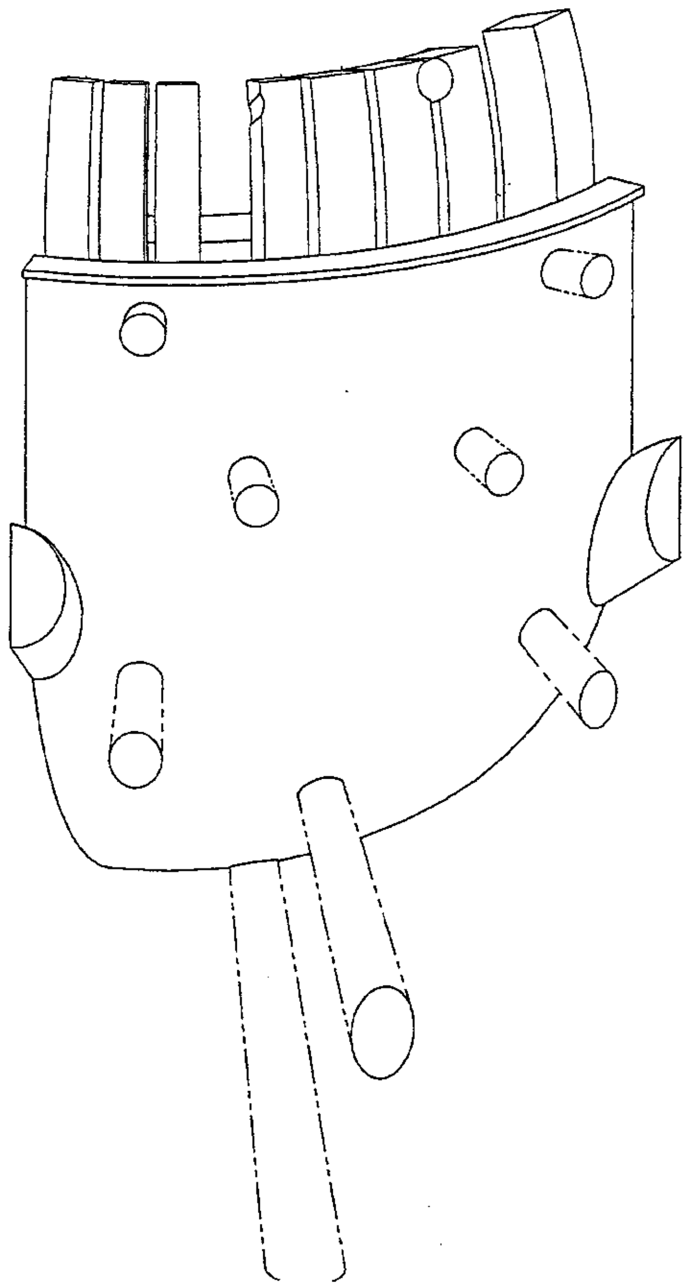


Figure 6.3.2-15 Reactor Vessel with First Wall Top Dome Removed

(k) The remainder of the blanket rings and first wall panels can then be removed in a similar sequence.

First Wall Attachment - The method of mounting and transferring loads from the first wall panels to the underlying structure was investigated to determine concept feasibility. A number of options were evaluated for the central cylindrical portion of the wall. This section of the wall is comprised of vertical wall panels as seen in Figure 6.3.2-16. These panels are assembled in a ring with the radial reaction taken by the blanket module edges. Figure 6.3.2-17 shows two options, composite leaf springs or adjustable wedges, for applying this preload. Detailed analyses of these approaches will be required as the design evolves.

6.3.2.6 Reactor Building Maintenance - Due to the number and the variation of components requiring maintenance in the Reactor Building along with the high level of the conceptual design study, only the maintenance of a few key systems were investigated to demonstrate applicable principles. Figure 6.3.2-18 illustrates the Reactor Building maintenance equipment and provisions. The bubbles indicate the location of various overhead cranes, mobile devices, and remote manipulators which are explained in the following figures and paragraphs.

Maintenance of the Target Injector System - The target injection system for the laser option is located at the top of the reactor and is mounted along the vertical axis of the machine. [The target injection system for the heavy ion beam option is located near the midline of the vessel in the vicinity of one of the beamline clusters.] The electromagnetic target injection system for the laser option is approximately 2 meters long. See Section 6.4.4 for additional information on this system.

This injection system is serviced from above as shown in Figure 6.3.2-19. Transportable power manipulators will be used in these service operations. Other maintenance equipment includes the overhead crane, target injector lifting rig, adjustable balancing beam, and assorted special purpose tools.

The target injection systems is removed from the operating position and transferred directly to the hot cell. This is achieved by attaching a lifting rig to the pellet feed line and disconnecting the feed line from the injector using the transportable power manipulator with an appropriate tool. When the line is free, it is lifted from the injector by the main crane. The main target injection system attachment locking device is disconnected and the injection system is removed by the main overhead crane for maintenance actions in the hot cell.

Final Mirror Maintenance - There are 60 laser beamlines symmetrically located around the reactor cavity. This arrangement provides the necessary direct drive target illumination uniformity. The beamlines are maintained with an interior pressure of a few mtorr. Bulk shielding is provided individually around each beamline out to and

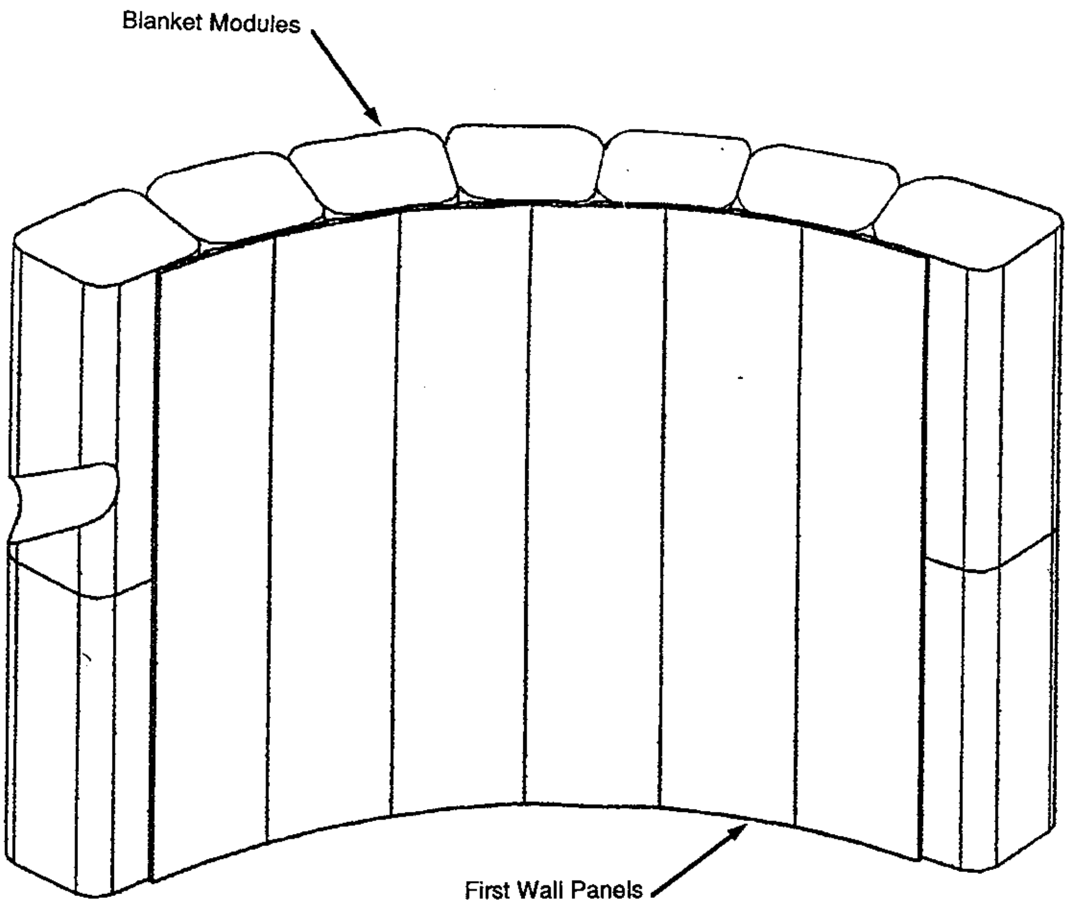


Figure 6.3.2-16 Vertical First Wall Panels are Attached to Blanket Modules

beyond the grazing incidence mirrors, the final mirrors, the neutron trap, and the neutron, which all lie inside the reactor building wall. Figure 6.3.2-20 illustrates a typical beamline arrangement and its principal elements. Both the grazing incidence metal mirror (GIMM) and the final focusing mirror must be replaced on a periodic basis, perhaps every 5 to 15 years depending upon material and coating developments. Beamline support structures allow attainment of the requisite beamline and mirror alignment requirements. The mirrors will also be cooled to maintain stable temperature and dimensional requirements. The mirrors will be removed and replaced with prealigned slide mounts to affect near final alignment. Final alignment will be accomplished with feedback from a surrogate target. Vernier adjustments will be made with the mirror mounts. Remote manipulators will be used to gain access to the mirror systems and remove/reattach the cooling fittings, if required.

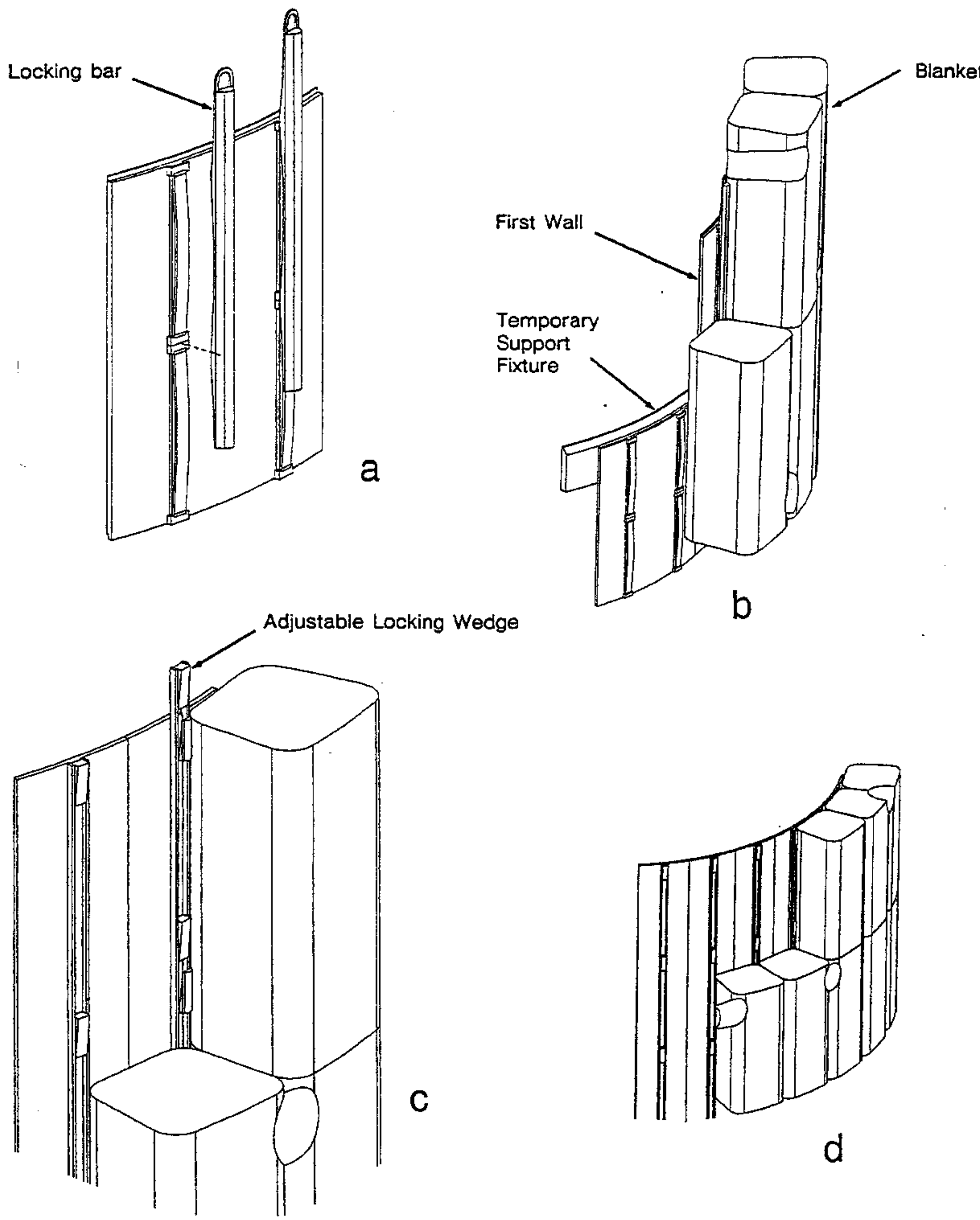


Figure 6.3.2-17 First Wall Attachment Options

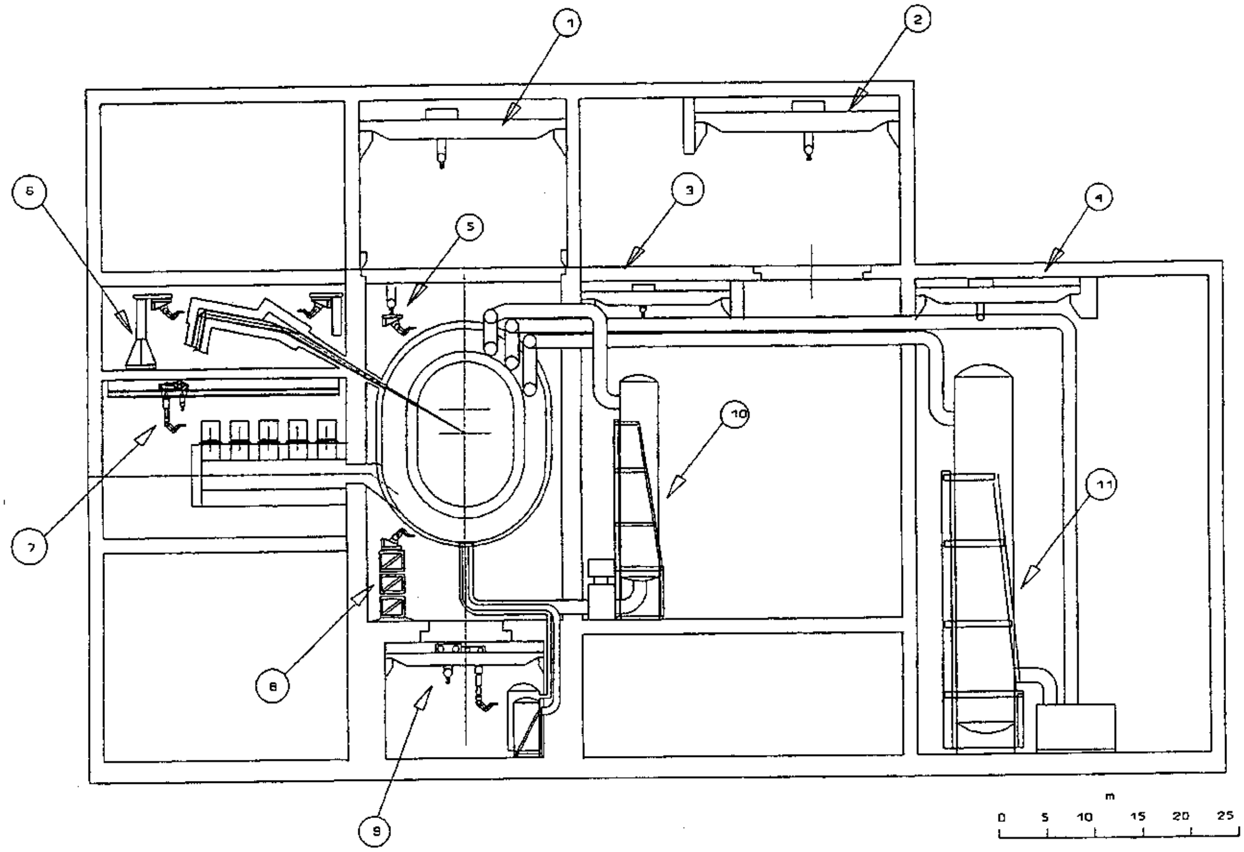
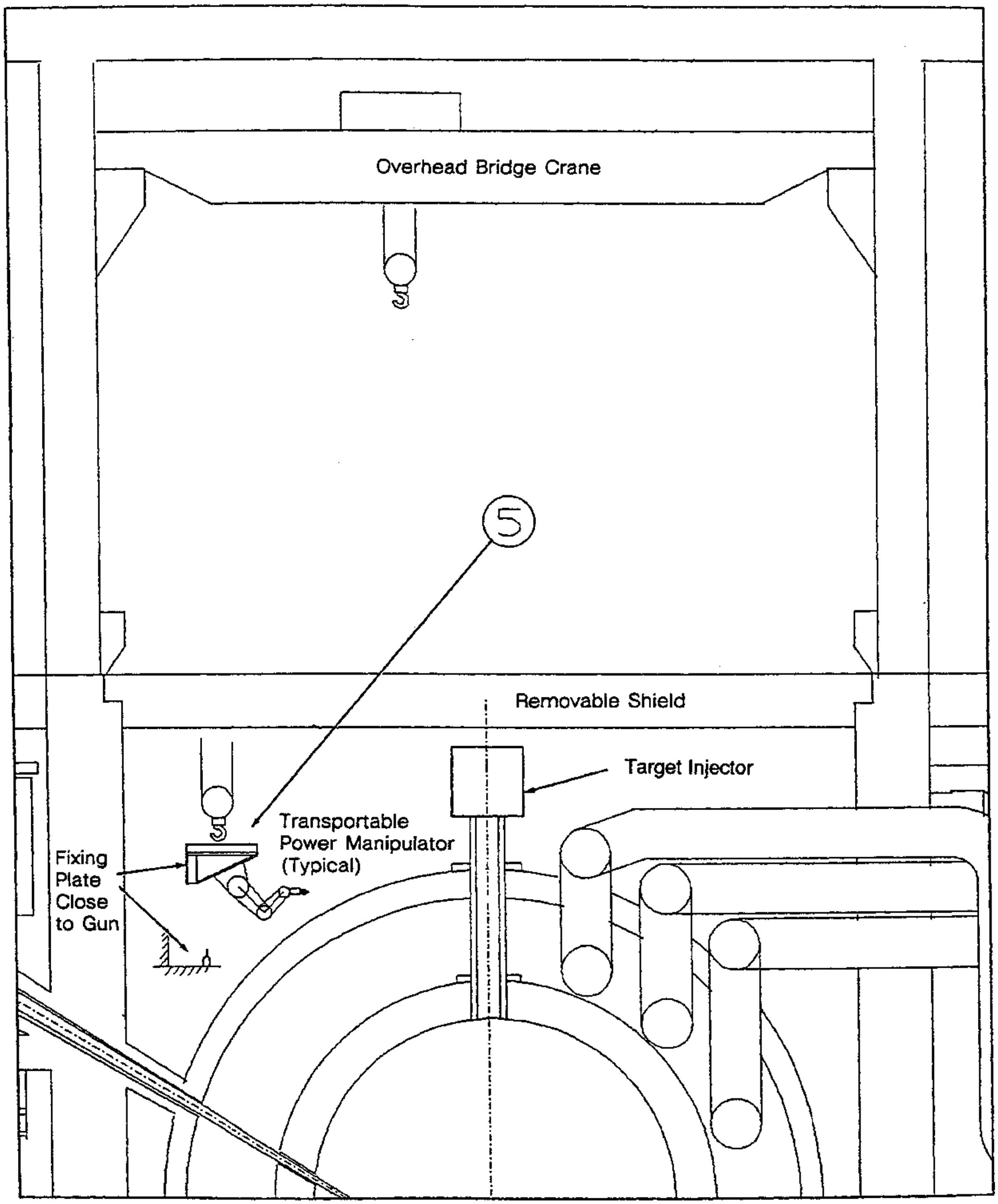


Figure 6.3.2-18 Reactor Building Maintenance Equipment and Provisions

Vacuum Pump Maintenance - The reactor chamber vacuum pumps are located on three main vacuum pump modules. Each pump module has ten cryogenic vacuum pumps on the upper surface of the module. The general arrangement is shown is several views on Figure 6.3.2-21. The vacuum pump provides pumping of the reactor chamber noncondensable gases to obtain a base pressure of a few mtorr. The lead condensation removes most of the condensable gases and traps some of the noncondensable gases. Figure 6.3.2-21 illustrates the relation of one of the vacuum modules compared to the beamlines and the wall/blanket sector.

The cryogenic vacuum pumps are very reliable. The only moving parts are the slide valves. During routine maintenance, these slide valves and pumps would be serviced or replaced. An overhead gantry crane would be used with a telescopic manipulator mast as shown in Figure 6.3.2-22. The mast has an interface with a dextrous and power manipulator. Pumps are mounted on manifolds such that the removal of the fixing clamp will allow vertical movement of the pump. Detailed maintenance will be accomplished in the hot cell.



Note: For Exo-Vessel maintenance or preparation work prior to removing Cavity Cap, the Transportable Power Manipulator is attached to an installed base.

Figure 6.3.2-19 Main Bridge Crane and Exo-Vessel Maintenance of Target Injection System

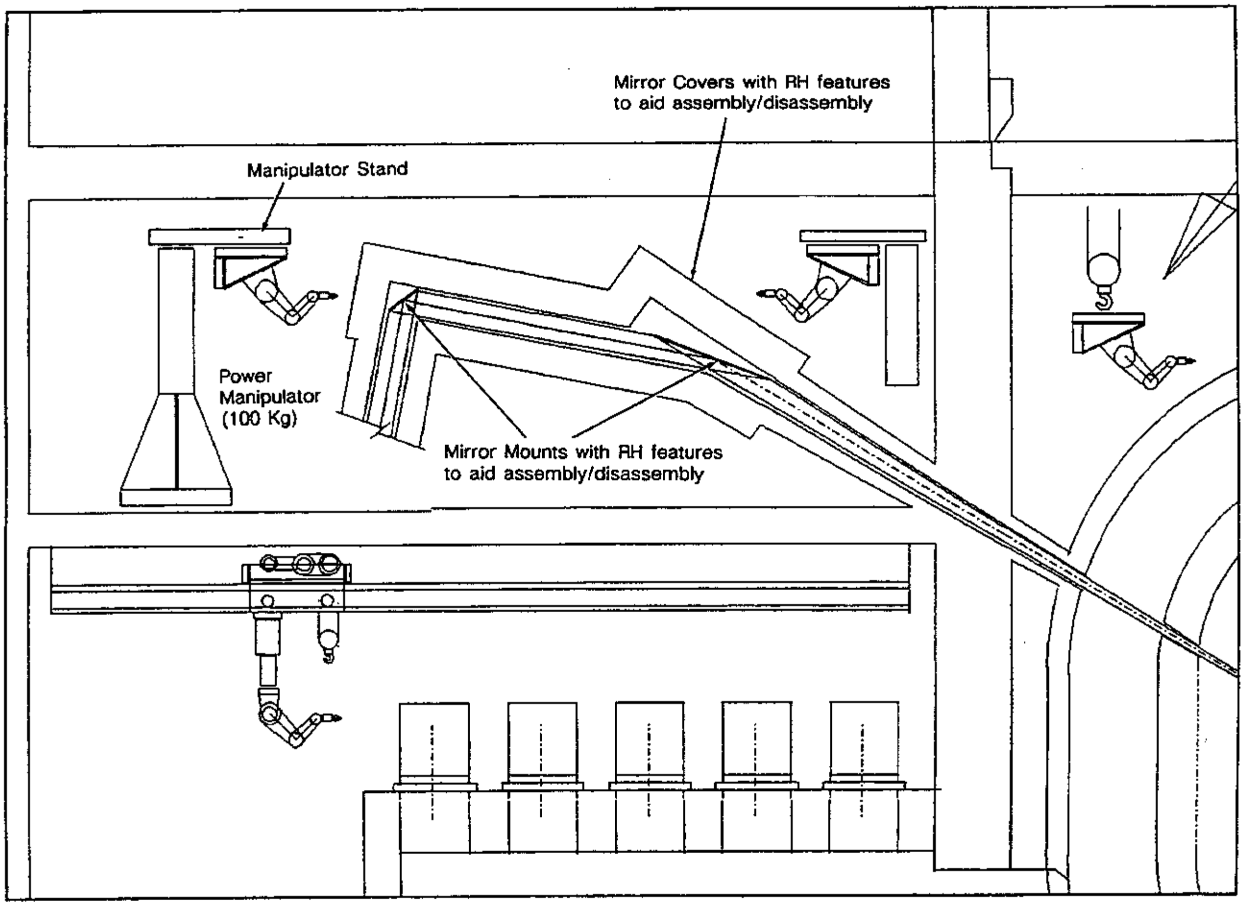


Figure 6.3.2-20 Remote Handling Equipment for Final Optical Elements

<u>Liquid Lead Steam Generator Maintenance</u> - Three liquid lead steam generators are mounted in the area outside the bulk biological shield at the -19 meter level. The liquid lead leaving the first wall cooling circuit, at the bottom of the reactor vessel, is pumped into the top of the steam generator. The lead flows downward through the generator, exiting to be returned to the top of the first wall system.

Liquid lead steam generators will require periodic maintenance and replacement. Before performing maintenance, the liquid lead must be drained from the entire circuit. A first wall liquid drain tank is located in the basement. Inspection and minor maintenance of tube headers can be made by accessing an entrance port at the bottom of the generator with a floor-mounted manipulator. Similarly, the bottom of the water circuit can be desludged by gaining access via a port at the bottom of the generator. For major repair, the steam generator would be replaced and repairs accomplished in the hot cell.

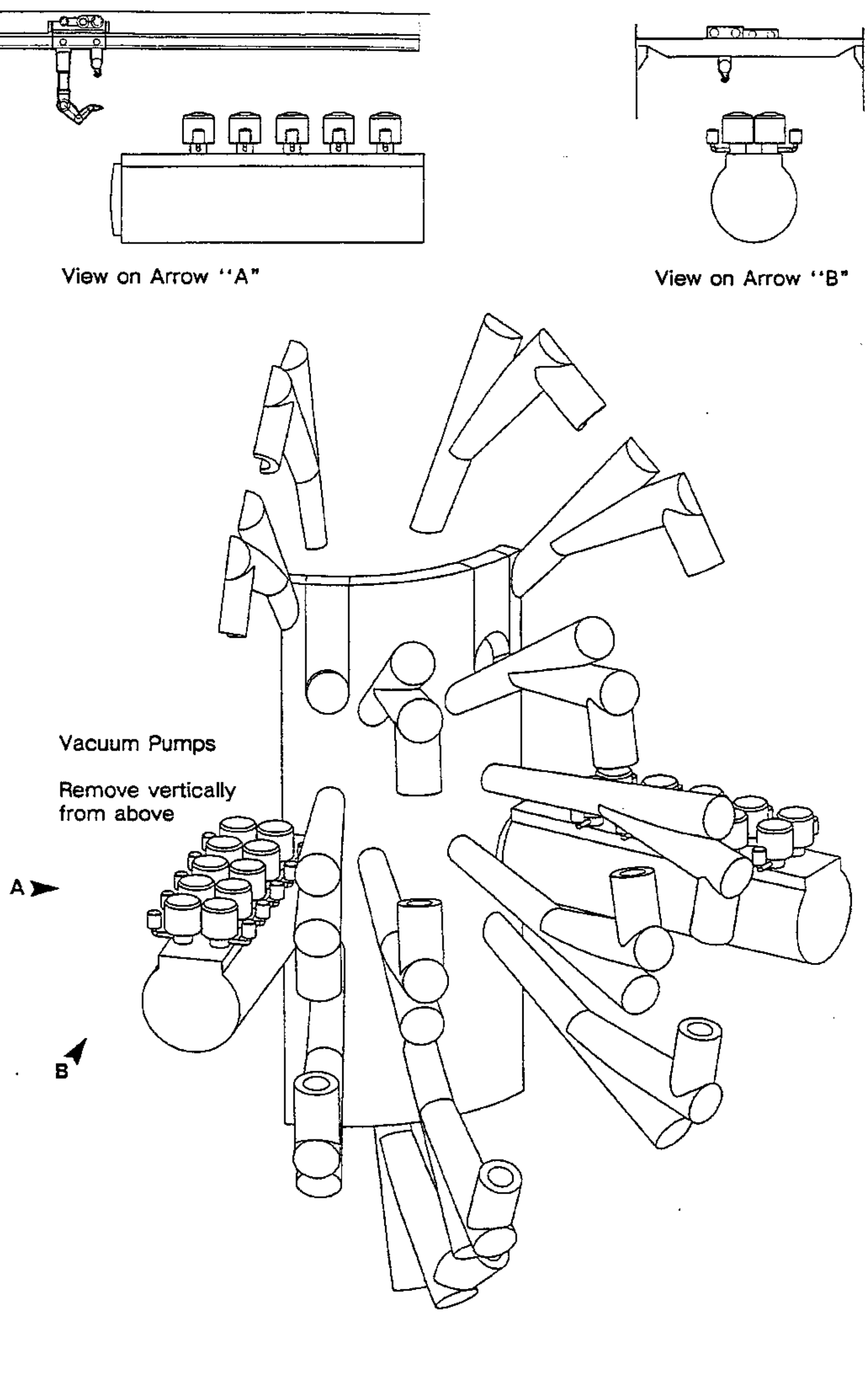


Figure 6.3.2-21 Sector of Bulk Shield Wall Showing Positions of Vacuum Pumps Relative to Laser Beamlines

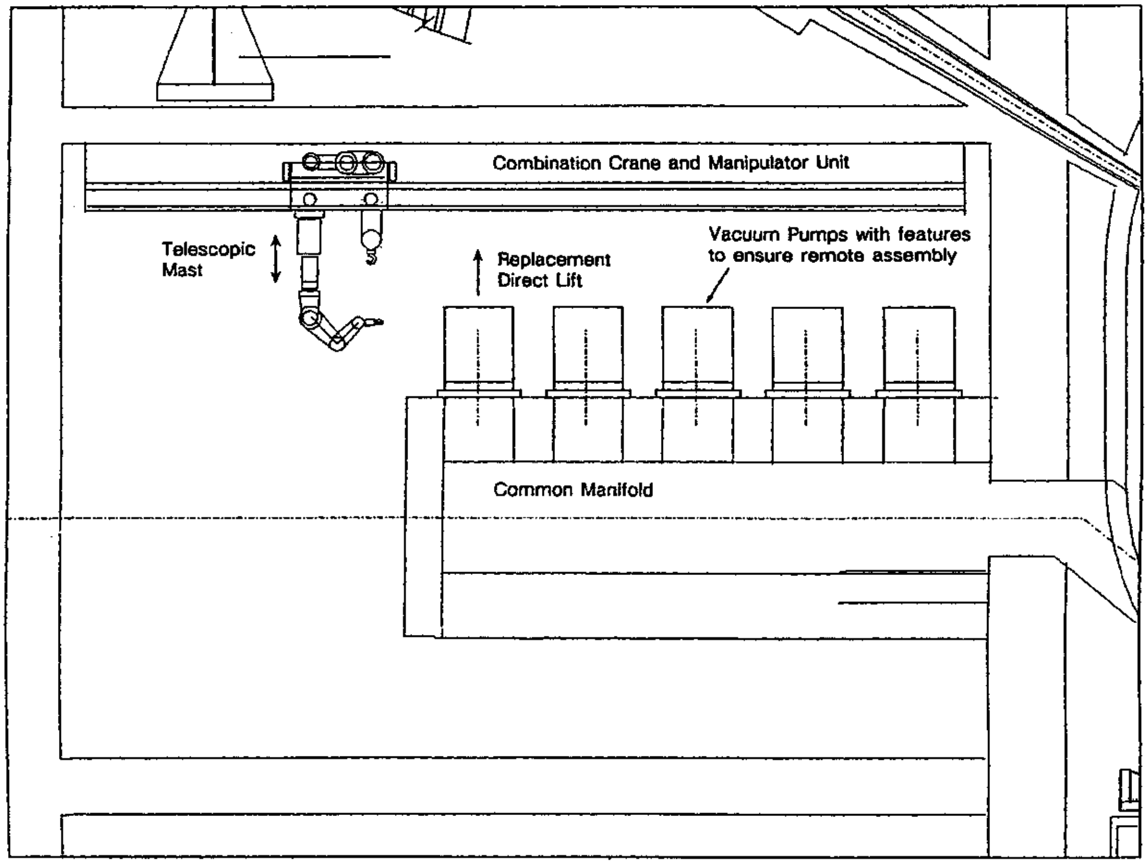


Figure 6.3.2-22 Schematic Arrangement of Remote Handling Equipment for Vacuum Pump Room

To facilitate handling and removal, steam generators are mounted in racks similar to those devised for chemical vessels in reprocessing plants. This arrangement is shown in Figure 6.3.2-23. Disconnection and lifting functions are carried out with a bridge crane and manipulator system (both dexterous and power). The rack is both a lifting rig and a strong back for the vessel. Vessels are normally connected to the feed lines by jumper pipes. When jumper pipes are disconnected and fasteners for the support rack are removed, an overhead crane can transfer the whole assembly from an operating position to the hot cell or decontamination facility. When replacing the unit, the rack has passive features which automatically locate the vessel and align the jumper pipe for remote connection.

Helium Steam Generator Maintenance - The helium steam generators are more remote from the reactor vessel. Levels of radiation are lower due to the environment and limited tritium migration within the helium coolant. However, there will be tritium in the coolant. Thus, the helium circuits must be detritiated to allow hands-on access with bubble suits. Figure 6.3.2-24 illustrates the size of the generators and maintenance with an overhead crane.

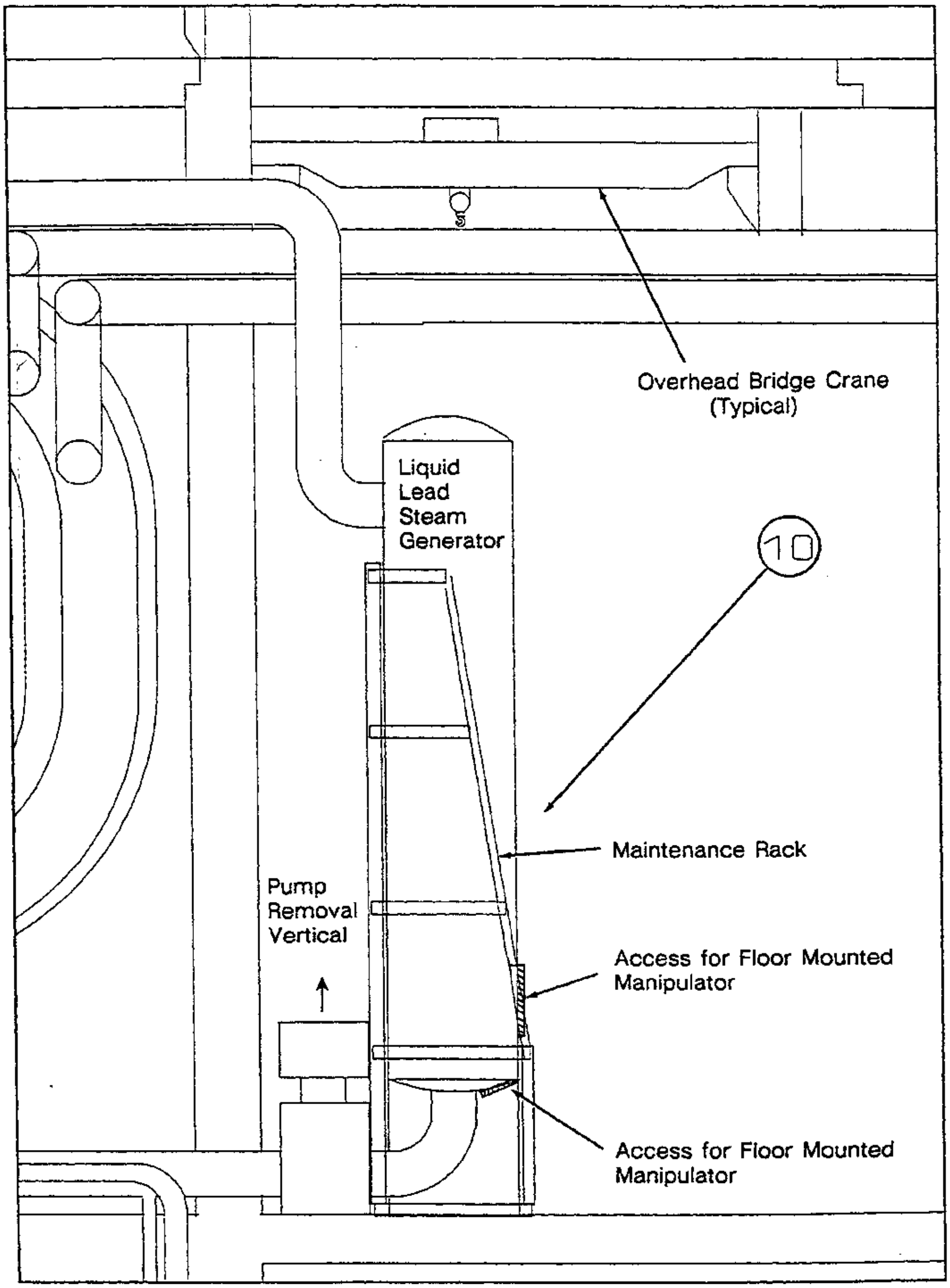
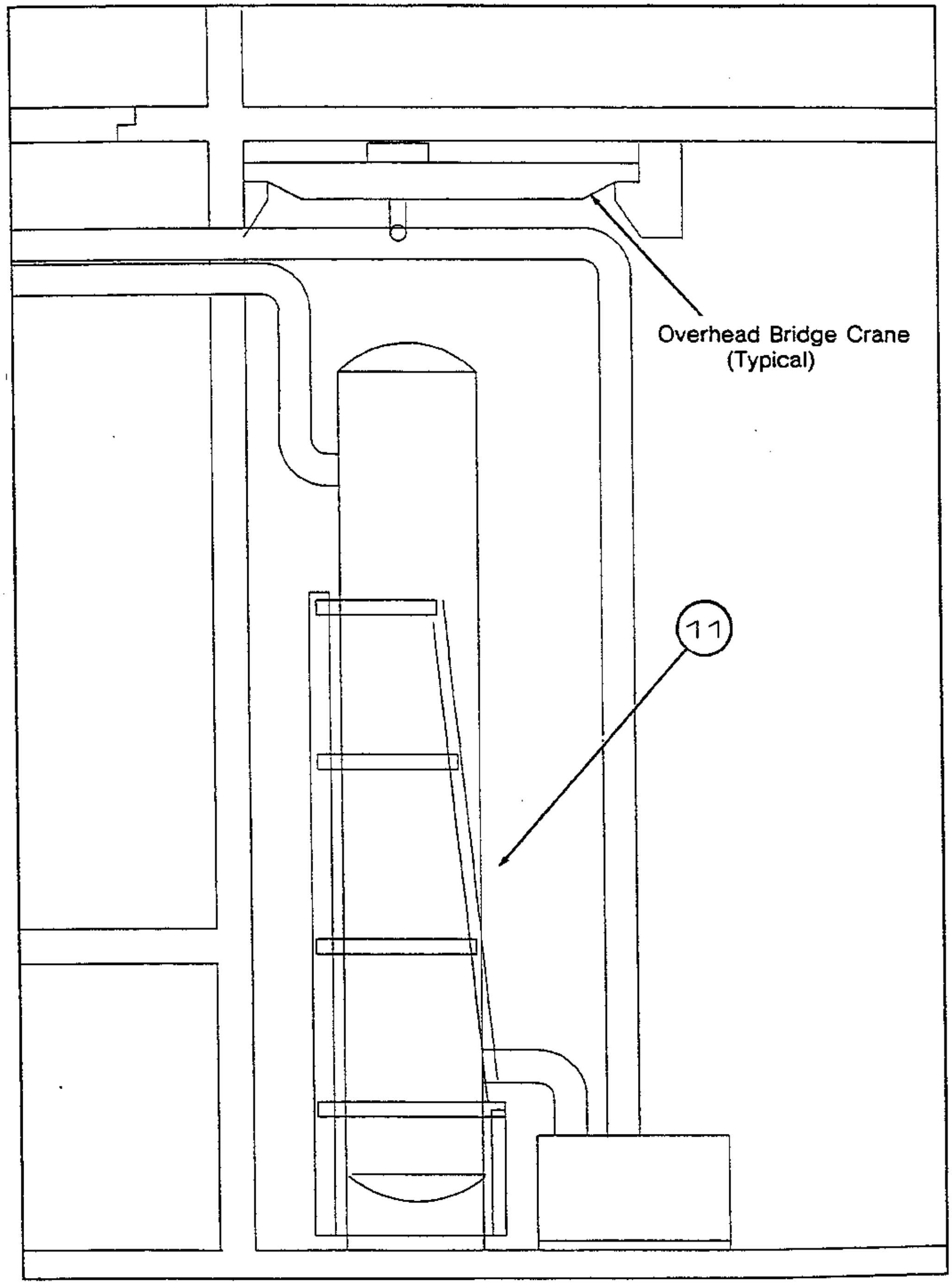


Figure 6.3.2-23 Lead-Steam Generator Maintenance



Note: For heat exchanger maintenance, access ports must be provided for the Floor-Mounted Manipulator

Figure 6.3.2-24 Helium-Steam Generator Maintenance

First Wall Liquid Lead Drain Tank Maintenance - The first wall coolant liquid lead drain tanks are located below the reactor vessel in the basement. To aid in replacement, the tanks are supported in equipment racks which are designed for remote replacement. Figure 6.3.2-25 shows the general arrangement and extent of the maintenance equipment. Minor maintenance actions on valves can be accomplished in place with replacement of parts. Larger items will require removal and replacement of the entire unit. The rack has location and alignment features which allow remote operations.

Contaminated Liquid Lead Hold Up Tank Maintenance - The contaminated liquid lead holdup tank is located in the basement alongside the drain tank. This tank collects the liquid lead which has a high level of contamination and is awaiting processing. The maintenance actions are identical to the liquid lead drain tanks.

6.3.2.7 Driver Building Maintenance - The two driver concepts chosen for Prometheus require different maintenance approaches and equipment. Figure 6.3.2-1 previously presented the site plan for the two reactors. The laser option uses an annular driver building, as shown in Figure 6.3.2-2, surrounding the reactor building. The laser driver is designed for an on-line maintenance of critical components in order to maximize the system availability. Moreover, the system is designed with enough redundancy in the main laser amplifier systems to accommodate a number of failures without adversely degrading the system performance in terms of target illumination uniformity. One of the critical driver system maintenance tasks is the replacement of the discharge laser power amplifier modules. Figure 6.3.2-26 illustrates the maintenance equipment used to replace the laser power amplifier modules which are approximately 0.44 m x 0.44 m x 2.0 m.

The heavy ion driver option uses a long but small cross-section tunnel to house the ion beam driver elements. A cross-section of the driver tunnel with overhead cranes was shown previously in Figure 6.3.1-23. The heavy ion driver maintenance will principally consist of change-out of the magnets and power supplies. The maintenance strategy chosen is simply an updating of the procedures used on existing accelerators such as CERN. A combination of heavy lift transporters and dexterous robots are deployed down the accelerator tunnel to perform the change-out operation remotely with human supervision. Figure 6.3.2-27 shows a typical existing setup for this type of operation. Due to the serial nature of the linear accelerator system where any major system failure causes the entire driver to be off line, the system will be optimized for high reliability and minimum maintenance times.

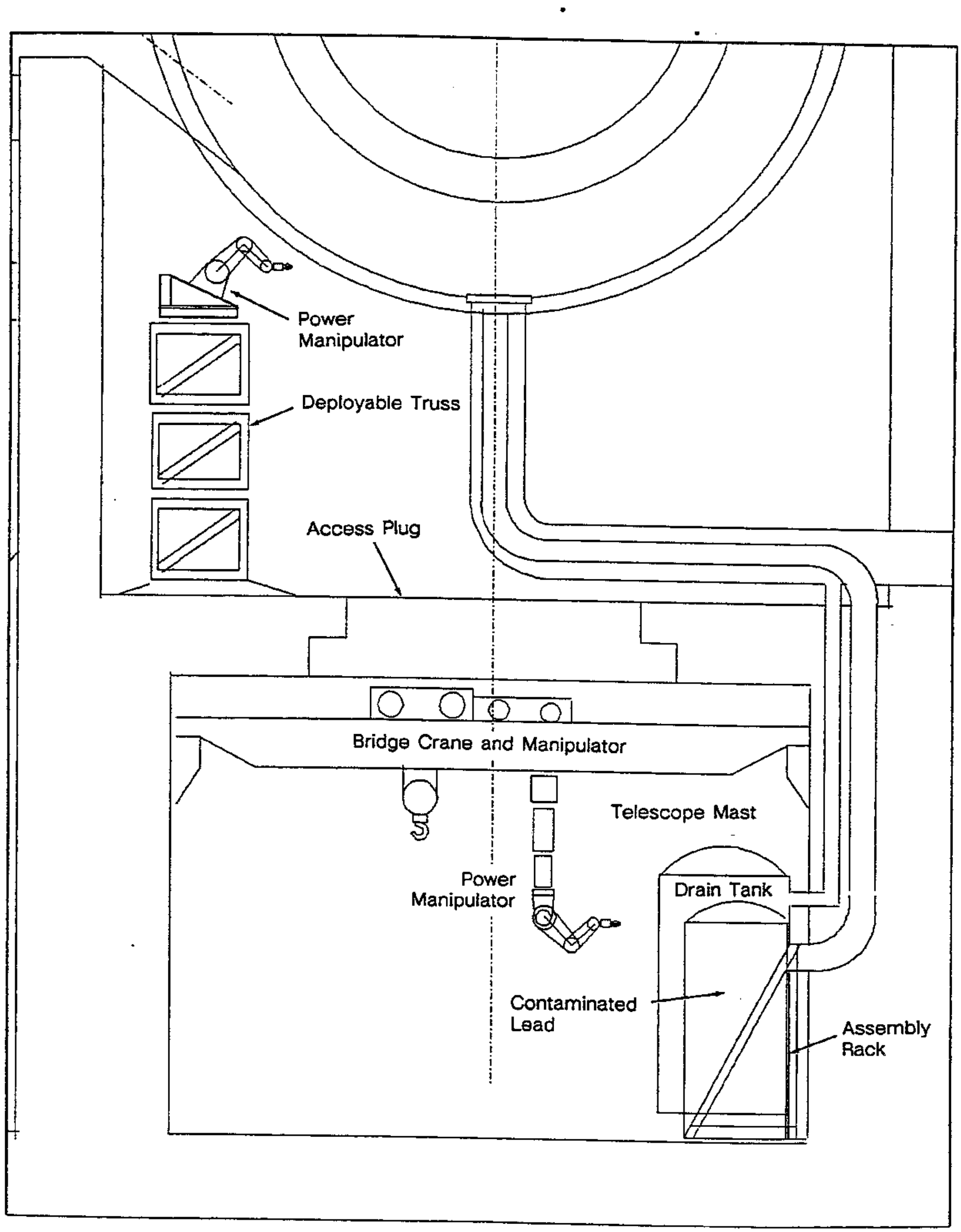


Figure 6.3.2-25 Lead Tank Maintenance

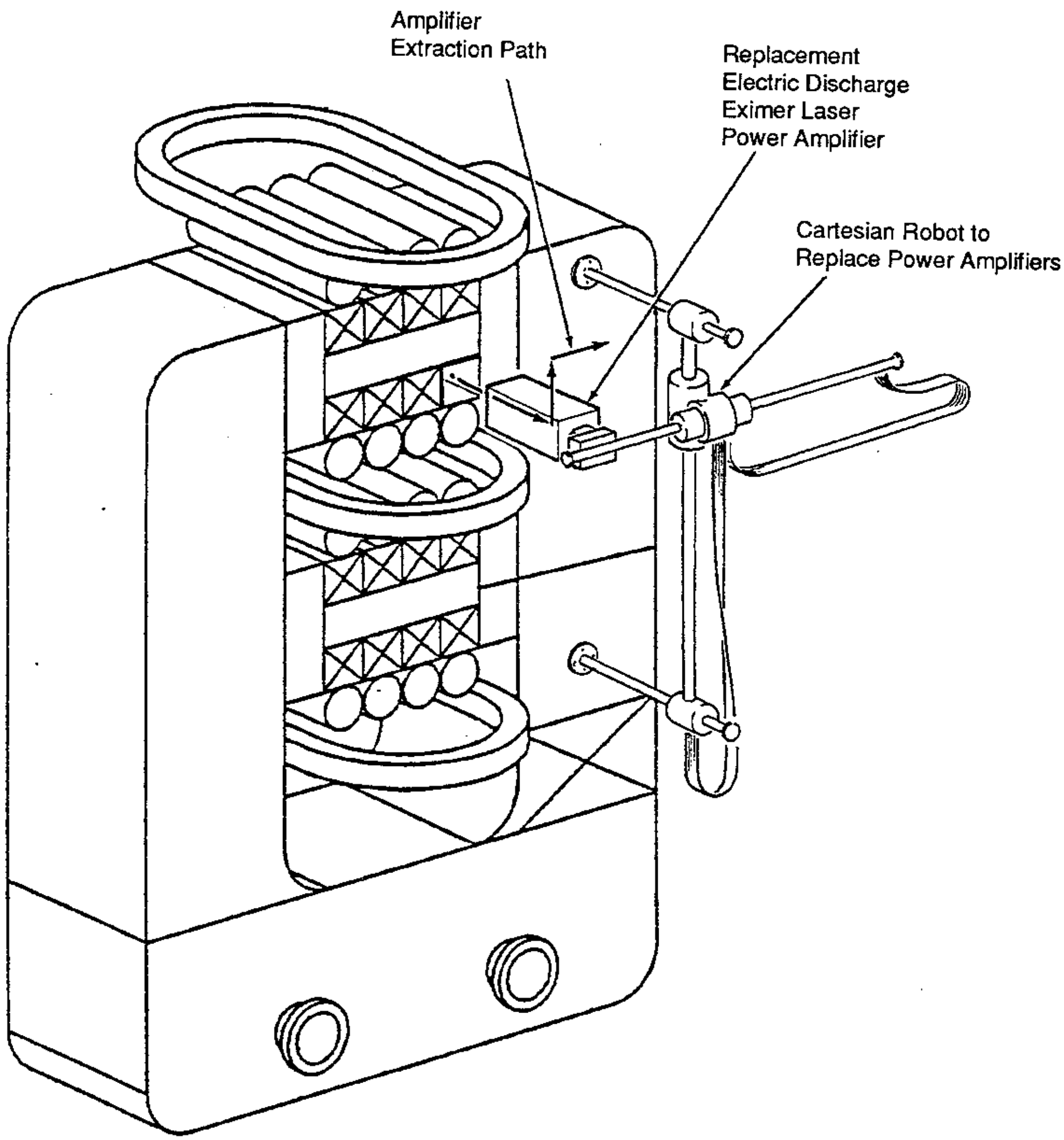


Figure 6.3.2-26 Maintenance of the Electric Discharge Power Amplifier Module

Tritium Building and Target Factory Maintenance - The Tritium Building and Target Factory both use a significant amount of process machinery. These types of applications are very suitable for a high degree of dedicated module replacement automation. In both of these applications, a failure of a critical element would cause the entire plant to be off-line. Thus the design approach is to have highly reliable components and systems, maximize the redundance of critical systems, and design the maintenance systems to minimize the maintenance times. The maintenance equipment associated with these functions were not considered in detail although general information can be found in Sections 6.4 (Target Factory), 6.7 (Fuel Processing), and 6.11 (Remote Maintenance Systems).

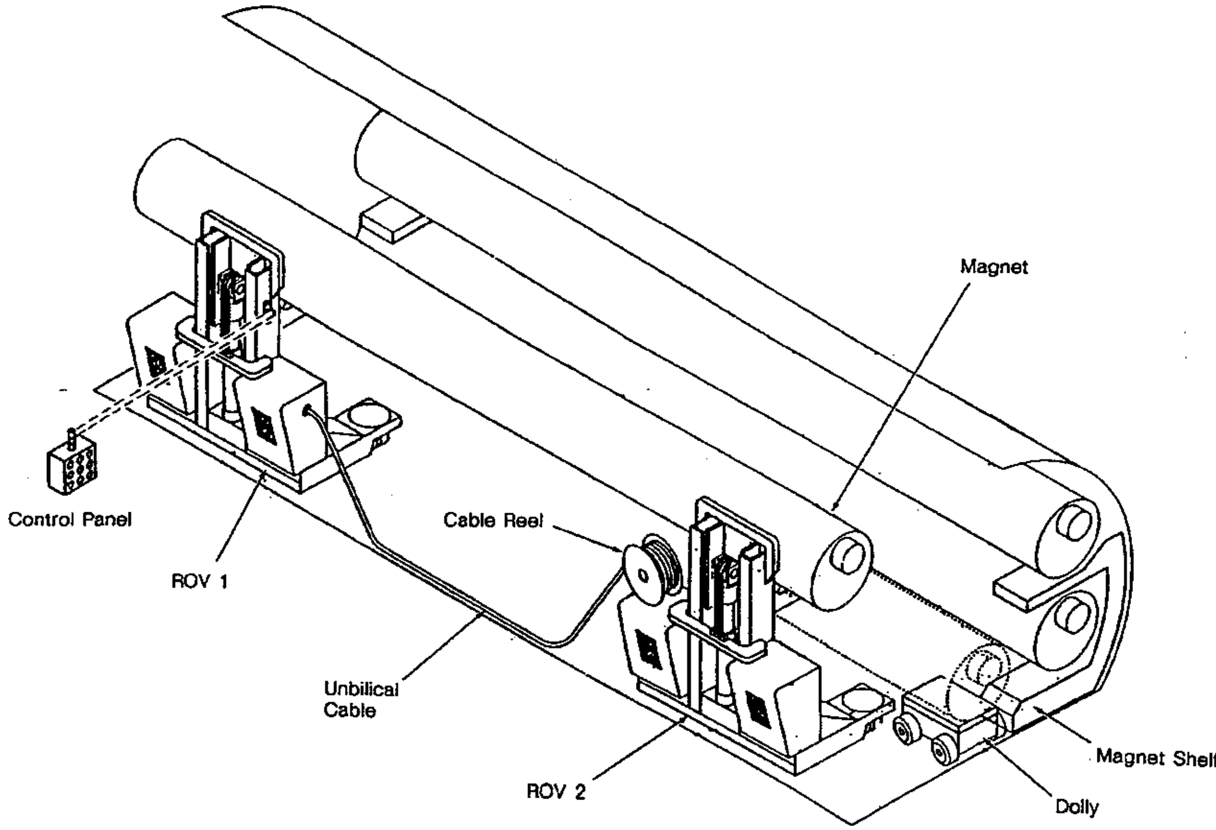


Figure 6.3.2-27 Typical Maintenance System for a Linear Accelerator

Turbine Building Maintenance - Experience in power plant turbine maintenance has been evolving over decades. The technology proposed in this design study is an extrapolation of current technologies. This involves significant hands-on maintenance using cranes and general purpose manipulators. However, we are forecasting for the 2030 timeframe, which would suggest increased automation would help speed and improve the maintenance of these systems. Autonomous cranes and smart tooling will reduce the manual labor role to that of supervision and technical expertise. Section 6.11 provides additional information on this subject.

Maintenance and Hot Cell Facilities - The normal mode of operation for maintenance in the majority of the plant is to remove and replace failed or worn equipment. This approach will provide the highest level of plant availability. This approach also reduces the sophistication of the local maintenance equipment to that required only for replacement and not for repair. For plant equipment with a high level of activation, the equipment will be transferred to a specialized hot cell for repair or disassembly and waste disposal. Figure 6.3.2-28 portrays the hot cell with a large number of reactor elements assembled in their operational configuration, perhaps in preparation for installation. Shown in the figure is a large overhead crane with a telescoping mast and a dexterous robot. The hot cell would have a large number of both general

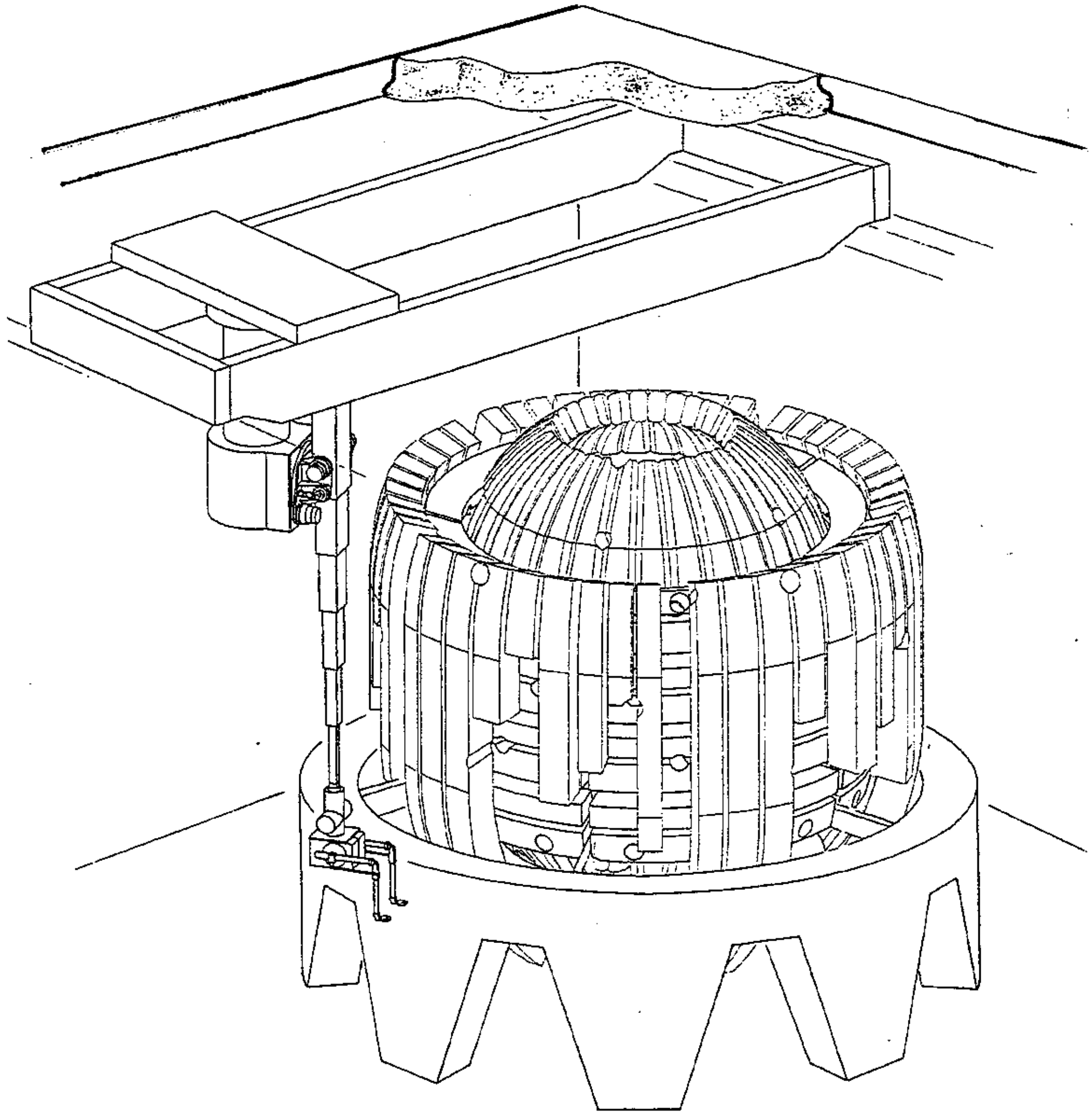


Figure 6.3.2-28 A Complete Set of Blanket Modules in the Hot Cell

purpose and specialized robots and manipulators for a variety of operations. The operations done in the hot cell include decontamination, failure analysis, disassembly, repair, system testing, and dimensional mockup (inspection). Due to the nature of the work accomplished in the hot cell, these are envisioned to be a complete range of operations from hands-on maintenance, human-assisted maintenance, and completely autonomous operations. Components which exhibit known and predictable wearout behavior are candidates for the more automated repair techniques.

6.3.3 Reliability, Availability, and Maintainability (RAM) Analyses - This section discusses the RAM analyses results along with the contributing factors. Production of economically competitive electric power is the ultimate goal of power plants. Several factors contribute to the production cost of electricity: net power, capital cost, operating cost, and plant availability. The plant must meet certain availability goals or attainment of all other performance and cost goals are meaningless. To achieve the plant availability goals, both plant reliability and maintainability requirements must be met.

6.3.3.1 Availability Summary - For both of the Prometheus reactor plant designs, analyses were conducted to determine the expected reliability and maintainability values of the key plant systems. These data were combined into the inherent availability for the respective subsystem or system. For this conceptual design, a complete analysis could not be accomplished because of the lack of complete technical definition of all systems. Rather, the major plant elements were analyzed which were estimated to account for 90% of the expected plant downtime. These data were then extrapolated to arrive at an estimated plant inherent availability value.

	Laser	Heavy Ion
Inherent Availability of Major Plant Elements	89.28%	90.68%
Projected Plant Inherent Availability	88.09%	89.64%

The conversion of the plant inherent availability into the average achieved availability takes into account the planned or unscheduled maintenance and the service shutdown for unplanned maintenance or repair. Typical of central station power plants, a 30-day annual shutdown is assumed. The longest scheduled task would take 15 days at three shifts per day. To account for a refit shutdown of 60 days every 5 years, an extra yearly shutdown allowance of 6 days is added.

	Laser	Heavy Ion
Total time per year, days	365	365
- Less scheduled annual shutdown, days	-30	-30
- Less refit allowance, days	- 6	- 6
Attempted run time, days	329	329
- Less unscheduled maintenance time*, days	-39.2	-34.1
Productive reactor time, days	289.8	294.9
Average achieved availability**, percent	79.4	80.8

* Unscheduled maintenance is computed from the plant inherent availability and the attempted run time.

** The average achieved availability is the ratio of the productive reactor time to the total time per year.

The estimated plant availability of 80% for the Prometheus reactors is well within the availability demonstrated by current commercial nuclear power plants. Table 6.3.3-1

Table 6.3.3-1 Reported Availability for Existing Power Plants (Reprinted from Nuclear Engineering International, August 1991)

Reactor name and country		Annual figures (for 12-months to end March 1991)		
		Rank	Load factor, %	Avail., %
Kariwa 5	J	1	99.8	100.0
Kori 2	SK	2	99.4	100.0
Pt Lepreau	C	3	98.5	97.9
Fukushima II 4	J	4	96.4	97.3
Prairie Isl 1	US	5	96.1	99.7
Tokai 2	J	6	95.9	
TVO 1	SF	7	94.9	95.7
Embalse	A	8	94.0	94.3
Philippsburg 2	D	9	93.9	93.2
Sendai 1	J	10	93.6	100.0
Almaraz 2	E	11	92.9	
TVO 2	SF	12	92.6	94.3
Three Mile Isl 1	US	13	92.4	
Bruce 7	C	14	91.4	94.4
Paks 2	HU	15	91.0	
Fukushima I 6	J	16	90.9	91.8
Neckar 2	D	17	90.4	90.8
Emsland	D	18	90.4	90.8
Hunterston B1	GB	19	90.2	98.1
Gundremmingen B	D	20	90.0	99.9
Paks 1	HU	21	89.9	
Waterford 3	US	22	89.6	92.3
Pilgrim	US	23	89.5	
Hatch 2	US	24	89.4	
Farley 1	US	25	89.4	
Ohi 2	J	26	89.4	
Tihange 2	B	27	89.2	
Shimane 2	J	28	89.1	90.2
Gosgen	CH	29	88.9	91.1
Hinkley Pt A1	GB	30	88.5	97.1
Tihange 3	B	31	88.4	
Byron 1	US	32	88.3	
Grohnde	D	33	88.1	89.9
Muehleberg	CH	34	88.1	90.3
Paks 3	HU	35	87.9	
Leibstadt	CH	36	87.9	
Takahama 3	J	37	87.7	
Tsuruga 1	J	38	87.6	
Doel 3	B	39	87.5	
Monticello	US	40	87.4	93.8
Pickering 5	C	41	87.4	89.3
Tihange 1	B	42	87.1	92.0
Bruce 6	C	43	87.0	88.8
Takahama 4	J	44	86.2	
Beznau 2	CH	45	86.0	86.4
Doel 4	B	46	86.0	
Wolsong 1	SK	47	85.9	85.5
Palo Verde 3	US	48	85.8	
Asco 2	E	49	85.8	88.2
Millstone 1	US	50	85.7	88.5
Prairie Isl 2	US	51	85.7	90.2
Hamaoka 3	J	52	85.4	
Asco 1	E	53	85.4	87.7
Loviisa 2	SF	54	85.3	88.0
Doel 1	B	55	84.8	
Kewaunee	US	56	84.8	
Vandellos 2	E	57	84.5	
Barsebaeck 1	S	58	84.4	
Paks 4	HU	59	84.4	
Loviisa 1	SF	60	84.3	87.3
Maanshan 2	TW	61	84.0	88.9
Diablo Canyon 2	US	62	83.9	90.8
Cofrentes	E	63	83.8	86.1
Point Beach 2	US	64	83.7	88.1
Beznau 1	CH	65	83.6	85.7
La Salle 1	US	66	83.6	86.5
Pickering 7	C	67	83.2	92.8
Hinkley Pt B2	GB	68	83.1	94.3
Shimane 1	J	69	83.1	83.2
Neckar 1	D	70	83.0	85.9
Ikata 2	J	71	83.0	
Dukovany 2	CS	72	82.9	88.6
Yongkwang 1	SK	73	82.4	85.7
Wolf Creek	US	74	82.3	87.2
Sendai 2	J	75	82.2	83.4
Point Beach 1	US	76	82.0	84.3
Bugey 2	F	77	81.9	95.2
Almaraz 1	E	78	81.9	
Barsebaeck 2	S	79	81.8	
San Onofre 2	US	80	81.7	89.0
Oconee 3	US	81	81.6	
Forsmark 3	S	82	81.5	93.7
Bruce 3	C	83	81.2	89.2
Dukovany 1	CS	84	81.1	84.8
Ringhals 4	S	85	81.1	92.2
Bruce 8	C	86	81.1	85.9
Arkansas 2	US	87	80.9	
Genkai 2	J	88	80.6	81.5
Isar 2	D	89	80.5	89.3
Vermont Yankee	US	90	80.5	
Bradwell 2	GB	91	80.4	99.9
Kruemmel	D	92	80.4	85.5
Mihama 3	J	93	80.0	
Beaver Valley 1	US	94	79.9	88.8
Oconee 1	US	95	79.9	
St Lucie 1	US	96	79.8	
Tricastin 3	F	97	79.6	86.9
Catawba 1	US	98	79.5	
Bruce 5	C	99	79.5	81.7
Maanshan 1	TW	100	79.5	83.1
Susquehanna 2	US	101	79.4	
Brunswick 2	US	102	79.3	
Wylfa 1	GB	103	79.3	99.5
Ginna	US	104	79.0	
Flamanville 2	F	105	79.0	85.7
Unterweser	D	106	78.9	79.0
Surry 2	US	107	78.9	
Callaway 1	US	108	78.9	81.8
Dresden 3	US	109	78.9	90.6
Borssele	NL	110	78.9	81.4
Vogtle 1	US	111	78.9	
Ulchin 2	SK	112	78.7	80.0
Forsmark 2	S	113	78.6	92.7
K-Kariwa 2	J	114	78.6	82.6
Cooper	US	115	78.5	
Peach Bottom 3	US	116	78.4	
Oskarshamn 2	S	117	78.3	90.2
Dukovany 3	CS	118	78.2	86.6
Pickering 6	C	119	78.2	80.2
Dukovany 4	CS	120	77.9	84.1
Oskarshamn 3	S	121	77.8	88.8
Trillo 1	E	122	77.7	
Chinon B4	F	123	77.7	80.0
Shearon Harris	US	124	77.6	
Krsko	JU	125	77.6	86.0
Ikata 1	J	126	77.6	
Kori 4	SK	127	77.3	80.8
Ulchin 1	SK	128	77.2	80.1
Gentilly 2	C	129	77.1	
Gravelines B4	F	130	77.1	80.8
Quad Cities 2	US	131	77.1	85.4
Stade 1	D	132	76.8	80.4
Gravelines B3	F	133	76.7	79.2
Koeberg 2	SA	134	76.7	84.9
Diablo Canyon 1	US	135	76.5	80.6
Paluel 2	F	136	76.4	81.9
Forsmark 1	S	137	76.4	90.1
St Lucie 2	US	138	76.1	
Braidwood 2	US	139	76.1	
Gravelines B2	F	140	76.0	81.6
Gundremmingen C	D	141	75.8	85.8
Cruas 2	F	142	74.8	82.4
Zorita	E	143	74.8	
Limerick 2	US	144	74.8	
Gravelines C5	F	145	74.7	83.8
Dampierre 3	F	146	74.1	83.3
Fukushima II 2	J	147	73.9	74.3
Blayais 1	F	148	73.5	78.4
Grafenrheinfeld	D	149	73.4	77.0
Onagawa 1	J	150	73.4	67.4
Summer 1	US	151	73.0	
Tsuruga 2	J	152	72.9	
Ringhals 3	S	153	72.8	93.4
North Anna 2	US	154	72.7	79.7
Brokdorf	D	155	72.2	73.7
Cruas 1	F	156	72.2	84.9
Tomari 1	J	157	72.1	
Davis Besse 1	US	158	72.1	
Blayais 2	F	159	72.0	86.4
Paluel 1	F	160	71.9	78.0
Dungeness A1	GB	161	71.9	99.1
Garona	E	162	71.8	78.1
Hope Creek	US	163	71.7	
Belleville 2	F	164	71.5	76.3
Oyster Creek	US	165	71.4	
Sequoyah 1	US	166	71.2	
Paluel 3	F	167	71.0	77.0
Kori 3	SK	168	70.9	76.1
Sequoyah 2	US	169	70.8	
La Salle 2	US	170	70.6	75.1
Tricastin 2	F	171	70.6	79.7
Doel 2	B	172	70.6	
Ringhals 2	S	173	70.5	72.5
Farley 2	US	174	70.5	
North Anna 1	US	175	70.5	81.6
Oconee 2	US	176	70.4	
Kori 1	SK	177	70.2	74.4
Kuosheng 2	TW	178	70.0	75.3
Sizewell A1	GB	179	69.6	91.8
River Bend	US	180	69.5	
Pickering 8	C	181	69.4	78.4
Isar 1	D	182	69.3	86.5
Susquehanna 1	US	183	69.3	
San Onofre 3	US	184	69.2	73.1
Gravelines C6	F	185	69.2	79.0
Philippsburg 1	D	186	69.1	70.1
Cruas 3	F	187	68.9	75.9
Oldbury 1	GB	188	68.8	99.6
Chinon B1	F	189	68.6	70.5
Chinon B2	F	190	68.3	84.7
Laguna Verde 1	MX	191	68.1	
Cruas 4	F	192	67.9	73.9
Nogent 1	F	193	67.8	73.4
Grand Gulf	US	194	67.8	
Crystal River 3	US	195	67.8	
Hatch 1	US	196	67.3	
St Laurent B1	F	197	67.3	70.3
St Alban 1	F	198	67.1	71.6
Surry 1	US	199	67.0	
Belleville 1	F	200	67.0	71.1
Millstone 2	US	201	66.9	70.0
Bugey 5	F	202	66.9	77.8
McGuire 1	US	203	66.9	
Ringhals 1	S	204	66.8	84.6
Takahama 1	J	205	66.6	
Blayais 4	F	206	66.5	72.8
Flamanville 1	F	207	66.5	80.5
Chinon B3	F	208	66.2	70.2
Tricastin 4	F	209	66.1	83.6
Fukushima I 2	J	210	66.1	67.3
Cattenom 2	F	211	66.0	71.5
Brunsbuttel	D	212	65.9	98.5
Fukushima II 1	J	213	65.8	66.5
Kuosheng 1	TW	214	65.4	80.0
Tokai 1	J	215	65.3	
Fessenheim 1	F	216	65.1	74.2
Catawba 2	US	217	65.1	
Chinshan 1	TW	218	64.7	69.7
Nogent 2	F	219	64.5	69.5
Fermi 2	US	220	64.4	
Yongkwang 2	SK	221	64.4	69.0
Chinshan 2	TW	222	64.3	77.4
Fukushima I 1	J	223	64.3	65.1
Beaver Valley 2	US	224	64.1	76.3
Wylfa 2	GB	225	64.1	81.1
Tricastin 1	F	226	64.0	72.5
Millstone 3	US	227	64.0	72.6
Perry 1	US	228	63.8	
Palo Verde 2	US	229	63.5	
Atucha	A	230	63.4	
Oskarshamn 1	S	231	63.4	66.1
Byron 2	US	232	63.3	76.2
Indian Pt 3	US	233	63.2	66.3
St Laurent B2	F	234	63.1	69.3
K-Kariwa 1	J	235	62.9	63.6
McGuire 2	US	236	62.8	
Fukushima I 4	J	237	62.5	63.8
Biblis B	D	238	62.4	77.0
Paluel 4	F	239	62.4	69.4
Fort Calhoun 1	US	240	62.1	71.6
Pickering 2	C	241	62.1	77.3
Arnold	US	242	61.8	71.2
Hunterston B2	GB	243	61.4	67.4
Blayais 3	F	244	61.3	65.0
Trawsfynydd 2	GB	245	61.3	84.3
Mihama 1	J	246	61.2	
Bruce 4	C	247	61.2	68.0
Rajasthan 2	IN	248	61.0	
St Alban 2	F	249	60.9	65.2
Bugey 3	F	250	60.8	62.9
Mapp 1	IN	251	60.7	62.8
Mihama 2	J	252	60.6	
Braidwood 1	US	253	60.4	
Fugen	J	254	60.1	
Fukushima I 5	J	255	60.1	61.1
WNP 2	US	256	60.0	65.6
Vogtle 2	US	257	59.8	
Pickering 1	C	258	59.6	77.9
Limerick 1	US	259	59.0	
Hamaoka 2	J	260	59.0	
Peach Bottom 2	US	261	58.7	
Fitzpatrick	US	262	58.6	64.6
Hartlepool 2	GB	263	58.4	71.2
Gravelines B1	F	264	57.5	63.0
Dampierre 4	F	265	57.3	68.4
Heysham A2	GB	266	57.2	71.2
Salem 2	US	267	57.2	
South Texas 2	US	268	57.1	
Trojan	US	269	57.0	59.3
Bruce 2	C	270	56.8	64.0
Cattenom 1	F	271	56.6	63.2
Hinkley Pt B1	GB	272	56.3	63.3
Arkansas 1	US	273	56.2	
Dampierre 2	F	274	56.0	71.6
Cook 1	US	275	56.0	
Indian Pt 2	US	275	54.8	59.3
Palo Verde 1	US	277	54.7	
Quad Cities 1	US	278	54.5	60.0
Bradwell 1	GB	279	54.5	64.1
Yankee Rowe	US	280	53.8	58.8
Maine Yankee	US	281	53.6	
Hartlepool 1	GB	282	53.2	63.2
Tarapur 2	IN	283	52.3	87.8
Oldbury 2	GB	284	51.9	72.3
Cook 2	US	285	51.7	
Chooz	F	286	51.6	73.0
Fessenheim 2	F	287	51.4	62.6
Tarapur 1	IN	288	51.3	76.6
Fukushima I 3	J	289	50.7	51.5
Turkey Pt 4	US	290	50.6	
Hinkley Pt A2	GB	291	50.4	63.6
Biblis A	D	292	50.3	53.3
Ohi 1	J	293	49.8	
Dungeness A2	GB	294	49.4	74.0
Salem 1	US	295	49.4	
Turkey Pt 3	US	296	46.7	
Genkai 1	J	297	46.6	48.6
Dampierre 1	F	298	46.2	49.3
Mapp 2	IN	299	45.7	
Bugey 1	F	300	44.7	66.1
Conn Yankee	US	301	43.8	50.8
Dresden 2	US	302	43.6	53.3
Wurgassen	D	303	43.5	45.0
Nine Mile Pt 2	US	304	43.1	55.4
Brunswick 1	US	305	43.1	
Heysham A1	GB	306	43.0	52.6
Torness 1	GB	307	41.9	48.0
Sizewell A2	GB	308	41.5	55.7
Angra 1	BR	309	41.4	81.0
Zion 1	US	310	41.2	45.1
Bugey 4	F	311	39.7	48.6
Darlington 2	C	312	38.3	
Robinson 2	US	313	38.3	
Trawsfynydd 1	GB	314	37.2	52.0
Koeberg 1	SA	315	36.8	45.4
Calvert Cliffs 1	US	316	36.1	41.0
Torness 2	GB	317	36.1	44.0
Clinton	US	318	35.3	
Zion 2	US	319	34.5	37.9
Seabrook 1	US	320	34.0	
Fukushima II 3	J	321	33.8	35.7
Nine Mile Pt 1	US	322	33.8	46.3
South Texas 1	US	323	32.5	
Dounreay	GB	324	31.5	36.4
Dungeness B1	GB	325	28.1	72.9
Palisades 1	US	326	27.4	
Phenix	F	327	25.8	28.9
Heysham B1	GB	328	25.5	33.5
Rajasthan 1	IN	329	24.1	
Heysham B2	GB	330	22.7	[illegible]
Pickering 4	C	331	21.6	[illegible]
Hamaoka 1	J	332	20.9	[illegible]
Narora 1	IN	333	20.7	
San Onofre 1	US	334	20.4	24.3
St Laurent 2	F	335	19.7	28.9
Takahama 2	J	336	17.8	
Bruce 1	C	337	16.2	28.3
Obrigheim	D	338	15.0	15.0
Dungeness B2	GB	339	7.6	26.0
Pickering 3	C	340	0.0	0.0
Calvert Cliffs 2	US	341	0.0	0.0
Browns Ferry 1	US	342	0.0	0.0
Browns Ferry 2	US	343	0.0	0.0
Browns Ferry 3	US	344	0.0	0.0
Mulheim Karlich	D	345	0.0	0.0
Creys Malville	F	346	0.0	0.0

is a summary of nuclear plant availabilities around the world which shows close to half the plants exceed 80% inherent availability. Additionally, these fission plants require periodic fuel replacement procedures which contribute to downtime. Fusion plants will be fueled continuously which would offer an availability advantage.

The 80% availability estimate is higher than that usually quoted for the comparable MFE conceptual design. There are several reasons for this difference. The Prometheus study devoted effort to analyze the reliability and maintainability of key systems and then calculate the availability of the plant rather than assume a likely range. The STARFIRE conceptual design adopted a value of 75% as an availability goal and then developed planned and unplanned maintenance activities to achieve the adopted goals. Most of the following MFE conceptual designs are built upon that premise.

The Prometheus power plants can achieve higher availability due to the more simple and reliable nature of the major plant elements. The reactor chamber is very simple with little interaction with the other plant elements. The two drivers have high levels of availability. The heavy ion driver has many magnet elements which must function in series, but the components are not highly stressed and are expected to have high reliability. The laser driver has a slightly lower reliability, but the ability to continue plant operation with several power amplifiers or beam elements not functioning, or functioning in diminished capacity, is highly beneficial. The laser driver has a higher degree of redundancy. The continued operation of the target plant is essential, thus the design is structured with a high degree of redundancy in all essential systems. The thermal conversion systems, electrical plant equipment, and balance of plant are improvements from the current proven systems. These systems will continue to make availability enhancements for the plant.

The availability of the Prometheus IFE power plants are expected to be approximately 80%. The difference between the two designs is not significant. Rather, the significant finding is that there is an availability advantage for IFE power plants. Moreover, the fusion power plants will be competitive with the availability demonstrated by current nuclear fission power plants.

6.3.3.2 RAM Introduction - Reliability, Availability and Maintainability (RAM) analysis was performed on a conceptual design for a tenth-of-a-kind commercial electric power plant. The concept features an inertial confinement nuclear fusion reactor representing the design maturity expected for a plant starting operation in 2045. Two design options were considered for the driver systems: the laser driver and the heavy ion driver.

The methodology of the RAM analysis process is defined in Subsection 6.3.3.3. The source data used in the analysis for the common and distinct elements of the two design options are described in Subsections 6.3.3.4 and 6.3.3.5. The analysis results are presented and discussed in Subsection 6.3.3.6. The design impact of the RAM study is discussed in Subsection 6.3.3.7.

6.3.3.3 Reliability, Availability and Maintainability Methodology - The RAM analysis is a numerical process. Results are determined by source data which are combined numerically in a manner representing the complexity and interdependence of plant components.

The plant is divided into subsystems and major components, for each of which reliability and maintainability data is determined. Subsystems that do not impact on plant availability, such as personnel services, are not considered.

The mathematical treatment of the data assumes that all component failures result in a plant outage of duration equal to the mean repair time. The exception to this is where parallel redundancy exists, since this allows operation to continue during repairs unless a second equipment fails while repairs are taking place. With redundancy, the outage is reduced. It is also assumed that spare components and support equipment are available on demand, repair procedures start immediately following failure, and restarting the plant requires negligible time.

Availability is calculated as follows:

(a) Identify plant components that impact availability
(b) Determine failure rates and repair times of components
(c) Define maintenance strategy and redundancy
(d) Calculate inherent availability of both drivers
(e) Calculate inherent availability of other key (reactor) parts
(f) Calculate overall inherent availability for key parts
(g) Estimate effect of balance of plant parts on overall availability
(h) Calculate overall inherent availability
(i) Determine annual maintenance shutdown times
(j) Determine refit shutdown time and interval
(j) Calculate achieved plant availability

Inherent Availability - Inherent availability A_I is the probability that a system or equipment used under stated conditions in a properly supported environment will operate satisfactorily at any given time. It accounts for outage due to corrective maintenance. Although A_I excludes preventative maintenance, logistics, and administration outages, the reliability data used assume that preventative maintenance is performed as specified. Failures are assumed to occur randomly with constant probability, ignoring infancy failures, design bugs, and wear out failures after prolonged operation.

A_I is computed from the Mean Time Between Failure (MTBF) and the Mean Time To Repair (MTTR) as follows:

$$A_I = \frac{1}{1+O_I} \text{ where outage is represented by } O_I = \frac{MTTR}{MTBF}$$

For a subsystem consisting of N identical equipment, the value of O_I is increased by the factor N. However, when one equipment is on hot standby (redundant), outage only occurs if a second equipment fails while the first is under repair:

$$A_I = \frac{1+(2N-1)O_I}{(1+NO_I)(1+NO_I-O_I)}$$

For a system consisting of several subsystems and major components, the outage is determined by:

$$\frac{MTTR}{MTBF} = \frac{MTTR1}{MTBF1} + \frac{MTTR2}{MTBF2} + \frac{MTTR3}{MTBF3} + \cdots$$

MTTR and MTBF can be obtained by analyzing records of the use of field-deployed equipment where these exist for identical or closely similar equipment. Alternatively, they can be calculated as follows:

MTTR = Fault isolation time + item retrieval time
+ preparation time + disassembly time
+ interchange or repair time + alignment time
+ re-assembly time + verification or inspection time

$MTBF = \frac{1}{\lambda}$ where λ is the statistical failure rate of an individual part.

All the above MTTR and MTBF values are in hours; λ is millions of hours.

Achieved Availability - The computation of A_A factors the calculated value of A_I to incorporate the impact of regular servicing, preventative maintenance, logistics and administration, and periodic shutdowns for major refits including end of life equipment replacement. For the IFE reactor generating station, these are factored using overall values typical of fission plant practice and computed values for design specific data. The factoring calculations are provided in Section 6.3.3.1.

6.3.3.4. <u>Failure Rates and Maintenance Source Data</u> - Failure rates and maintenance times for subsystems and major components are used as source data for the RAM analysis process. The validity of this source data is determined by the relevance of the available data sources.

For a mature technology, data is readily available based on field experience. This is the case for the non-nuclear portions of the plant such as electrical generation.

For the new technology to be used in the reactor and related subsystems, field experience is unavailable. Where applicable, field data on similar equipment is adjusted using expert opinion to allow for changes of duty cycle, conditions of operation, etc.

In a few cases no similarity with existing, field deployed equipment can be found. For these cases the source data is entirely based on expert opinion, allowing for technological maturity to be expected in a tenth-of-a-kind plant.

Redundancy is specified in the given descriptions of several subsystems and major equipment. Generally the need for redundancy is determined by the need to maintain a safety-related system or to improve inherent availability. In addition, if a related subsystem is already redundant, it may be feasible to integrate the component parts of the two subsystems, making both redundant.

The estimated failure rate and repair time for each subsystem and major component is listed in Table 6.3.3-2; MTBF values are for single equipment, not the quantity needed for the subsystem. Table 6.3.3-2 also contains notes on such issues as redundancy and on-line maintenance. The sources for the data listed in Table 6.3.3-2 are discussed in the following paragraphs.

Sixty-six percent of the reliability and maintainability data is based on established data or similarity to field deployed equipment, 12% is derived from detailed analyses, and 22% represents totally new technology for which opinions were obtained from experts in these fields. This mix of data sources provides an acceptable level of confidence in the validity of the data. Whenever possible, to further improve confidence, subsystems with new technology are decomposed into components with available field data, as shown in Table 6.3.3-3 for the Heavy Ion Driver.

The established data which was derived from field service records and published data is available from the following sources:

Reliability Statistics Manual (Summarized in Table 6.3.3-4), Production and Transmission Branch, Nuclear Generation Division, Ontario Hydro

Non-electrical Parts Reliability Data (NPRD), Reliability Analysis Center, Rome, NY.

Table 6.3.3-2. IFE Failure Rates and Repair Times for Subsystems

Item	Data Sources	Description	Notes	MTBF (HRS)	MTTR (HRS)
Target Factory	Dr. Douglas Drake, KMS Fusion Inc.; Dr. Steven Wineberg, NPRD	Large facility for producing 300,000 to 500,000 cryogenic fuel pellets per day. Deuterium and tritium are injected into plastic capsule which is then frozen and sealed. High pressure and cryogenics are used.	Cryogenics is a mature field, but expect problems with pressure system. Subjective evaluation, no data from field or similar equipment. Deuterium and tritium supply failure rate considered elsewhere. Assumed that isolated pellet non-conformance is rejected by automatic inspection system. Special design features required to achieve MTTR.	2924	24
Target Injector	Dr. Alice Ying, UCLA; Dr. Douglas Drake, KMS Fusion, Inc.	System injects fuel targets into reactor cavity. Precisely aligned before assembly. Coolant flows round cavity penetration which is screened from fusion reaction.	Subjective evaluation, no data from field or similar equipment. MTTR and MTBF (three years) are estimated. Target gun to be inspected at same time as first wall.	26280	24
Laser Power Amplifier	Dr. Gary Linford, TRW	960 amplifiers used with a pulse rate of 5 Hz. Associated power units, blowers, gas units. Each amplifier weighs approx. 100 Kg. A single failure will not shut reactor down.	Pulses per year = 1.6×10^8. Required amplifier failure rate is 1 in 10^{10}, current rates are 10^8. One hundred times reliability improvement is realistic in this recent field. Replacement requires disconnection from gas flow circulation system. Sixty sets of 16 units, assumed one unit in a set can fail without reactor outage. Redundant.	556000	8
Laser Gas Circulation Blowers	NPRD Table 6.3.3-3	Provides laser amplifier cooling; 10 sets of 16 blowers. One blower supplies 6 amplifiers. Gas is circulated at 100 KPa.	Loss of one blower reduces laser power by 7% which is assumed not enough to shut down reactor. Field data on similar devices used. Redundant system.	411000	194

Table 6.3.3-2. IFE Failure Rates and Repair Times for Subsystems (Cont.)

Item	Data Sources	Description	Notes	MTBF (HRS)	MTTR (HRS)
Laser Heat Exchanger	NPRD Table 6.3.3-3	One heat exchanger per six amplifiers, as blowers.	Redundant, as gas circulation blowers.	367174	98
Final Optics	NPRD SPAR, Solar Array Program Records	The final optics consists of a pointing and alignment system using three magnetic actuators each (and associated power units) for 60 grazing incidence mirrors.	The optics themselves are unlikely to fail unless the vacuum chambers become contaminated (assumed once every ten years). Field data on similar devices used.	450000	4
Laser Optics Backing Pumps	NPRD Table 6.3.3-3	Laser Optics Backing Pumps evacuate laser optics. Pumps operate at 135 Pa. Pumps are duplicated for each of 60 beamlines.	Field data on similar devices used. Redundant. A hard vacuum is not required so MTBF data for normal pumps used. MTBF for vacuum pump is normally 64,666.	114929	194
Heavy Ion Driver	Table 6.3.3-2	Two systems, each comprising a source and a linear particle accelerator, storage rings and a final transport section. Superconducting magnets used.	Assumed warm iron magnets, which are not cycled during normal operation, and heavy duty cryogenic system to reduce warm-up and cool-down times to achieve needed MTTR.	2190	24
Reactor First Wall Panels	Dr. Nasr Ghoniem, UCLA Table 6.3.3-4	Thirty full length porous silicon carbide panels line the inside the reactor cavity, cooled with liquid lead which also coats and protects the inner surface.	Totally new technology, no material or application experience base. Lifetime estimated at three years. MTBF = 175,200 hours (6.7 x lifetime for passive unit) with considerable surface stress.	175200	120
First Wall Lead Cooling Pump	NPRD Table 6.3.3-4	Two centrifugal pumps, one on standby.	Field data on similar devices used.	114929	84

Table 6.3.3-2. IFE Failure Rates and Repair Times for Subsystems (Cont.)

Item	Data Sources	Description	Notes	MTBF (HRS)	MTTR (HRS)
First Wall Heat Exchanger (lead to steam)	NPRD Table 6.3.3-4	A heat exchanger consist of a fan or compressor, cooling pipes and the operating fluid. There is one heat exchanger in the plant.	Field data on similar devices used	367175	98
Blanket Assembly	Table 6.3.3-4; Dr. Nasr Ghoniem, UCLA	The blankets are hollow silicon carbide panels filled with Li_2O granules which are cooled with helium. Exposure to neutrons breeds tritium.	Totally new technology, no material or application experience base. Lifetime estimated at five years. MTBF = 876,000 hours (20 x lifetime for passive unit) with no moving parts. 180 units per reactor.	876000	240
Blanket Helium Coolant Pumps	NPRD Table 6.3.3-3, Table 6.3.3-4	Centrifugal blower pumps operating at 1.5 MPa. Two pumps for each of the five helium/steam heat exchangers, one of each pair acting as standby (redundant).	Field data on similar devices used. Redundant.	114929	72
Blanket Heat Exchanger (Helium to steam)	NPRD Table 6.3.3-4	Five helium-to-steam heat exchangers used.	Similar to lead-to-steam heat exchanger. Values factored for increased quantity.	367175	98
Blanket Tritium Extraction Pumps	NPRD Table 6.3.3-3	Blanket Tritium Extraction Pumps feed blanket tritium to the tritium extraction loop. Two pumps for redundancy.	Field data on similar devices used. Redundant.	114929	194
Tritium Extraction Loop	NPRD Ronald Matsugu and Otto Kveton, CFFTP; Paul Gierszewski	The tritium extraction loop consists of a circulating pump pair, a molecular sieve bed with heaters, liquid nitrogen cooling, valves and tanks.	Cryogenic absorber use proven technology. The system is mostly static except for the pumps. Field data on similar devices used where appropriate. 24 hour warmup/cooldown time assumed for cryogenic system.	43647	72

Table 6.3.3-2. IFE Failure Rates and Repair Times for Subsystems (Cont.)

Item	Data Sources	Description	Notes	MTBF (HRS)	MTTR (HRS)
Reactor Vacuum Pumps	NPRD Table 6.3.3-3	Ten reactor vacuum pumps used at each of three ports.	Field data on similar devices used. Redundant.	64666	194
Lead Decontamination System	NPRD	No description provided.	Assume MTBF and MTTR are similar to the Tritium Extraction Loop, but cooldown/warmup times reduced.	43647	48
Lead Drain Pump	NPRD Table 6.3.3-3	No specification, assumed similar to Tritium Extraction Pump	Field data on similar devices used. Redundant.	114929	194
Reactor Computer Control System	J. Richardson, OH Table 6.3.3-3	The computer control system is a safety system; therefore, a hot standby system is always available.	Computer system has a prescribed unavailability of 1×10^{-3} MTBF computed to achieve this. Redundant.	223776	224
Helium Extraction Pump	NPRD Table 6.3.3-3	Assumed similar to blanket tritium extraction pumps. Two pumps for redundancy.	Field data on similar devices used. Redundant.	114929	194
Helium Extraction Loop	NPRD	Similar to the tritium extraction loop.	No specific data available so data assumed similar to the tritium extraction loop.	43647	72
Heat Exchangers, Helium Low and High Pressure Reheaters	NPRD Table 6.3.3-3, Table 6.3.3-4	Similar to lead-to-steam heat exchanger. Two reheaters in the circuit.	Field data on similar devices used.	367175	98

Table 6.3.3-3. Heavy Ion Driver: Failure Rate and Repair Time Analysis

DATA SOURCES:

SSC Laboratory, TRIUMF and Fermilab, and NPRD Data

DESCRIPTION:

Comprises ion source, LINAC, storage rings, and final transport. Only components that are significant contributors to failure rates and repair times shown.

DESIGN NOTES:

Data assumes welded warm iron magnets, infrequent thermal cycling, minimum Lorentz force stresses. Heavy duty cryogenics reduce warm-up and cool-down time. Focusing and steering magnets have similar characteristics. Neutron bombardment is insufficient to cause brittle welds. Estimates final transport magnet count.

FAILURE RATE:

Where lifetime is quoted, MTBF values are 10 x Lifetime. Redundant function data shown in the format (functions used) + (% redundancy).

Device	Magnets	Cells	HV Supplies	Injectors	Pumps
Lifetime/Basis	Fermilab	Est.	$2x10^{11}$ shots		
Unit MTBF hours	4,000,000	556,000	800,000	114,929	114,929
Unit MTTR hours	24	2	2	2	194
Units per:					
Ion Source	0	0	1	1	1
LINAC	878	439	439	0	12
Storage Rings	64	0	0	0	4
Final Transport	96	0	0	2	2
Unit Totals	1,038	439	440	3	19

NOTE:

Vacuum pumps fully redundant with hot standby.

Table 6.3.3-4. In-Service Reliability Records

Equipment	Units	MTTR
Pumps/Gas Blowers	16	194
(number of records)		10
(at hours)		1935
Heat Exchangers	16	404
(number of records)		5
(at hours)		2019
Active Computer Safety Systems	2	224
(number of records)		1
(at hours)		224

6.3.3.5 Maintainability Task Analyses - For complex, highly design-specific subsystems, maintenance field data is not available. These tasks were identified, and maintainability task analyses were performed. Table 6.3.3-5 summarizes the maintainability task analyses.

Table 6.3.3-5. Maintainability Task Analysis Summary

Item	Activity	Estimate (Hours)
1	Remove Hemispherical Pressure Vessel Top	46
2	Remove (One) First Wall Panel	4
3	Replace First Wall Panel	4
4	Remove (One) Blanket Module	4
5	Repair Blanket Module	4
6	Replace Blanket Module	4
7	Remove and Replace First Wall Panel in Third Layer	120
8	Remove and Replace Blanket Module in Third Layer	240
9	Remove First Wall Lead Coolant Pump	19
10	Replace First Wall Lead Coolant Pump	23
11	Remove First Wall Lead Coolant Heat Exchanger	25
12	Replace First Wall Lead Coolant Heat Exchanger	31
13	Remove Blanket Helium Coolant Pump	15
14	Replace Blanket Helium Coolant Pump	21
15	Remove Blanket Helium Coolant Heat Exchanger	21
16	Replace Blanket Helium Coolant Heat Exchanger	28
17	First Wall Panel Inspection	49.8
18	Blanket Inspection	41

6.3.3.6 Reliability, Availability and Maintainability Analysis Results - The results of the A_I analysis of key reactor plant parts are shown in Table 6.3.3-6. The impact on availability of large quantities of identical equipment and redundancy in some subsystems has been accounted for in the calculations. The A_I of key plant items is then factored down by considering remaining equipment and the effect of human mistakes. The A_I values for key plant parts are defined as contributing to 90% of unplanned maintenance down time. Human factors derating K are not included (normally between 1.1 and 1.6) due to anticipated benefits of maintenance planning (see Section 6.3.2).

The overall plant A_A accounts for all outages throughout the life of the plant. It is computed from A_I by factoring in allowances for random failures in the rest of the plant (about 40% of total), 30-day shutdowns at yearly intervals, and major refits at longer intervals. Yearly 30-day outages for scheduled inspection, and adjustment and service are typical practice for existing commercial nuclear fission generating plants. The outage times for major reactor refits and the interval between them take into account the expected life of the Blanket and First Wall and the total replacement times for them as calculated in Table 6.3.3-5 and summarized in Table 6.3.3-7. Note that these times include a concurrent portion since the First Wall must be removed to access the blanket.

Table 6.3.3-6. IFE Inherent Availability Computations

Subsystem	MTBF Factor	Redundancy	Sets	MTTR	A_i
Target Subsystem					
Target Factory	2924		1	24	99.18
Target Gun	26280		1	24	99.90
Laser Driver Option Only					
Laser Amplifier	556000	16	60	8	99.98
Laser Amplifier Blower	411000	16	10	194	99.46
Laser HX	367174	16	10	98	99.82
Final Optics	450000		60	4	99.94
Optics Backing Pumps	114929	2	60	194	97.98
Complete Laser Driver					97.24
Heavy Ion Driver Option Only					
Magnets	4000000		1038	24	99.38
Induction Cells	556000		439	2	99.84
HV Supplies	800000		440	2	99.89
Injectors	114929		3	2	99.99
Vacuum Pumps	114929	2	19	194	99.79
Complete Heavy Ion Driver					98.91
First Wall					
Reactor First Wall	175200		30	120	97.98
Coolant Pumps (Pb)	114929	2	1	84	99.99
Coolant HX (Pb/Water)	367175		1	98	99.97
Blanket					
Blanket Assembly	876000		180	240	95.30
Blanket Coolant Pumps (He)	114929	2	5	72	99.99
Blanket HX (He/Water)	267175		5	98	99.81
Tritium Extraction Pump	114929	2	1	194	99.99
Tritium Extraction Loop	43647		1	72	99.83
Reactor Miscellaneous					
Reactor Vacuum Pumps	64666	10	3	194	99.27
Lead Decontamination S/S	43647		1	48	99.89
Reactor Lead Drain Pump	114929	2	1	194	99.99
Reactor Control S/S	223776	2	1	224	99.99
He Extraction Pump	114929	2	1	194	99.99
He Extraction Loop	43647		1	24	99.94
Summary					
Laser Option					89.28
Heavy Ion Option					90.68

Note: HV = High Voltage S/S = Subsystem HX = Heat Exchanger

Table 6.3.3-7. Summary of Blanket and First Wall Reliability and Maintainability Data

Item	Life (hours)	Replacement Time (hours)	Equivalent Outage (hours/year)
Blanket	43800 (5 yrs)*	260	52
First Wall	26280 (3 yrs)*	212	71

* The final design for the Blanket and First Wall predicted lifetimes of 10 and 5 years, respectively.

For comparison, the reactor outage for 16 Ontario Hydro CANDU (Nuclear Fission) reactors for the period 1987 through 1991 was 184,196 hours, including 160,384 hours for refitting several older reactors. The balance of 23,812 hours' outage were for non-refit reasons and occurred during an estimated 540,416 hours attempted reactor run time. These values are distorted by an unusually high number of major refits during the period, equating to 73.7% achieved availability which is low due to the refits and 95.6% for inherent availability which is high since many reactors were recently commissioned or refitted. The two values bracket the value used for the fusion reactor. Table 6.3.3-1 previously showed a recently reported selection of nuclear plant availabilities from around the world. Nearly 50% of the reporting power plants had availability exceeding 80%.

6.3.3.7 **Design Notes** - In order to achieve the availability computed for the fusion reactor generating station, the assumptions embedded in the computations must be realized in the final design. The most significant assumptions are outlined below.

Target Factory - Because of its complexity and high pressure technology, the target factory has a relatively poor MTBF. Thus, it is important to implement a redundant design. In order to reduce its impact on the reactor A_I to a manageable level, the design must achieve a MTTR of 24 hours. MTTR was originally calculated at 105 hours.

Laser Amplifiers - Large numbers of these are used. The value for MTBF is a significant improvement over what is achieved currently, representing expected design improvements in this immature field. In order to further reduce the impact of laser amplifier failure rates on the reactor A_I to a manageable level, each group of 16 amplifiers serving a beamline should continue to function with one unit under repair. If the resulting 6% power loss has an unacceptable effect on reactor performance, then a 17th (redundant) unit is required. The design should facilitate repair of the amplifiers while the reactor is on-line. (This is a general requirement for all redundant units.)

Laser Heat Exchanger - The calculated figure for MTTR (98 hours), based on Table 6.3.3-4 calculations applicable to the first wall heat exchanger, is significantly less than field records (404 hours). It is believed to be a reasonable value but the design should accommodate the requirement if it is a design challenge. It is assumed that the heat exchangers are arranged in groups similar to the laser amplifier blowers to provide a measure of redundancy. An integrated blower/heat exchanger design would be advantageous if feasible.

Optics Backing Pumps - The MTBF of 114,929 hours is taken from pump data and is better than the typical vacuum pump MTTR which is 65,666 hours. This is justified on the grounds that the vacuum required is not an especially good one. However, it may represent a design challenge.

Heavy Ion Driver - The MTTR of 24 hours is a target for the complete exchange of a superconducting magnet including warm-up and cool-down. It may represent a significant design challenge and probably involves the use of a warm iron design, which cools down and warms up more rapidly than a cold iron design since the iron core is outside the cryostat. The cryogenic equipment requires extra capacity. The use of techniques to accelerate magnet removal, replacement and alignment, including automated beam vacuum pipe cutting and rejoining, has been explored for the proposed KAON Factory at TRIUMF, Vancouver, and the MTTR is believed to be feasible.

6.3.4 Design for Decommissioning - Fusion reactors using a deuterium/tritium cycle have the advantage over fission reactors in that there is no radioactive spent fuel to be disposed of; the reactor structure is the only radioactive waste at the end of plant life. Use of low activation materials was chosen to keep activation to a minimum. The choice of total remote maintenance for key parts is expected, by itself, to greatly simplify and reduce the cost of final disassembly. The design process, therefore, took into account not only maintenance but also final disassembly.