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FUSION POWER DEMONSTRATION (FPD) MAINTENANCE AND DISASSEMBLY CONSIDERATIONS*

P. T. Spampinato
Fusion Engineering Design Center/Grumman Aerospace Corporation
Oak Ridge National Laboratory
P.O. Box Y, FEDC Building
Oak Ridge, Tennessee 37831
(615) 576-5476

ABSTRACT

The Fusion Power Demonstration study is the development of a tandem mirror reactor design that follows the operation of the Mirror Fusion Test Facility. It is a power-producing device utilizing the deuterium-tritium fuel cycle; hence, much of its maintenance must be accomplished remotely because of neutron-induced gamma activation. This paper discusses the maintenance philosophy adopted and its impact on the device configuration and examines some of the specific requirements of scheduled and unscheduled component replacements. This work is being used for the next phase of mirror reactor concepts: the Mini-Mars reactor study.

INTRODUCTION

The Fusion Power Demonstration (FPD) study is an evolution of three reactor designs, FPD-I, -II, and -III, which follow the operation of the Mirror Fusion Test Facility (MFTF-B). They are based on configuration concepts that support advances in mirror fusion physics theory, and FPD-III is the basis for the next phase of mirror studies, the Mini-Mars reactor design. FPD is a power-producing device utilizing the (D-T) fuel cycle; hence, much of its maintenance must be accomplished remotely because of neutron-induced gamma activation. All operations within the shielded boundary of the device must be done remotely, but limited personnel access is permitted in the reactor hall.

FPD-I was configured similar to the MFTF-α+T,[1] which has been previously discussed;[2] therefore, configuration features for FPD-II and -III only are considered in this paper. Each configuration consists of a central-cell region and two end cells. The central cell contains circular blanket modules which are vertically removable along with solenoid coils. The modules weigh approximately 250 tonnes and are readily accessible. The end cell for FPD-II contains a series of superconducting coils similar to MFTF-α+T, whereas FPD-III contains a new octopole coil design with additional removal difficulties. Figure 1 shows the major and minor octopole arrangements in the FPD-III end cell. Also shown is one of the circular blanket modules at the end of the central cell.

Each FPD configuration is designed with a large, removable access cover over the end cell for vertical access, and each has a direct converter/halo scraper assembly integral with a separate shielded cover. The FPD-III contains an additional small centerline hatch, which is needed to disassemble the mirror/shaping coil assembly from the major octopole and is shown in Fig. 1.

MAINTENANCE PHILOSOPHY AND REQUIREMENTS

The maintenance requirements for FPD are based on the earlier work done for the Technology Demonstration Facility (TDF)[3] and MFTF-α+T.[1] These requirements were used to guide the development of the configuration in the areas of shield design, component locations, and access.

The primary thrust of these requirements is that contact operations are permitted on the device 24 h after shutdown, provided the plasma chamber is unopened and all shielding is in place. The biological shield is designed to limit activation to 0.5 mrem/h one day after shutdown. This is in accordance with Department of Energy (DOE) Order 5480.1, Chapter XI, "Requirements for Radiation Protection," which stipulates that a design objective of one-fifth the maximum permissible dose to radiation workers will meet the ALARA requirement of 1 rem/year. Under these conditions, workers may spend up to 2000 h/year (40 h/week) near the device. This enables personnel to routinely perform hands-on inspection, disassembly of connections, maintenance equipment setup, and

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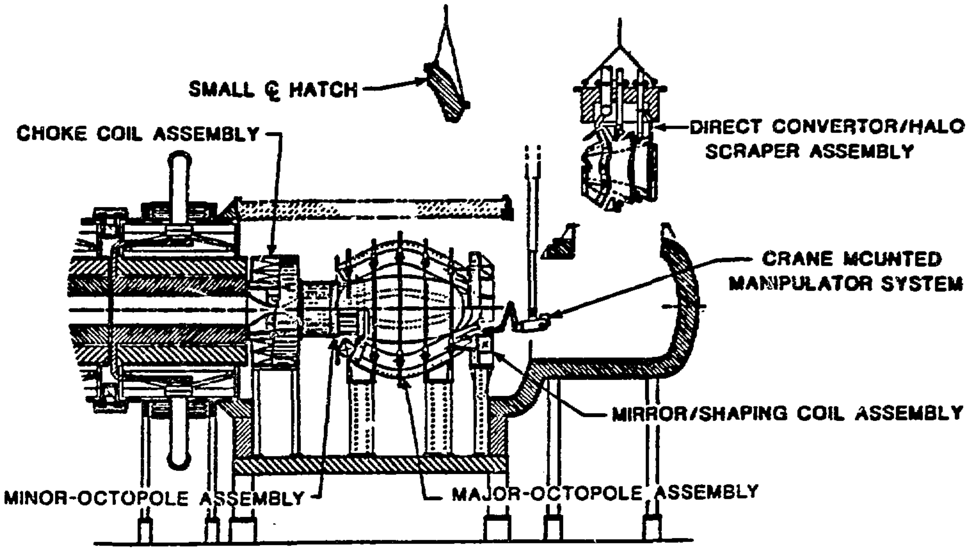

Fig. 1. FPD-III end cell arrangement.

supervision of maintenance activities in the reactor cell prior to any device disassembly.

Maintenance operations that require opening the plasma chamber must be done remotely because of the high gamma radiation within the shield boundary. These operations are assumed to utilize proven remote equipment technology in the areas of manipulator handling and viewing.

Component installations are modularized and arranged so that independent disassembly and removal may be accomplished wherever it is practical to use overhead lifting. In addition, reasonable access on the device and within the reactor cell is provided to accommodate lifting fixtures and remote equipment. An example of this is the overhead access into the end cell to vertically remove "cee" coils, octopoles, or the choke coil set as independent modules. For FPD-II, the end cell access cover is estimated to weigh 85 tonnes (without water); the "cee" coils are <85 tonnes; and the choke coil set is 130 tonnes (without shielding). Each of these components weighs less than the main crane capacity of 250 tonnes. Table 1 is a listing of major component weights for FPD-I and -II.

In-vessel inspection precedes operations that require opening the plasma chamber. Numerous locations along the length of the FPD (approximately every 10 m) with air-lock interfaces allow full viewing of the components internal to the plasma chamber without the requirement for venting. These are not shown on the FPD but are discussed in ref. 1.

Table 1. Major component weights for FPD-I and -II

Component	Weight (10^3 kg)
Center cell module	250
End cell access cover	235[a]
Center cell solenoids	40
Halo scraper/direct converter	10
Transition coil (T1)	78
Transition coil (T2)	56
Recircularizing coil	15
Choke coil set (w/out shield)	130
Anchor coil (A1, A2)	56
Plug coil (P1, P2)	66

[a]FPD-I; the cover for FPD-II weighs 85 tonnes.

Several other maintenance requirements are noteworthy, even though they do not impact the configuration design:

1. Personnel and maintenance equipment are not permitted in the reactor cell during device operation.

2. Prior to and during maintenance operations, power supplies are shut down and coils are deenergized.

3. Superconducting coils may be kept at cryogenic temperatures for maintenance operations which do not require venting the plasma chamber.

OPERATIONS AND AVAILABILITY

Assume the operating life for FPD is ten years with an availability objective of 25%, defined as a percentage of total calendar time. If the operation plan used for MFTF-α+T is assumed for FPD, the annual allocation of time is as follows:

	% of total	Hours
Average operating time of the device	25	2190
Scheduled downtime; 2 weeks/month, 5 days/week, 2 shifts/day	23	1950
Potentially available but not operating (PABNO); all remaining calendar time	52	4550[a]

[a]This time is potentially available for device operation or maintenance.

The operating time for the device is assumed to occur in a 5-6-day week with two working shifts similar to that of scheduled downtime. The scheduled downtime is assumed to average two weeks per month but may occur at irregular intervals, depending upon the mean time between failures (MTBF) and mean time to repair (MTTR) of components. All remaining time (PABNO) consists of the third daily shift and weekends and is approximately one-half of the calendar year. PABNO can be considered the reserve for unscheduled maintenance operations, thermal cycling of the superconducting coils and plasma chamber reconditioning, and additional device operation beyond the availability objective.

COMPONENT REPLACEMENTS

Several major components have been identified as requiring scheduled replacements. These are listed below, along with estimates of their MTBF and the total number of replacements required, assuming 2190 h/year of device operation. All other components are considered to be lifetime, but with varying degrees of risk. Only those replacements in the neutral beam system and possibly the replacement of diagnostics do not require venting the plasma chamber. Therefore, all other operations are assumed to require thermal cycling of the superconducting coils.

Component	~MTBF (h)	No. of replacements
Choke coils	2200	8-10
Ion sources	900	20-24
Ion dumps	1800	10-12
Cryopanels	4400	5
Windows	1600	12-14

The coils are designed to accommodate 120 warmup/cooldown cycles over the ten-year life of the device, and it is estimated that each cycle may require six weeks of downtime.[1] Clearly, it is not possible to accommodate 120 cycles during the device lifetime. An estimate of the number of cycles can be made by assuming that the scheduled downtime plus the PABNO is available for cycling, if some maintenance activities can be accomplished in parallel. In addition, it can be assumed that plasma chamber detritiation and reconditioning occur simultaneously with thermal cycling. Therefore, 6470 h are potentially available for an upper limit of six thermal cycles per year.

FPD-III END CELL MAINTENANCE

The configuration for FPD-III is an iteration of the FPD-II design; and except for the end cell, maintenance and component disassembly requirements are essentially the same. The end cells contain a magnet system made up of a choke coil assembly, a major and minor octopole assembly, and a mirror/shaping coil assembly shown in Fig. 1. Except for the choke coils, each of these is interlocked to some degree. Hence, vertical removal through the end cell hatch is more complex for FPD-III.

The design of the end cells was based upon removal of the primary components as modular units. The direct converter/halo-scraper assembly is removable as a module and is integral with the shielded access hatch shown in Fig. 1. Its removal is accomplished as a vertical lift using the primary overhead crane (300 ton) supplemented by remote operations using one or both crane-mounted manipulator systems.

The choke coil assembly is removed through the main end cell hatchway after disassembly of the appropriate shield modules and service connections. This module consists of three superconducting coils and one resistive coil with integral shielding. This is the heaviest component in the end cell, with an estimated weight of 126 tonnes. Because of the high operating magnetic field of the resistive coil and its proximity to the plasma, the choke coil assembly is not considered to be a lifetime component. Hence, some finite number of replacements are expected. The frequency of replacements and the duration of downtime can be used to determine the impact to availability, which becomes the basis for utilizing either a complete spare module or replacement of the copper insert as a serial hot cell operation.

The primary problem of interest is replacement of the minor octopole assembly. This is the smallest end cell component (7.5 ton), as shown in the listing of Table 2. However, because it is nested within the major octopole, its removal requires disassembling one or two of the major-octopole window-frame coils, depending upon which end cell is being considered. The octopole coils have a 45° axial rotation to each other between the east and west end cells. Because of this, removal of the minor octopole is more complex in one end cell and can be seen by comparing Figs. 2 and 3.

Table 2. Approximate weights for FPD-III end cell components

Component	Weight (tonnes)[a]	
Choke coil assembly	126.0	
Major octopole (per frame)	42.5	
Minor-octopole assembly	7.5	
Mirror coil	15.0	50.0
Shaping coil	35.0	
Annual shield module	115.0	
End cell main hatch	85.0	

[a]Including estimates for structure.

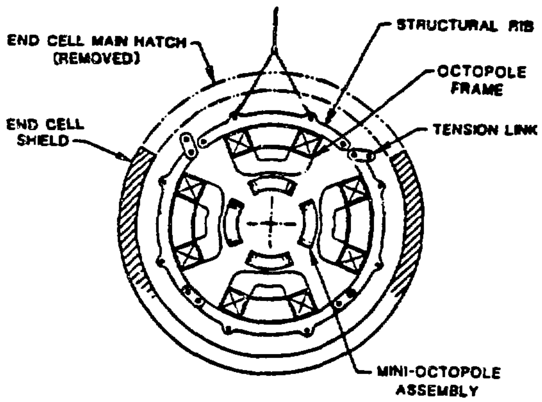

Fig. 2. End cell which requires removal of one octopole frame for access to the mini-octopole.

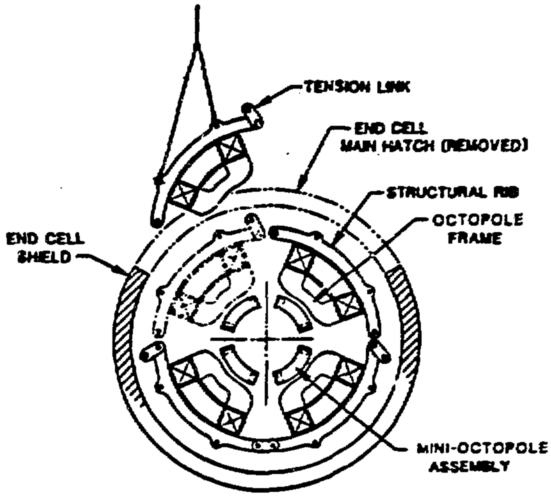

Fig. 3. End cell which requires removal of two octopole frames for access to the miri-octopole.

Seven primary operations are required for removal of the minor octopole, and all of these must be accomplished remotely. A brief description of each is discussed below:

1. Remove the end cell hatch to provide access for all subsequent overhead operations. The hatch is stored in the vault "laydown" area and serves as the holding fixture for the frame coils subsequently removed from the end cell. Disassembly of the structural attachments and the vacuum seal of the hatch may be accomplished with personnel prior to pumping out the shield water contained in the hatch.

2. Disconnect electrical and coolant lines to the major-octopole frame(s) to be removed and disconnect those to the minor octopole.

3. Remove the upper link attachments on the structural ribs of the frame coils, as shown in Figs. 2 and 3.

4. Remove the small centerline hatch for access to the structural attachments between the octopole assembly and the mirror/shaping coil assembly, as shown in Fig. 1. Only those attachments into the frame being removed need to be disassembled. It was estimated that 48 5-cm bolts are needed to react the 60-MN (13.5 $\times 10^6$ lbs) tensile load

at this interface; therefore, each frame interface has 12 bolts. The crane-mounted manipulator is shown in Fig. 1, removing the upper bolts using an impact wrench. Advanced manipulator systems (presently under development) are suitable for this operation. Note that the telescoping boom requires one articulated joint because of the location of the centerline hatch.

5 A portion of the inner shield annulus shown in Fig. 4 must be removed to gain access to the structural attachments between the minor octopole assembly and the frame(s). In order to reach this shield using the overhead manipulator, a trapezoidal access opening (100 × 90 × 75 cm) is needed through the inner and outer structural shells of the top frame(s) between the third and fourth ribs.

The details of this portion of the end cell are not developed in sufficient detail, but it appears that the space constraints indicate that this operation may not be feasible for the present configuration. An alternative approach may be to simply not have structural attachments between the upper frame(s) and the minor octopole, since this interface is always in compression when the coils are energized. The lower frames would have attachments for stability (and possible off-normal conditions), and these would be accessible after removal of the upper frame(s).

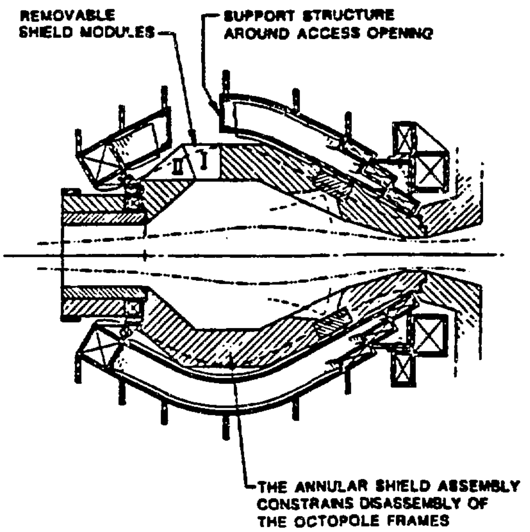

Fig. 4. Access requirements for minor-octopole detachment.

6. The octopole frame to be removed must be translated 0.5 m toward the center cell in order to clear the mirror/shaping coil assembly prior to vertically lifting the frame from the end cell. In the present configuration, this operation is not possible since the annular shield constrains lateral movement of the frame. Therefore, either the mirror/shaping coil assembly must be moved back 0.5 m, or the annular shield must be modularized such that it becomes part of the frame assembly. Additional development of the end cell configuration is needed to determine which is the most feasible approach.

7. Lift out the minor-octopole assembly after removing the remaining structural attachments to the frames.

CONCLUSIONS

The development of the FPD configurations was based on providing access to modular component installations. In general, all component replacements take advantage of the linear geometry of the tandem mirror design and vertical lifting. Sufficient device shielding is provided to allow limited personnel access to the device 24 h after shutdown, and access for remote operations is ample via the large, removable hatches. The configuration developments for the FPD-III end cell are complex due to the interlocking of octopole magnets, shaping coils and shielding, and these designs require modifications for the removal of the components.

Several design changes were identified in the end cell for disassembly and component removal that must be considered in the next phase of mirror reactor studies:

(1) The addition of a small, centerline hatch (1 × 2 m) behind the main hatch to gain access to the structure of the mirror/shaping coil assembly

(2) The addition of an access opening through the inner and outer structural shells of the upper frame(s) between two ribs to gain access to the annular shield and the structure between the minor and major octopoles

(3) Design of the annular shield to have two removable pieces for access to the octopole structural attachments and the consideration of eliminating the upper structural attachments between the minor and major octopoles

(4) Evaluation of modularizing the annular shield vs moving the mirror/shaping coil assembly for removal of octopole frames.

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