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REMOTE-MAINTENANCE OPERATIONS ON THE FUSION ENGINEERING DEVICE*

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REMOTE MAINTENANCE OPERATIONS ON THE FUSION ENGINEERING DEVICE

Preface

The content of this document was excerpted from the FED Baseline Design Description (ORNL/TM-7948). Although this is a lengthy writeup, the material provides a basis for understanding the configuration evolution and the maintenance and disassembly procedures required for this device. In view of the diverse participation at this seminar, it was felt that this approach would be beneficial for those who are not familiar with the FED or tokamaks in general.

The Appendix at the end of this paper is a copy of the slide material presented and represents the most current direction of FED maintenance considerations. Included in this material are the conceptual development of maintenance equipment, in-vessel operations, and considerations for decontamination.

Introduction

In the overall development of the FED configuration, the initial device assembly was considered as well as the subsequent disassembly required for component maintenance. A fully integrated configuration requires that initial assembly and subsequent disassembly be accommodated. Both operations must be investigated because much of the initial device assembly is different from the operations needed for component replacements. For example, the initial installation of the lower superconducting EF coil is independent of the torus and TF coil installations, but its subsequent replacement is very much affected by these components. In order to describe the considerations and design features for each operation, this document is divided into two parts. The first is a description of the basic assembly sequence of all major components. The second part is a description of the maintenance approach.

1. Assembly Sequence of the Device

The assembly sequence is divided into three phases. Phase I is primarily the installation and assembly of the magnet systems, Phase II is that of the plasma chamber systems, and Phase III addresses the assembly of the peripheral components. Table 1-1 shows the breakdown of major components by assembly phases. Figure 1-1 illustrates eight major steps in the assembly sequence described as follows.

The bucking cylinder is the first component to be assembled. It is placed on a temporary support structure which becomes redundant after the TF coils and the ring beams are in place. (At that time, the bucking cylinder is supported by the 10 TF coils.) EF coil #3 is then positioned into the reactor cell pit area along with the lower ring beam for subsequent installation onto the lower support structure of the TF coils. The 10 TF coils are then positioned and installed onto the support columns; the columns are configured as a truss to provide lateral restraint for the TF coil system. The upper and lower support structure between TF coils (the intercoil supports) are preassembled to the coils in half sections. The final shimming and joining of this structure are accomplished after the coils are in place. The final installation of the lower ring beam and the addition of the upper ring beam completes the TF coil support system. The temporary support under the bucking cylinder is removed at this time.

After the final installation of EF coil #3, the lower cryostat containment and the torus support columns are assembled. The cryostat vessel is also built up around the inner and upper legs of the TF coils. EF coil #2 is placed into the upper ring beam structure, although this can be done at a later stage. The same is true for the installation of the OH solenoid and the cryostat dome. Their assembly can be delayed if it is advantageous to do so. EF coil #1 is brought into the cryostat enclosure in two 180° segments through the window and temporarily

Table 1-1. Phased assembly of major components

Primary Device Components		Peripheral Components
Phase I	Phase II	Phase III
Bucking cylinder	Torus platform	RF heating
EF #3	Spool and frames	Limiter blades
TF coils	Torus sectors[a]	Pumps and ducts
Cryostat (less dome)	Solenoid[b]	Fuel injectors
EF #2	Cryostat dome[b]	Test modules
EF #1, 4		Diagnostics

[a]Many of the peripheral components may be preassembled to the torus prior to installation.

[b]May be installed at the end of Phase I or in Phase III.

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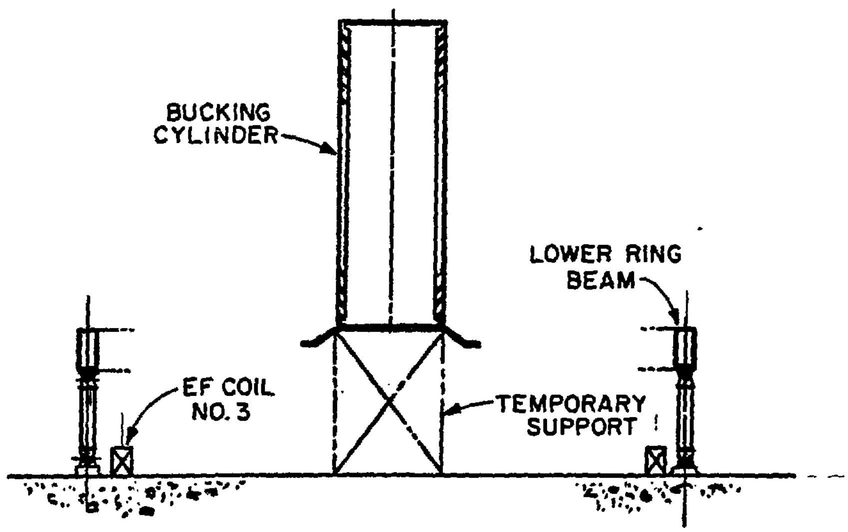

Fig. 1-1a. Initial assembly of the FED device — installation of temporary support bucking cylinder, EF coil #3, lower ring beam.

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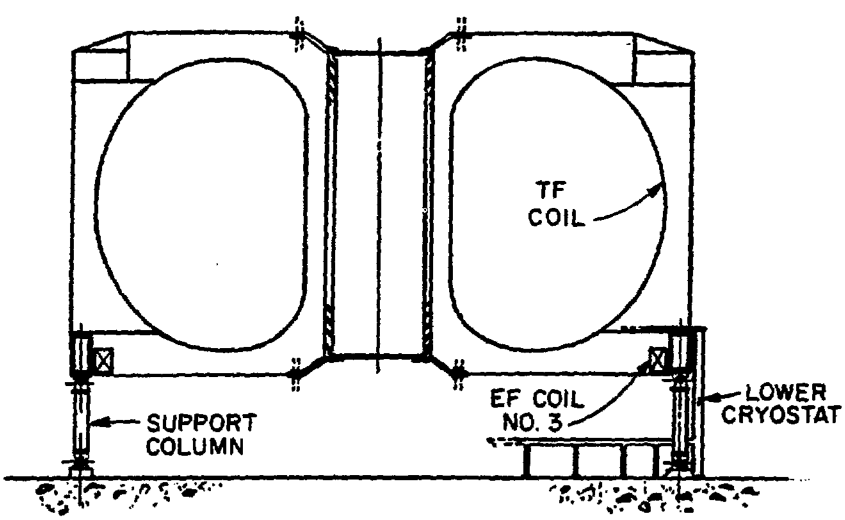

Fig. 1-1b. Initial assembly of the FED device — installation of TF coils, support columns, EF coil #3, lower cryostat.

ORNL-DWG 81-17033R FED

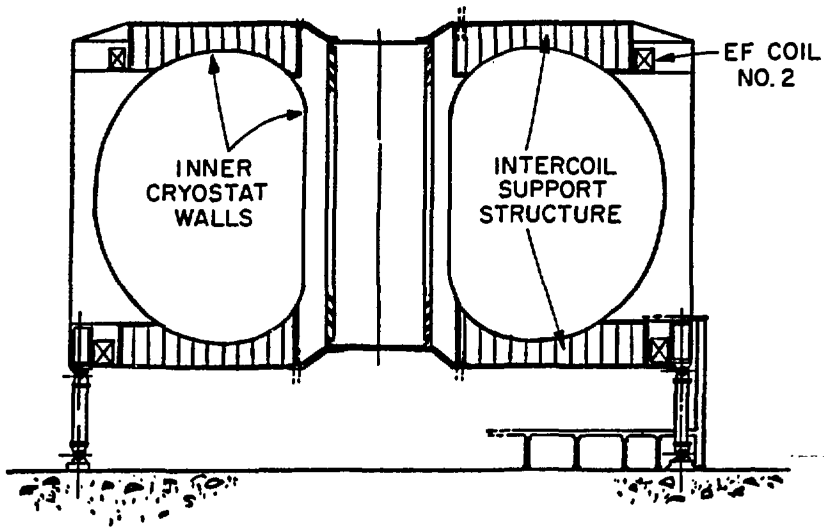

Fig. 1-1c. Initial assembly of the FED device — installation of intercoil supports, EF coil #2, inner cryostat walls.

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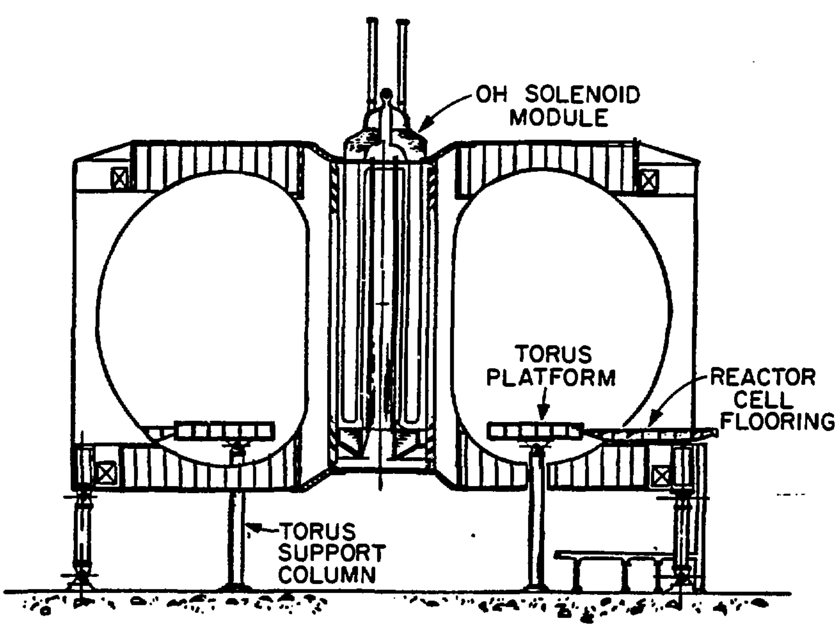

Fig. 1-1d. Initial assembly of the FED device — installation of torus supports, torus platform, OH solenoid module.

ORNL-DWG 81-17032R FED

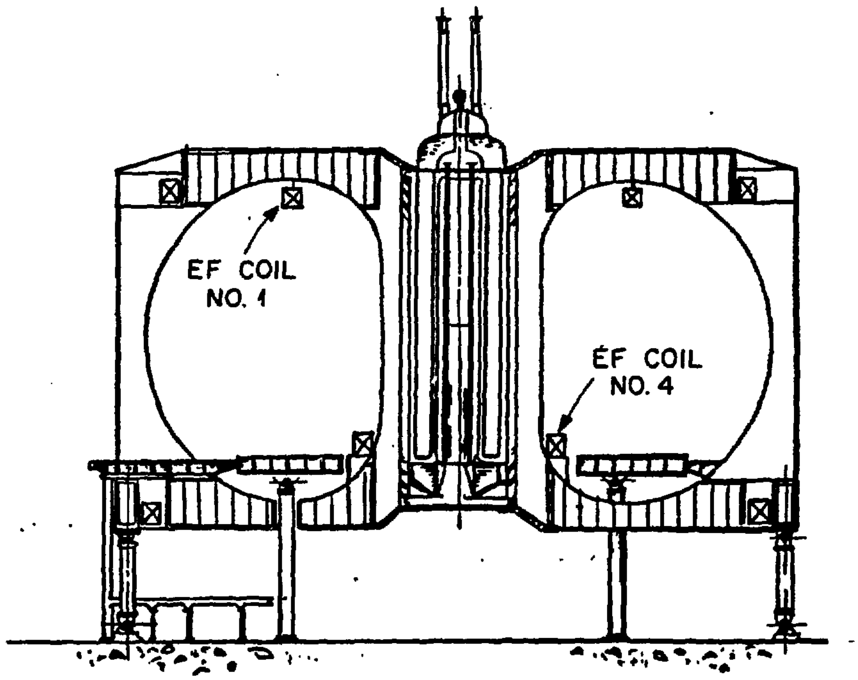

Fig. 1-1e. Initial assembly of the FED device — installation of jointed copper coils, EF #1 & #4.

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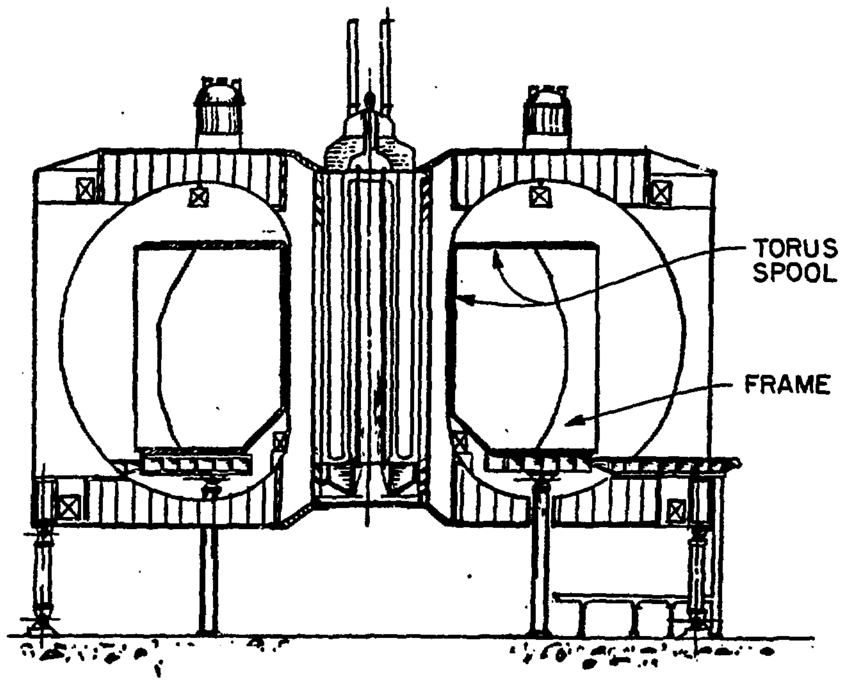

Fig. 1-1f. Initial assembly of the FED device — installation of torus spool and frame structure.

ORNL-DWG 81-17029R FED

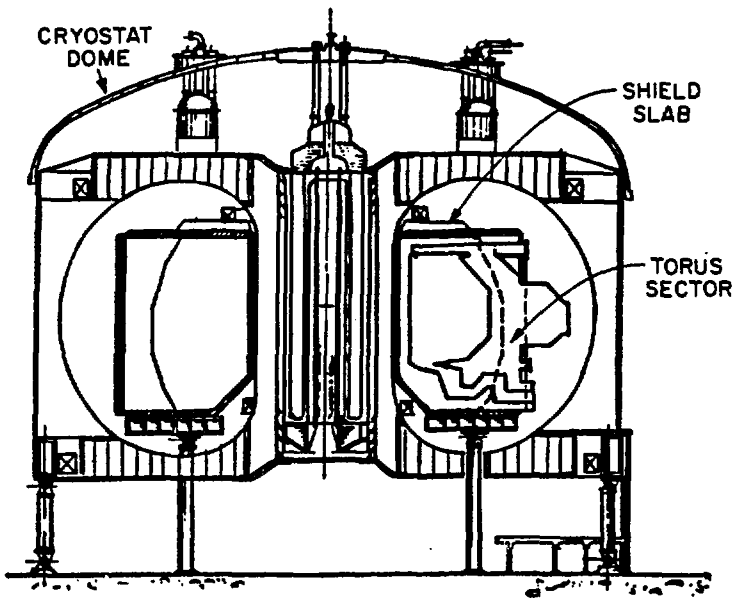

Fig. 1-1g. Initial assembly of the FED device — installation of torus sectors, shield slab, EF coils #1 & #4, cryostat dome.

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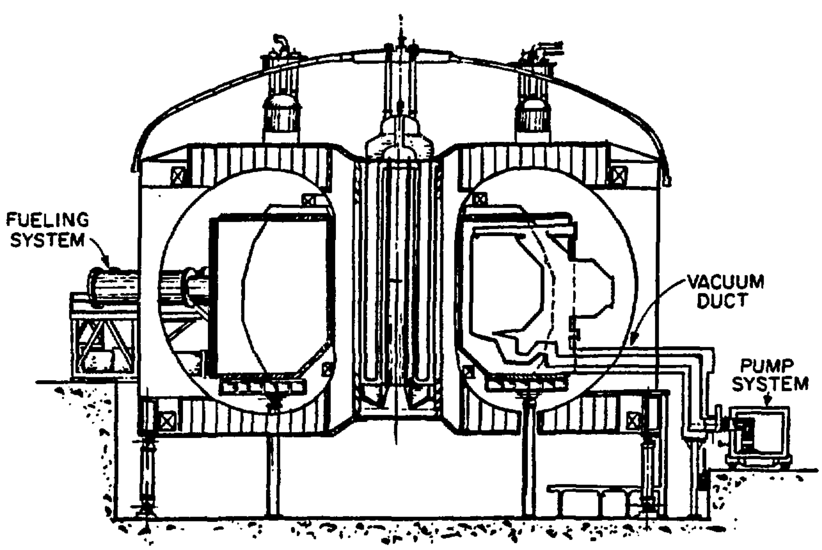

Fig. 1-1h. Initial assembly of the FED device — installation of peripheral components.

suspended from the upper intercoil structure. It remains in that position until the torus spool structure is completed. EF coil #4 is also introduced as two 180° segments through the window, but it is assembled into a ring coil and temporarily located on a support platform which is built into the lower cryostat surface. It remains there until the spool is completed.

The torus platform structure is introduced through each window in ten segments. Each is attached to a torus column support which is already in place and then joined to form a continuous platform for the torus. The flooring which bridges the torus platform and the reactor cell floor is next installed to aid the assembly of the spool structure. Ten spool pieces are then assembled on the platform after passing through the windows. They are joined to each other along with vertical frame supports to provide structural and vacuum integrity for the 10 sectors. EF coil #4 is then raised to its final position behind the truncated portion of the spool. The upper shield slab is passed through each window as a segment and installed on top of the spool structure. EF coil #1 is taken from its suspended position and joined into a ring coil on top of the slab.

The device is essentially complete at this stage except for the torus sectors and their peripheral components. Each of the 10 sectors is passed through its appropriate window opening for final installation into the spool. It is conceivable that each sector could be preassembled with its adjunct components, i.e., limiter blade modules, ICRH and ECRH systems, diagnostics, etc., although these could be the last items to be installed on the device prior to operational testing. After the sectors are in place, the pump limiter ducts, the 10 pairs of pump systems, and the fuel injector system are the last major components to be installed.

2. Maintenance

Maintenance and disassembly of the major FED components are prime drivers of the configuration evolution and have influenced both the design and the location of the major systems. The maintenance approach for the

FED is threefold and considers the mode of maintenance operations, the complex geometry of the tokamak, and available maintenance technology. This approach established the framework for developing the device configuration. It is briefly described below.

1. In general, all areas outside of the device shield can be maintained by contact operations about one day after shutdown if the plasma chamber is unopened and if torus penetrations are properly shielded. In addition, all systems are being designed with the ability to be remotely maintained for emergency situations when personnel entry into the reactor cell could be prohibited.
2. Those components whose replacement requires an extended device shutdown are classified as semi-permanent and are designed to function normally without replacement for the life of the device. The capability to accommodate their unexpected repair or replacement, however, is one of the criteria guiding the configuration development.
3. All components are designed to be maintained using existing or near-term remote maintenance equipment and technology in the areas of manipulator systems, viewing systems, and transport systems.

In discussing tokamak maintenance, the tendency is to focus on remote operations because of their inherent difficulties, and likewise that is the thrust of this subsection. However, it is important to note the benefits of contact operations for routine inspection and maintenance while the device is fully assembled. The shield is designed to permit this flexibility. Even so, many of the maintenance activities will require remote operations, particularly the replacement of major components. This is true not only because of neutron-induced activation, but also because many of the components are large and heavy, thereby limiting contact procedures to inspection, supervision, and equipment setup.

This subsection is divided into four parts. The first is a discussion of scheduled and unscheduled maintenance. The second part describes the influence of maintenance and disassembly on the device configuration, and the third part covers disassembly scenarios of the major components. The last is a discussion of conclusions and future work.

2.1 Scheduled and unscheduled maintenance

Maintenance activities for the device fall into two broad categories: those which are scheduled or planned for and those which are unscheduled.

Scheduled repair (or replacement) is anticipated for components whose life is limited by mechanical wear or physical degradation resulting from operation in the reactor environment. The fuel injector is a rotating mechanical device which will require lubrication and bearing changes every 2 1/2 years. The limiter blades are expected to be changed periodically. Also included as scheduled operations are components which will be changed or added to the tokamak as its operating mission changes. These include instruments, diagnostics, and experiments.

Unscheduled events are not preplanned occurrences even though they have been anticipated in the configuration design. Even the most reliable components, those designed to last the life of the device, have a finite probability of at least one failure during the device lifetime requiring a replacement. In many cases, these will have a significant impact on the device downtime, particularly those classed as semipermanent installations. Some examples of components which may require unscheduled maintenance are: the ICRH and ECRH launchers and waveguides, PF coils, TF coils, vacuum and coolant containment systems, the torus spool, and possibly even primary and secondary support structure. Pumps, valves, and the like are also in this category but will not present serious maintenance problems because they are relatively small and accessible. These components will be designed for quick, remote changeouts.

A discussion of specific component replacements and the resulting downtime is presented later in this section.

2.2 Influence of maintenance on the configuration

Much of the overall configuration development is associated with the concern for maintenance and disassembly. Some of the maintenance considerations which have significantly affected the configuration include:

- Straight, radial translation for torus sector removal dictated that the number of sectors be equal to the number of TF coils.

- The required size of the window-like opening for sector removal established the minimum TF coil size and also provided access for torus penetrations.
- External vacuum sealing of the torus sectors led to the development of the fixed spool structure.
- The PF coils are positioned to provide clear access for sector removal.
- Major components which require periodic replacement are designed to be modular so they can be removed with a minimal impact to other components, e.g., the limiter blade.

The configuration description which follows is presented from the perspective of maintainability and disassembly of the device. Several major design iterations led to the present FED reference configuration, and each of these was strongly influenced by maintenance requirements.

One of the most important maintenance operations influencing the development of the configuration is removal of the torus sectors. Earlier trade studies indicated that a minimum number of large sectors is the most efficient means of disassembling the plasma chamber. The minimum number of sectors which can be arranged for any tokamak configuration is simply equal to its number of TF coils. In such an arrangement, the access necessary for removing a sector is bounded by the outer TF coil leg (actually the cryostat) and the upper and lower cryostat enclosures. Figure 2-1 is a drawing of this "window concept." The window permits each sector to be removed in its simplest form of translation which is straight, radial motion.

The window also provides the maximum amount of clear space for penetrations into the torus. In the FED reference design, the major component penetrations are: 4 ICRH antenna launchers for bulk heating, 10 waveguides for ECRH heating, 2 fuel injectors, 10 pump limiter ducts, electrical and coolant lines for the internal PF coil system, and coolant piping for each of the 10 torus sectors. In addition to this required listing of components, there will be numerous penetrations for instrumentation and diagnostic equipment, as well as modular components for engineering testing.

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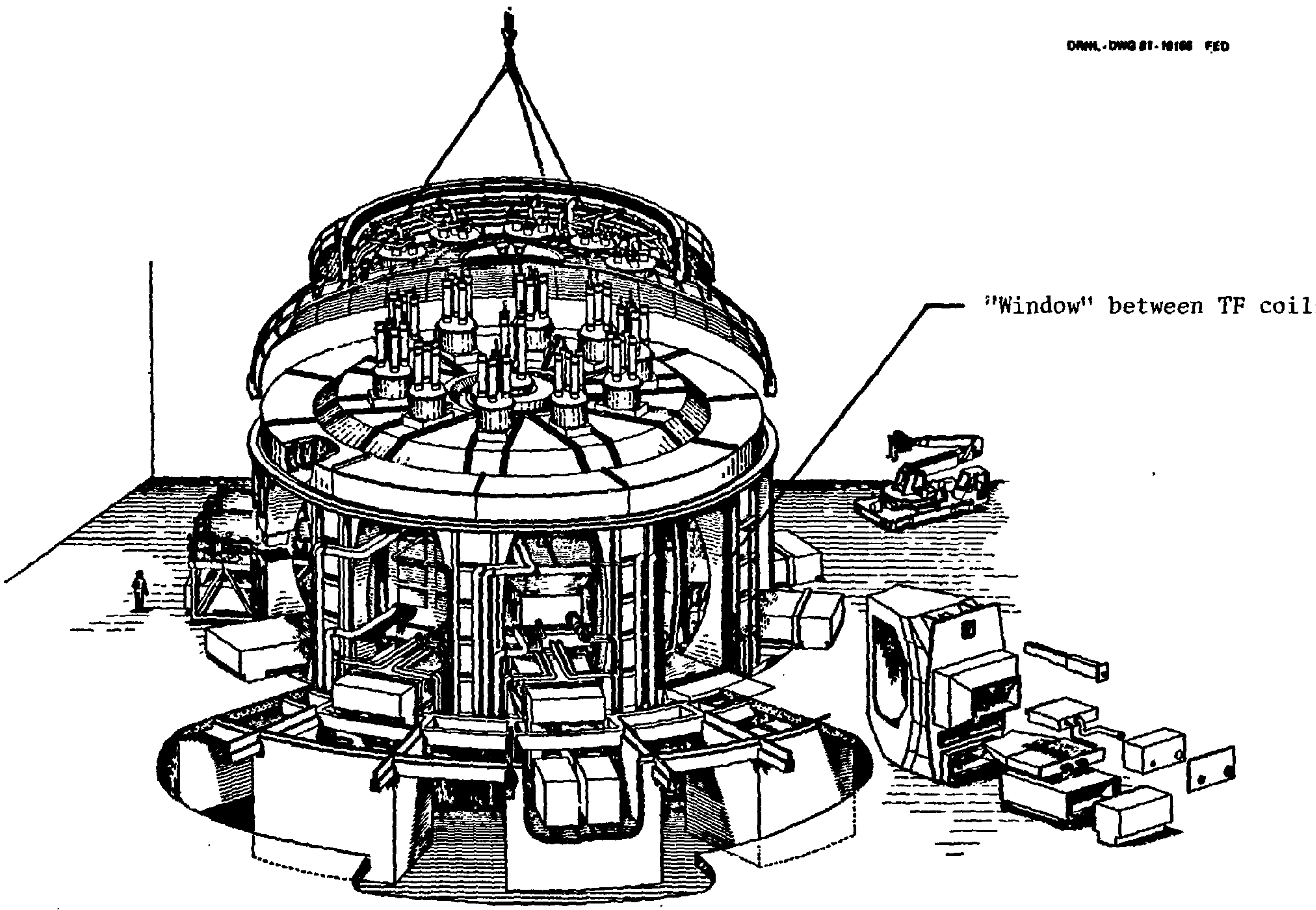

FED REFERENCE CONFIGURATION
DIMETRIC VIEW

Fig. 2-1. The TF coil/cryostat window allows for radial extraction of the torus sectors.

One of the more significant tasks for sector removal is disengaging the vacuum closure of the torus seal. The flange is totally accessible through the window and is external to the plasma chamber. However, because of the compactness of the design (aspect ratio = 3.8), the clearance between the torus and the inner TF coil cryostat does not permit disassembly operations by contact or remote means. Therefore, there is no possibility of providing external sealing between adjacent sectors around each external interface. This design constraint led to the fixed-spool concept which is illustrated in Fig. 2-2. A portion of the plasma chamber is designed to be a semipermanent installation surrounding the common cryostat of the inner TF coil legs. It provides monolithic support for the individual torus sectors and also makes up three vacuum sealing surfaces of the plasma chamber. Each of the sectors is nested in this spool-like structure and rigidly attached to the outer edge of the spool and the vertical posts. These posts act to support the upper and lower spool flanges and are located in the plane of the TF coils.

Disassembly of the sector, including the vacuum closure, can therefore be accomplished by completely external operations. The operations which prepare the torus for removal can be accomplished "hands-on."

Adoption of the window concept influenced the location of PF coils. The FED design uses a hybrid system made up of internal and external EF coils. These coil positions are arranged to be compatible with clear access through the window for sector removal. The advantage of this configuration is the fixed location of the coils, unlike the earlier ETF design which required raising and lowering of the inner EF coils. Figure 2-3 illustrates the coil positioning around the open window.

The design of the limiter blade is another example of the influence of maintenance and disassembly on the configuration. It can be removed from the plasma chamber without disturbing the sector or other peripheral components (i.e., the ICRH launcher or the vacuum pump shielded duct). It is sized to fit within the boundary of the window and has an independent vacuum seal interface with the torus. Figure 2-2 also depicts the pump limiter module removal. This feature of independent removal is

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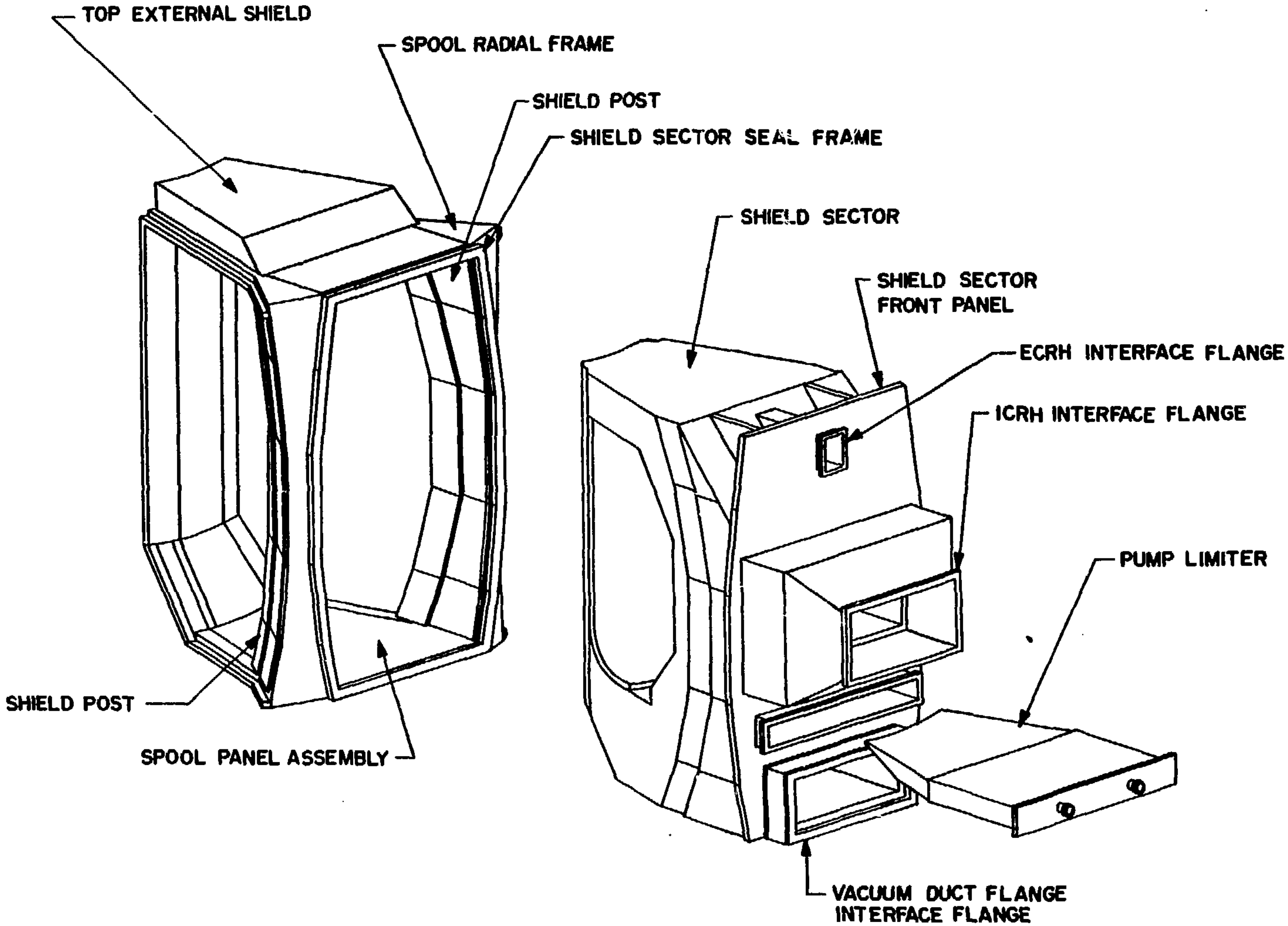

Fig. 2-2. The spool arrangement provides vacuum integrity and allows the torus seal to be totally accessible through the window.

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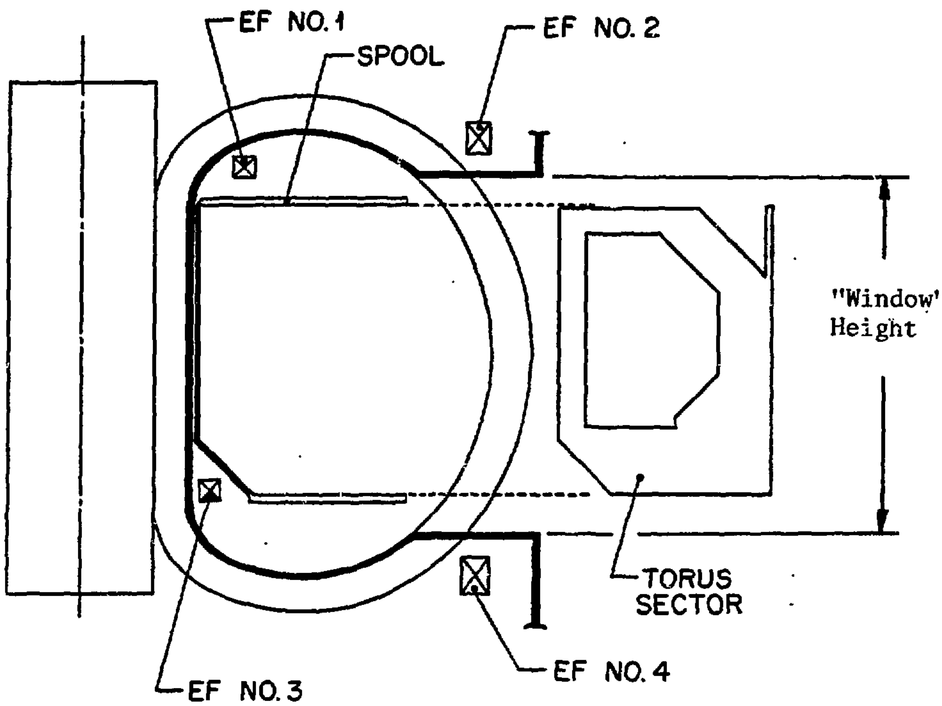

Fig. 2-3. The poloidal field coil locations are compatible with the window concept.

particularly attractive for this component because of its anticipated frequent replacement.

2.3 In-vessel operations

Generally speaking, all component repairs are accomplished outside of the reactor cell, and repaired components or spares are refitted into the device. This philosophy has led to component modularization as a means of increasing device availability. However, there are some situations where in-vessel operations offer a distinct advantage. The ability to have routine in-vessel inspection, without opening the plasma chamber is one example. Visual monitoring of the first wall, the limiters, and certain test modules, in situ, will provide valuable data without an adverse impact to availability. It is presently estimated that reconditioning the plasma chamber after it has been opened to the reactor cell may take one week. Consequently, viewing systems have been considered for each of the 10 sectors. One option is a modified periscope system which is built into the vacuum integrity of the plasma chamber.

The armor tiles of the first wall are designed for the life of the machine; however, it is expected that a finite number of tiles will fail and will require replacement. Their replacement can be accomplished by removing the sector (or sectors) affected, with a potential downtime of many weeks, or they can be replaced in situ in perhaps half of the time. In order to accomplish this, four entry ports have been identified around the device for introducing a manipulator system. They are in bays I, IV, VI, and IX and are also penetrations common to other systems. Figure 2-4 shows the location of the bays and the locations for introducing a manipulator system to reach all surfaces in the first wall.

2.4 Disassembly scenarios

The disassembly scenarios discussed here generally do not reflect the routine maintenance operations, but instead describe major component changeouts which represent worst case occurrences. These are the scenarios

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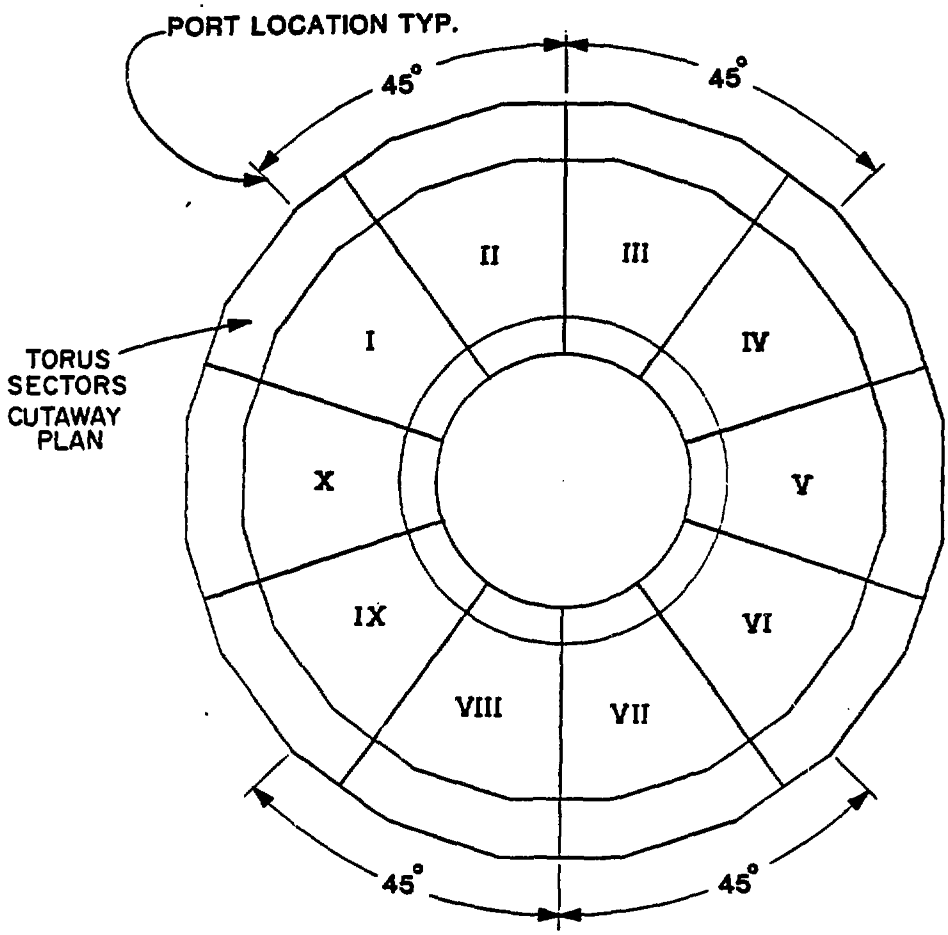

Fig. 2-4. In-vessel manipulator operations are accomplished through four ports.

upon which the configuration is based. A summary of the component replacement times is given in Table 2-1.

The time estimates assume that maintenance and disassembly operations occur in three full shifts, seven days per week. Figure 2-5 shows the components which are discussed in this section.

2.4.1 Torus sector

The plasma chamber is made up of 10 sectors which are fitted into the spool structure. They are externally sealed to the upper and lower spool pieces and the vertical support frames. Their removal is through the TF coil/cryostat window. The removal of a sector may be required for any of several reasons: an internal coolant or vacuum leak, severe erosion of the first wall and armor, or the replacement of a TF coil. While none of these are scheduled occurrences during the device lifetime, they must nevertheless be accounted for. A tabular summary of the major steps necessary for sector removal is shown in Table 2-2. Two things should be noted: 1) the first twenty-four hours after device shutdown, a "cooldown" period is required to permit personnel access into the reactor cell; 2) the cryostat maintains all of the superconducting coils and their structure at liquid helium temperature during this scenario.

It is assumed that the components which are installed on the torus are not disassembled but remain in place, i.e., ICRH launcher, ECRH waveguide, diagnostics, and limiter. The additional downtime required for the repair or replacement of the failure in the torus is not included in the total elapsed time; it is assumed that a spare sector is available.

2.4.2 *Limiter module*

The pump limiter is a modular component which is positioned in each of the ten torus sectors. It is a blade-like component which is made up of a replaceable sleeve and a reuseable core, and its scheduled changeout is on the order of once per year. Because of the relative frequency of these operations, this component is designed to be removed independently of the torus sector and the shielded ducting.

Table 2-1. Summary of component replacements

Component	Quantity	Physical Characteristics (per unit)	Replacement Time (days)[a]
Torus sector	10	375 tn 7 × 5 × 4 m	11
Limiter module	10	30 tn 4 × 3 × 0.5 m	10
Pump system	20	<10 tn 2.5 × 2 × 1.5 m	2
ICRH launcher	4	<10 tn 3.3 × 2.5 × 1.3 m	9
ECRH, diagnostics	10	--	8
OH solenoid	1	350 tn 12 × 3 dia. m	44
EF coil #2	1	350 tn 19 dia. m	45
EF coil #3	1	450 tn 19 dia. m	209
EF coils #1, 4	1	90 tn 3.9 dia., 3.1 dia. m	43
TF coil	10	235 tn 7.4 × 10.9 m clear bore	168
Fuel injector	2	<20 tn 6 × 3 dia. m	<2
Valves, pumps, etc.	--	--	<2

[a]The times listed are for one individual component; it does not follow that removal of all components is a multiple of the time shown; also assumes around-the-clock operations.

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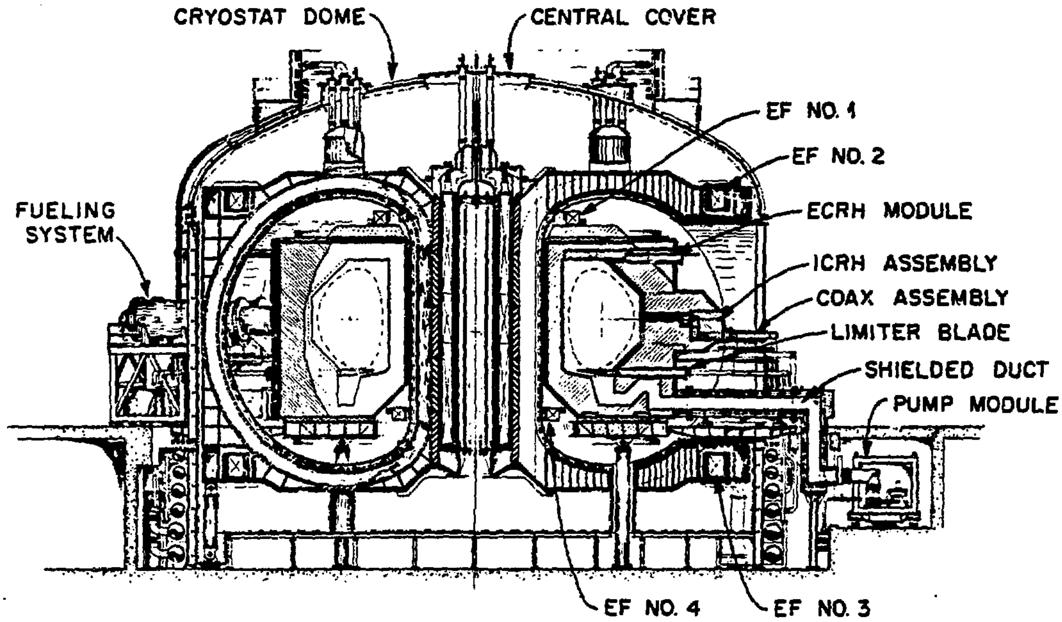

Fig. 2-5. The disassembly of major components influenced the configuration design.

Table 2-2. Torus sector replacement

	Steps	Mode of Operation[a]	Duration (hrs)
1.	General device shutdown	A	↓
	Magnetic coils discharged	A	
	Torus sector drained of coolant	A	
	Maintenance equipment is readied	-	
	Bakeout at elevated temperature	A	24
2.	Disconnect electrical and coolant lines including those of adjunct components	C	8
	Cut torus vacuum seal and limiter duct seals	C/R	8
3.	Extract limiter duct; install shield plugs to all duct openings	R	4
	Remove sector through window	R	
	Transport to hot cell	R	4
4.	Decontaminate area	R	4
5.	Install sector through window	R	4
	Remove shield plugs; install duct	R	4
6.	Weld torus vacuum seal and duct seals	R	16
7.	Connect electrical and coolant lines	C	8
8.	Recondition plasma chamber	A	168
9.	Refill coolant, energize coils	A	4
	TOTAL		256 hrs (10.7 days)

[a]A = automated operation
C = contact operation
R = remote operation

The primary maintenance equipment needed for this removal is a transporter device which is used to extract the module after the flange attachments to the sector have been disassembled. This operation utilizes the shielded duct as a platform to support both the transporter and the engaged limiter module. It is assumed that 10 spare modules are available for the sequential changeout of the entire limiter system, and that contact maintenance procedures are possible before the extraction of a blade.

A summary of the major steps necessary for limiter replacement is shown in Table 2-3. The time required to replace one limiter blade is 9.4 days; it can be shown that replacing 10 limiter blade modules in a sequential operation is approximately 13 days.

2.4.3 Vacuum pump system

The 10 pairs of vacuum pump systems are located below the reactor cell floor. This arrangement conserves valuable space around the reactor and allows the pumps to be maintained with minimal impact to other device systems. Scheduled maintenance for the turbomolecular pumps (TMP) is expected after 25,000 hours of operation for bearing replacements, and after 6 months of operation for oil changeout. The replacement steps and time estimates are given in Table 2-4. The secondary pumps in this system are assumed to be repaired within these same periods.

The pump system is enclosed in a magnetic shield which could serve as a secondary containment for tritium if required. Therefore, the pump and shielding system is treated as a modular component. Its removal requires closing the isolation valve at each TMP in order to maintain vacuum integrity in the plasma chamber. After separating the duct interfaces with the module, the pump system is lifted out of the pit to the hot cell. The single most important feature in this system design is its isolation from the plasma vacuum. This increases device availability since the one week of plasma chamber reconditioning is not required.

Table 2-3. Limiter blade replacement

	Steps	Mode of Operation	Duration (hrs)
1.	General device shutdown	A	
	Limiters drained of coolant	A	
	Maintenance equipment is readied	-	
	Bakeout at elevated temperature	A	24
2.	Disconnect coolant lines	C	4.5
	Disassemble mechanical seal and install extractor	C/R	9
	Remove module to hot cell	R	2.5
3.	Install replacement module	R	4
	Assemble mechanical seal	R	8.5
	Test seal integrity	C/R	1.5
4.	Connect coolant lines	C	4.5
	Recondition plasma chamber	A	168
	TOTAL		226.5 hrs (9.4 days)

Table 2-4. Vacuum pump system replacement

	Steps	Mode of Operation	Duration (hrs)
1.	General device shutdown	A	
	Discharge coils	A	
	Close isolation valves	A	↓
	Remove floor over pit	R	24
2.	Cut vacuum seals	C/R	4
	Lift out pump system module	R	1
3.	Install and align pump system module	R	2
	Weld vacuum seals	R	6
4.	General device startup	A	4
	TOTAL		41 hrs (1.7 days)

2.4.4 ICRH launcher

The launcher system is essentially an integral part of the torus and is located in 4 sectors. It is made up of 4 subassemblies which can be sequentially removed from the sector. They are: the coax assembly, the cover plate, the shield plug, and the waveguide sleeve. Replacement of the waveguide sleeve requires a complete disassembly of the launcher system. Assuming that spares are readily available, a waveguide sleeve can be replaced in about 9 days — without removing the torus sector (see Table 2-5).

2.4.5 ECRH, diagnostics, test modules

These components are discussed as a group because of their common relationship with the torus interface. They penetrate the torus in a plug-like or drawer-like manner, and they are of a size which is relatively manageable. The ECRH waveguide assembly shown in the elevation drawing (Fig. 2-5) is also representative of many of the diagnostic assemblies; they can be removed and replaced like a drawer in a cabinet.

Removal of the waveguide assembly requires simple tasks in a totally accessible region within the TF coil window. A mechanical or welded structural seal must be opened prior to disassembly of the waveguide coupling and inlet and outlet coolant lines. It is estimated that each of these components can be replaced within a 16-24 hour period after device shutdown. The dominant downtime penalty for these changeouts is the reconditioning required for the plasma chamber, estimated to be one week. Total replacement time for these components is 192 hours (8 days).

2.4.6 PF coil system

Maintenance and disassembly of the poloidal field coil system has been a major concern in the design of tokamak reactors. The poloidal coils, because of their interlocking relationship with the rest of the device, require a systematic design process for integration into the

Table 2-5. ICRH launcher replacement

	Steps	Mode of Operation	Duration (hrs)
1.	General device shutdown	A	↓
	Magnetic coils discharged	A	
	Maintenance equipment readied	-	
	Bakeout at elevated temperature	A	24
2.	Remove all electrical and coolant connections	C	4
	Remove coax assembly	C	2
	Remove cover plate	C/R	1
3.	Remove shield plug	R	2
	Remove waveguide sleeve	R	2
4.	Replace waveguide sleeve	R	2
	Replace shield plug	R	2
	Replace cover plate	R	1
5.	Install coax assembly	C	2
	Connect electrical and coolant lines	C	4
6.	Recondition plasma chamber	A	168
	TOTAL		214 hrs (8.9 days)

overall reactor system. Among the early work on PF coils was the hybrid system proposed at ORNL by Peng. It was a mix of copper resistive and superconducting coils, respectively, located inside and outside of the TF coil bore. This system was adopted for the Oak Ridge TNS Study, which incorporated movable resistive coils to permit sector removal. It did not address coil replacements. The present FED design embodies a hybrid system without movable coils and it also has fewer coils than were used in the previous studies.

The options for coil replaceability were: 1) installing redundant coils during initial device assembly; 2) winding coils in situ; and 3) removing failed coils and replacing them with jointed copper coils for the inside coils and continuous superconducting coils for the outside coils. The third option was chosen.

The PF coil system which evolved from combining the requirements of plasma stability (startup, position, and control) and coil replacement has not yet yielded a totally acceptable coil configuration. After numerous trials using variations ranging from all-exterior to various mixes of hybrid coils, it can be concluded that the PF system should not drive the device configuration. It is the configuration which must drive the coil design. Nevertheless, much has been learned about PF coil replacement in developing the present configuration, and new options are available for future work.

The present PF system design consists of the ohmic heating solenoid, two interior copper resistive coils denoted as EF #1 and #4, and two exterior superconducting coils, EF #2 and #3. EF #1, #3, and #4 are the most difficult to replace as illustrated in the following discussions.

OH solenoid

The OH solenoid is concentrically located within the bucking cylinder, in a cryogenic environment. It is designed to be removed by access only through the cryostat dome. A ring flange which is bolted to the upper TF coil support structure locks the solenoid assembly into a cradle support. The cradle ties the lower TF structure together. Table 2-6 is a summary of the solenoid disassembly/reassembly scenario. It can be

Table 2-6. OH solenoid replacement

	Steps	Mode of Operation	Duration (hrs)
1.	General device shutdown	A	↓
	Cryostat warmup	A	336
2.	Disconnect He lines and electrical leads	C	↓
	Remove central dome cover	C	
	Remove support ring structure	C	
	Engage lifting hook	C	12
	Lift out solenoid assembly	R	↓
	Transport to hot cell	R	4
3.	Transport from hot cell	R	
	Lower solenoid assembly into bucking cylinder	R	4
4.	Install support ring	C	↓
	Install dome cover	C	
	Connect He lines and electrical leads	C	12
5.	Cryostat cooldown	A	672
	General device startup	A	4
	TOTAL		1044 hrs (43.5 days)

seen that the major contributor to device downtime for these operations is the cryogenic thermal cycling time. Figure 2-6 shows the sequence of operations. The total time shown only accounts for the disassembly and subsequent reassembly. The time needed in the hot cell for repairs or the time required to obtain replacement components has not been estimated.

EF coil #2

EF coil #2 is readily accessed and replaced after removal of the cryostat dome. Like the OH solenoid, its replacement time is significantly affected by cryostat cycling. Figures 2-7 and 2-8 show the disassembly sequence. The maintenance steps and time estimates are given in Table 2-7.

The total time shown only includes disassembly and replacement assuming that a spare coil is available. A detailed economic evaluation is required to trade off the cost of spares vs the impact of downtime while waiting for repair or fabrication of a new coil.

EF coil #3

The detailed steps of the disassembly of this coil along with a discussion on the impact to the surrounding structure and components are summarized here. The sequence shown in Fig. 2-9 shows four stages of the coil removal (or replacement) along with the support structure impacted. A major change incorporated into the device configuration, was to move the TF support columns to the outside diameter of the machine (Earlier designs located a support under the bucking cylinder and within the diameter of EF #3). This reduces the number of affected TF coil support columns to four instead of ten and provides a relatively clear space under the center of the machine.

Three adjacent vacuum pump systems require removal along with their shielded ducts. In order to maintain contact operations in the reactor cell, the three open ducts just outboard of the window are closed with shield plugs. The reactor cell flooring beyond these pumps is then

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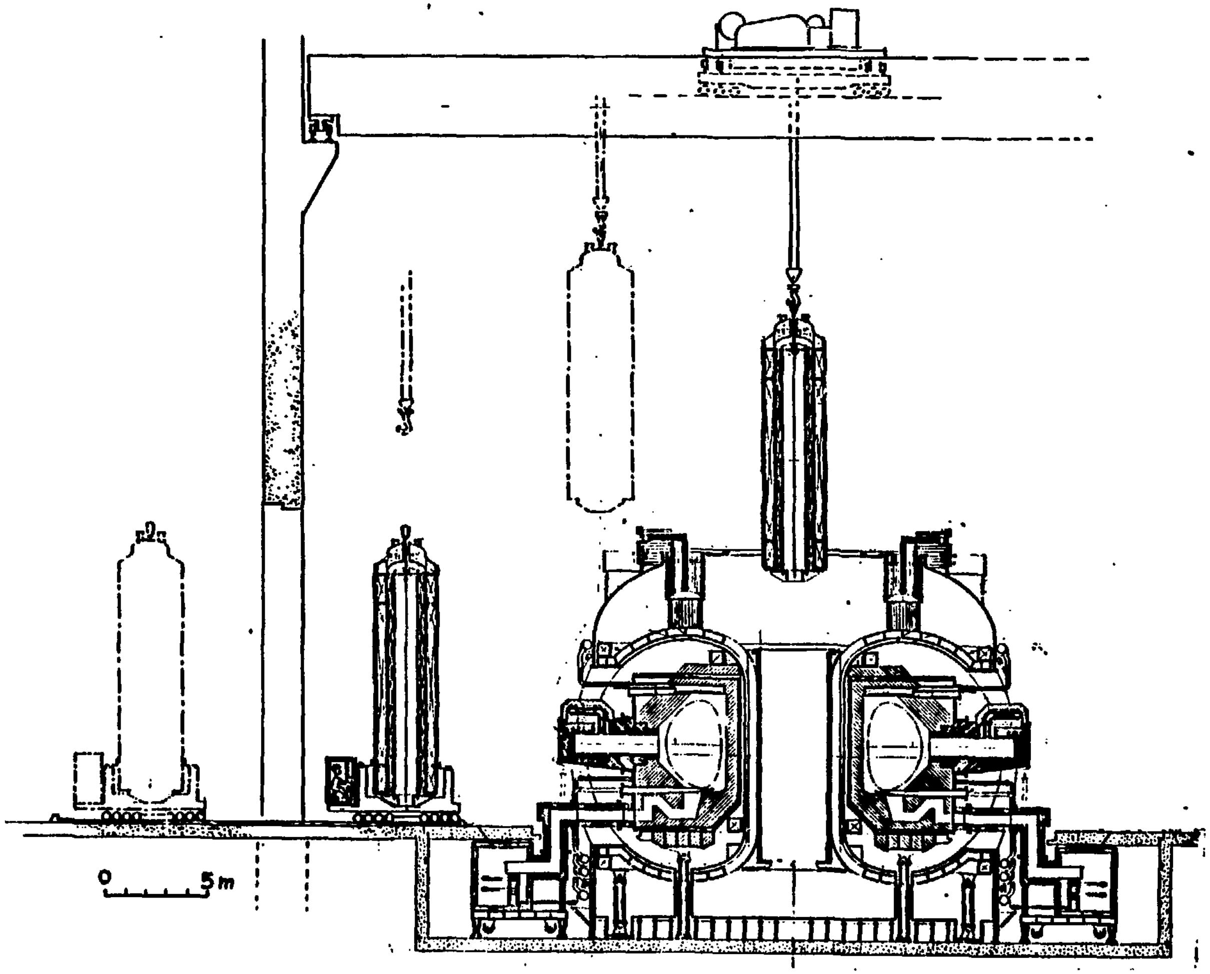

Fig. 2-6. OH solenoid removal.

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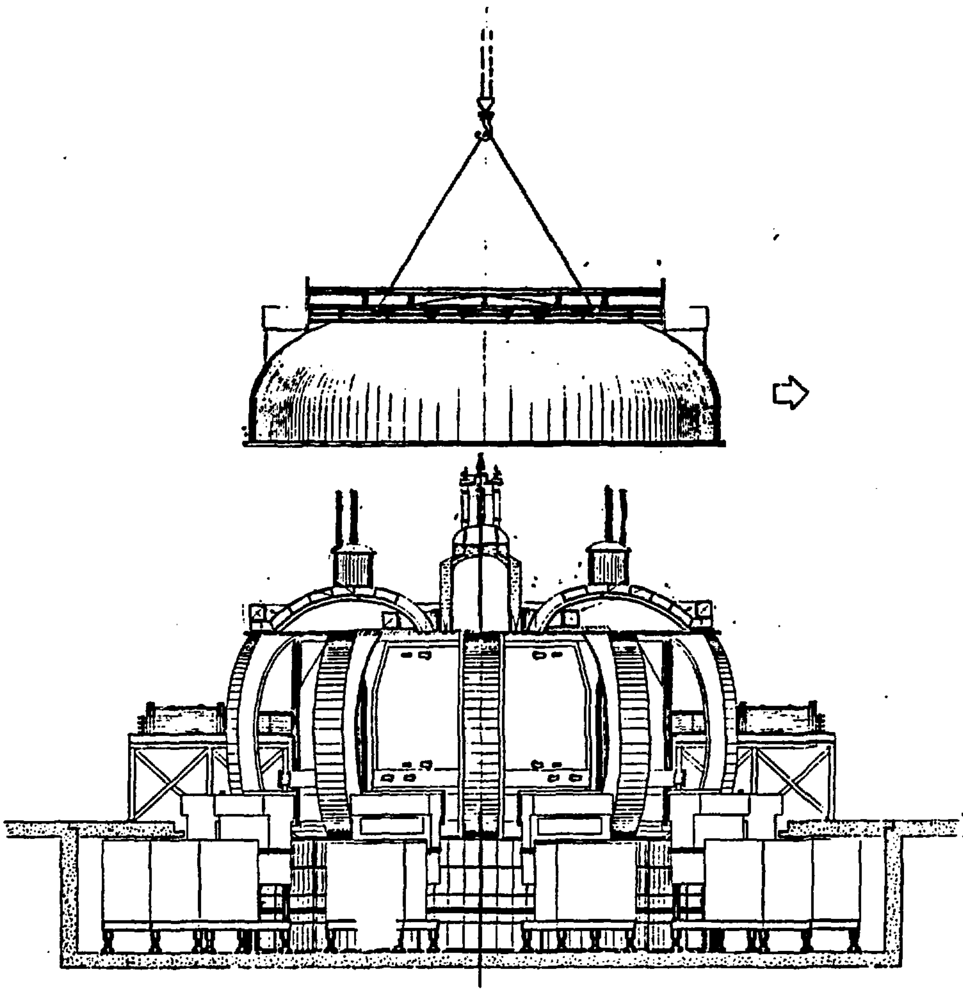

Fig. 2-7. Removal of the cryostat dome.

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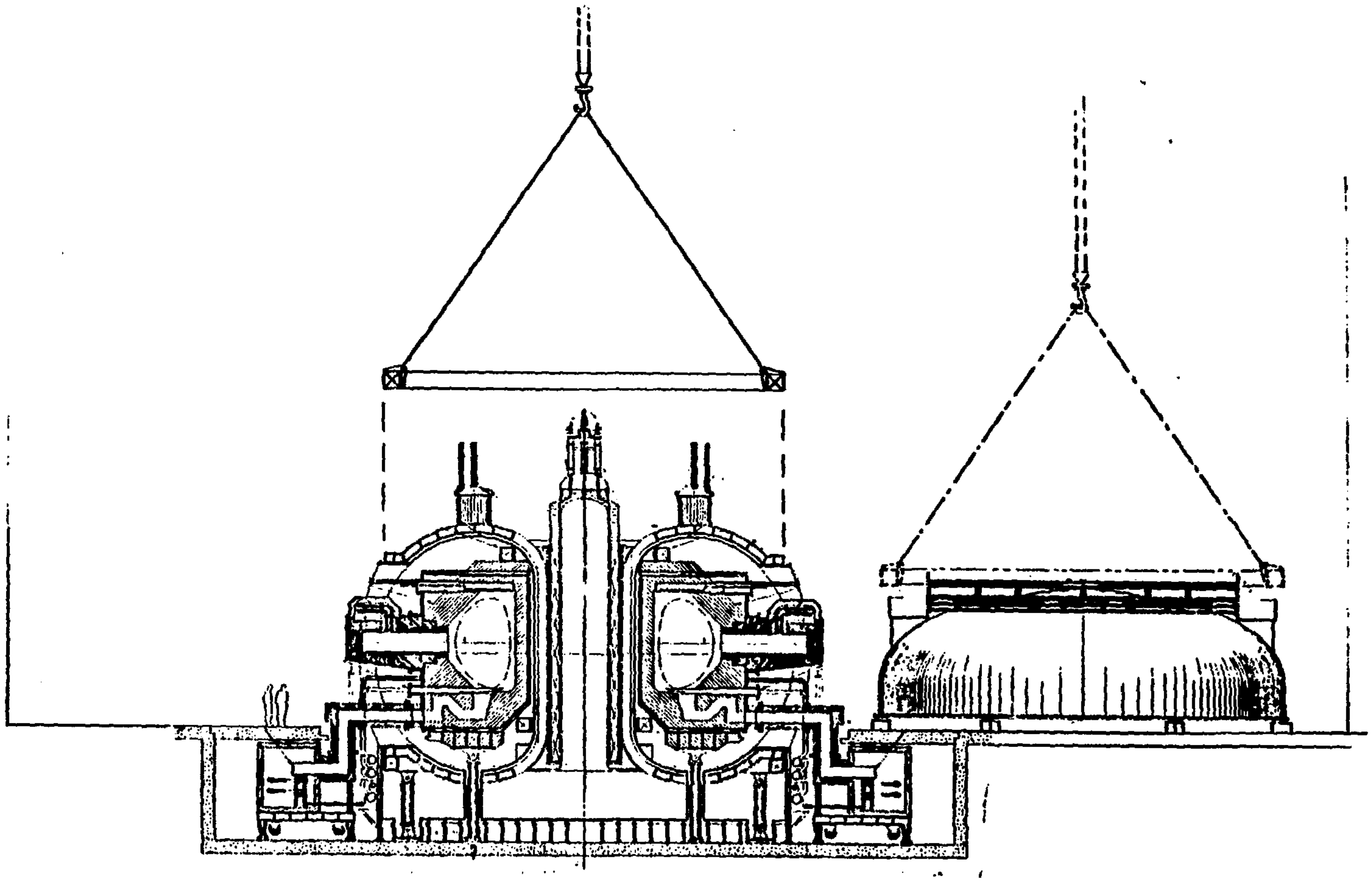

Fig. 2-8. EF coil #2 is stored in the laydown area on top of the dome.

Table 2-7. EF coil #2 replacement

	Steps	Mode of Operation	Duration (hrs)
1.	General device shutdown	A	
	Cryostat warmup	A	336
2.	Disconnect lines to solenoid	C	
	Remove central cover	R	
	Disconnect He and electrical lines of EF coil #2	C	
	Disconnect He reservoirs to TF coils (if pool boiling)	C	
	Remove cryostat dome bolts	C	
	Remove dome to laydown area	R	24
3.	Remove plate structure over coil	C	
	Install hoist fittings	C	
	Engage sling and lifting hook	C	
	Remove coil to laydown area	R	16
4.	Replace coil into device	R	
	Install plate structure	C	12
5.	Install dome and attaching bolts	R/C	
	Connect He reservoirs	C	
	Connect He and electrical lines of coil	C	
	Install central cover	R	
	Connect solenoid lines	C	24
6.	Cryostat cooldown	A	672
	General device startup	A	4
	TOTAL		1088 hrs (45.3 days)

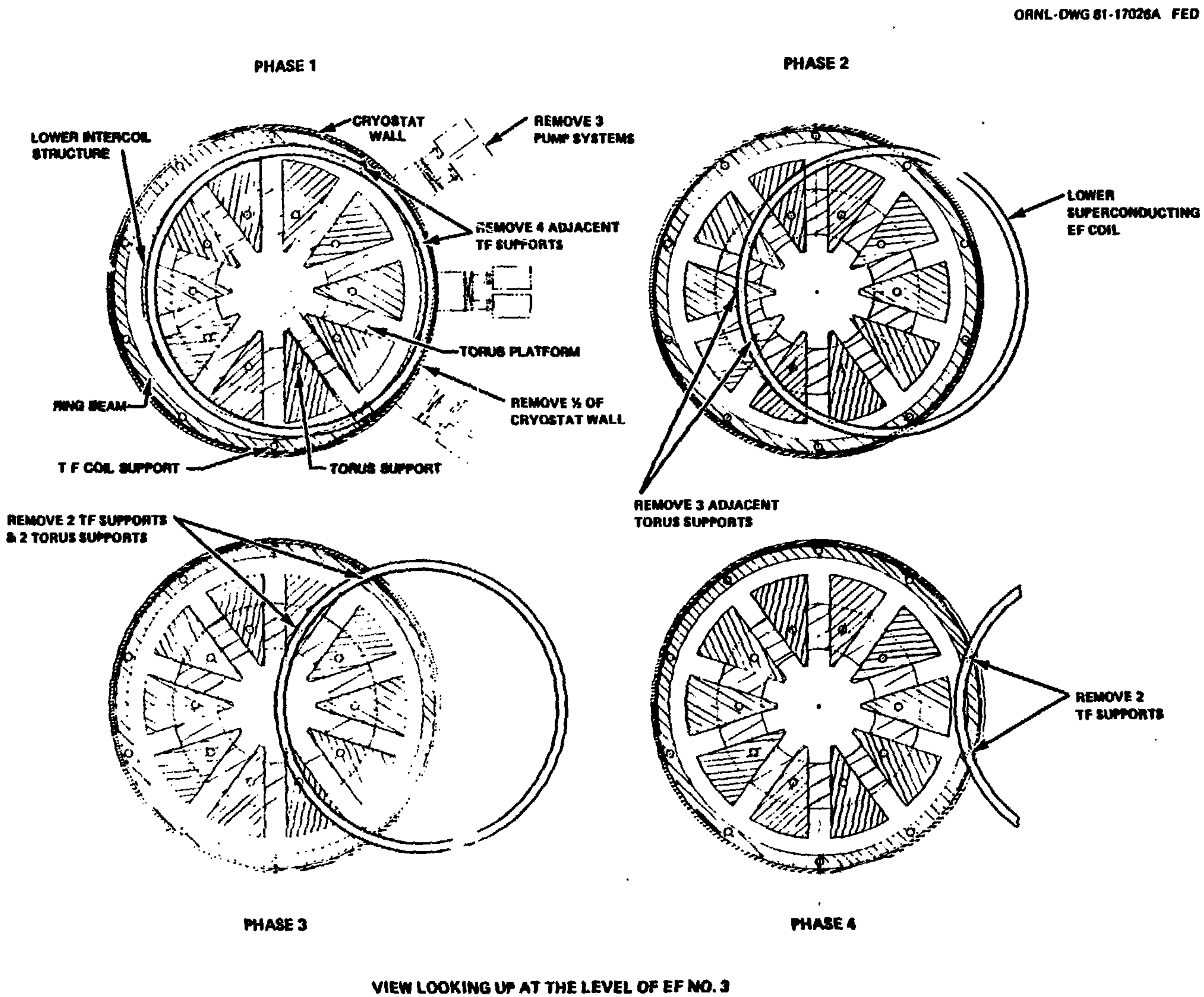

Fig. 2-9. Removal of EF coil #3 is a four-phase operation.

removed to create the pit area into which the coil is moved. One hundred and eighty degrees of the lower cryostat wall is disassembled next to provide access under the device. Mobile stands with jacks are then placed under the coil at 20 locations. They are used to lower the coil from its support in the lower TF structure and provide the means for moving it into the pit area.

In Fig. 2-9 it can be seen that the initial coil translation has the most significant impact on the support structure. Four adjacent TF columns require removal and consequently, the installation of at least two temporary supports under the intercoil structure. As the coil is moved outward, the supports are intermittently removed and replaced. The same procedure is followed when the coil intersects the torus support columns. When the coil is finally positioned in the pit area, it is removed with the overhead crane.

The reverse procedure is required for the installation of the replacement coil. The impact of this replacement operation on machine availability is severe considering the duration time of 7 months (see Table 2-8). It is obvious that a high degree of reliability for fail safe operation of the superconducting coils is essential.

EF coils #1 and #4

These are the two interior copper coils located above and below the plasma chamber. Locating the equilibrium field coil system close to the plasma has distinct performance advantages and results in a relatively simple coil system. It was originally thought that the vertical opening of the TF coil/cryostat window would provide the necessary access for coil replacement. As it turned out, the structural requirements for reacting the out-of-plane TF coil loads would not permit a large enough opening. Consequently, removal of these coils, particularly EF coil #4, is made extremely difficult because of limited access.

This problem is further compounded by the need for mechanical joints in the coils. Each turn is spirally wound so that disassembling a coil requires removing individual turns, layer by layer between joints. The coils are jointed at 180° to permit their initial installation as two

Table 2-8. EF coil #3 replacement

	Steps	Mode of operation	Duration (days)
1.	General device shutdown	A	1
	Cryostat warmup		14
	Remove pump systems	C/R	2
	Remove ducts and install shield plugs	R	1
2.	Remove reactor cell floor	C	21
	Remove lower cryostat wall	C	30
3.	Install mobile jacks	C	6
	Lower the coil assembly	C	1
4.	Remove (and replace) column supports as required	C	↓
	Install (and remove) temporary supports as required	C	↓
	Translate coil into pit	C	16
5.	Translate coil under device	C	↓
	Add and remove support structure as required	C	16
6.	Install coil	C	1
	Remove jacks	C	3
7.	Reassemble cryostat wall	C	45
	Install reactor cell floor	C	21
8.	Install ducts	R	1
	Install pump systems	R	2
	Cryostat cooldown	A	28
	TOTAL		209 days (7 months)

prefabricated segments. It has been assumed that the failed coil is cut up in place and removed, and the replacement coil installed in many layered pieces. This arrangement can require as many as several hundred joints for a 3-5 megamp coil.

A special-purpose manipulator system such as that shown in Fig. 2-10 may be required for disassembly of the mechanical joints. The figure shows the device positioned under EF coil #4. A summary schedule for the disassembly of these coils is presented in Table 2-9.

2.4.7 Fuel injector

The fuel injector system is a modular component consisting of the mechanical injector (either centrifugal or pneumatic) and a series of shielded duct sections. These can be separated from the plasma chamber by activating an isolation valve. The modules are track mounted on a support platform. The most likely module to experience failures is the mechanical injector which is located with abundant overhead and horizontal access. Like the pump system, it can be replaced without disturbing the vacuum integrity of the plasma chamber. It is estimated that a modular changeout of the injector system can be accomplished with contact operations, within one day after personnel entry into the reactor cell. Therefore, the total downtime will be less than two days, assuming spares are available.

2.4.8 Valves, pumps, ancillary equipment

The components in this category fit into the same mode of replacement as the fuel injector. If contact operations are an advantage, then <2 days of downtime can be expected. Many of these replacements may actually be done by remote means within the twenty-four hour shutdown period normally required for safe reactor cell access. This presumes that the components are designed to be efficiently handled by remote means.

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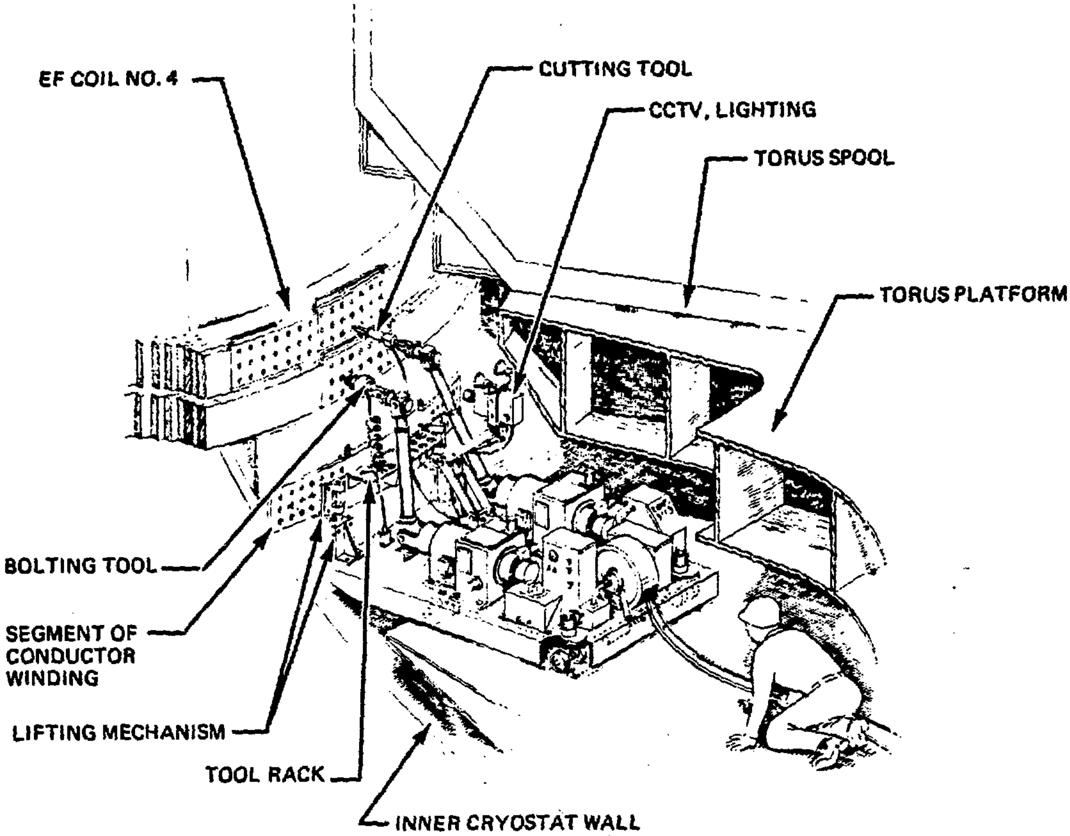

Fig. 2-10. Remote disassembly of EF coil #4.

Table 2-9. EF coil #4 replacement

	Steps	Mode of Operation[a]	Duration (hrs)
1.	General device shutdown	A	24
	Deenergize coils		
	Drain EF #4 of coolant		
	Activation decay to safe level		
2.	Remove limiter ducts (10)	C/R	40
	Install shield plugs (20)	R	40
	Lower coil onto platform	C/A	--
	Install tracks, hoists, disassembly tools; provide bay access as required	C	168
3.	Cut coil into segments and remove (300)	C	200
4.	Assemble and install jointed segments (300)	C	100
	Install bolts (3600)	C	100
	Braze coolant tubes (300)	C	25
	Insulate joints (300)	C	100
5.	Test completed system	C	48
	Remove tools and equipment	C	48
	Raise coil into position	A	--
	Remove shield plugs	R	20
	Install ducts	R/C	40
	Replace components cleared away for access	C	96
	TOTAL		1049 Hrs (43.7 Days)

2.4.9 TF coil

Replacement of a TF coil has a significant impact on device availability because it involves disassembling a large portion of the semi-permanent structure. The replacement scenario is presented in summary form as follows (refer to Table 2-10).

The two torus sectors adjacent to the failed TF coil are first removed. The open plasma chamber and the open vacuum ducts must then be covered with shield plugs in order to restore contact operations in the reactor cell for the remaining disassembly tasks. Removal of the cryostat dome is the next major disassembly and requires several intermediate steps (see Fig. 2-7):

1. Electrical and coolant leads to all PF and TF coils which emerge through the dome central cover are disconnected.
2. The dome central cover is removed using the overhead crane.
3. The ten helium reservoir interfaces on the dome are disassembled and removed (for pool boiling TF coils).
4. The circumferential interface of the dome flange to the cryostat is disassembled and the dome is moved to its laydown area using the overhead crane.

Removal of the upper external PF coil (EF #2) is accomplished using the overhead crane and is shown in Fig. 2-8. The laydown area for this large diameter coil is on top of the cryostat dome. Repositioning the lower external PF (EF #3) coil downward, clear of the TF coils, is the next major operation. This is accomplished using mechanical jacks. The exposed spool structure in the two adjacent open bays is the next major disassembly, and it is assumed that only half of each adjacent spool sector needs to be removed. An operation such as this will require extensive cutting of large, heavy structure and may also require the emplacement of temporary platforms and tracks to extract these components clear of the TF coil for overhead hoisting. At this stage, the disassembly and removal of a quadrant of each of the jointed interior coils, EF #1 and #4, are assumed. Each piece will weigh on the order of 20 tons and requires the use of boom-type cranes. The vertical frame support in the shadow

Table 2-10. TF coil replacement

Steps	Mode of Operation	Duration (days)
1. General device shutdown	A	1
Cryostat warmup	A	14
Remove two torus sectors and vacuum ducts	R	3
Install shield plugs		1
2. Remove cryostat dome	C	1
Rémove EF coil #2	C	1
Lower EF coil #3	C	7
3. Remove two half sectors of spool structure	C/R	12
Remove EF coils #1 and 4	C/R	4
Remove the vertical frame support	C	2
4. Remove cryostat surfaces	C/R	10
Remove a portion of the torus platform	C	2
Disassemble the intercoil structure	C	4
Unfasten the bucking cylinder interface	C	1
Translate the coil outward and up using the overhead crane	C	1
5. Replacement of the TF coil is assumed to take 50% longer than disassembly	C/R	75
6. Cryostat cooldown	A	28
TOTAL		168 days (5.5 mos)

of the TF coil is the next component to be removed. Because of the relative instability of this unsupported structure, large holding fixtures will be required during and after spool removal. Partial extraction is accomplished using the temporary platforms in order to clear the plane of the TF coil. Overhead hoisting then removes the frame because the cryostat dome (and hence the coil window) is not a constraint in this partially disassembled configuration. The inner cryostat surfaces which are also in the shadow of the TF coil are disassembled next. The cryostat containment around the outer leg of the coil can be left in place and removed as part of the TF coil assembly. (It may also be part of the initial TF coil assembly.) Disassembly of the inner cryostat wall and the spool requires extensive cutting of welded structure and therefore their joints must allow for the requirements of automated, remote equipment for both cutting and rewelding. Removal of all of these cut segments is through vertical access using the overhead crane. Removal of the torus platform structure in the plane of the TF coil is the last operation prior to removing the TF coil. The final step is to provide lateral and vertical support to the TF coil when unfastening the shear and moment connections to the bucking cylinder and the intercoil structure, and this is accomplished using the overhead crane. The crane then moves the coil outward and up after its outer leg support is unfastened.

The total time estimate for the TF coil replacement assumes that a spare coil is available.

3. Conclusions

The FED configuration is the result of the integration of component designs for all of the major systems and components. The changes from earlier design studies were based on evolutionary design studies and were partially derived from a better understanding of performance and cost and guided by the need to improve maintainability. Without the influence of maintenance considerations, each of the systems would have been developed around its own particular needs, and it is likely that the overall configuration would suffer from access and disassembly capability. Hence, configuration development must go hand-in-hand with device maintainability.

The purpose of this study was to gain a better understanding of FED maintenance and, specifically, to determine the impact of maintenance tasks on downtime. One fact that clearly emerges from studying the replacement scenarios for the major systems is that the unscheduled occurrences dominate the potential downtime of the device. Perhaps that should not be surprising, except that most of these components, even though they are high-reliability designs, do have some probability of failure. The results from this study indicate that further improvements in the configuration are highly desirable, so as to lessen the possible impact of component replacements on the operating lifetime.

Future work will include not only configuration changes related to the above discussion, but also more in-depth studies of disassembly which will further define the steps involved, their required time, and the maintenance equipment and concepts required. In addition, concepts for in-vessel inspection and operations will be investigated. These include routine inspection systems which do not impact device availability and a manipulator concept which can operate in the plasma chamber.