

11. DESIGN LAYOUT AND MAINTENANCE

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11. DESIGN LAYOUT AND MAINTENANCE

11.1. INTRODUCTION

The complexity of the maintenance operation and the required time for its completion are strongly influenced by the machine design and plant layout. The machine should be designed to permit rapid replacement of those components that are expected to need periodic maintenance and/or replacement. The plant layout must also provide easy access to those components. Because of this interconnection, operational and maintenance aspects of the ARIES-I reactor have been incorporated into the design process from the beginning. The maintenance philosophy of the ARIES-I reactor was developed through our examination of the maintenance procedures for commercial fission power plants, other conceptual fusion-reactor designs, and existing experimental fusion facilities (Sec. 11.2). The ARIES-I fusion power core (FPC) comprises 16 self-contained large-scale modules and the maintenance approach is based on replacing a complete large module as a single unit. All modules are pretested prior to installation in the reactor vault. The layout of the the ARIES-I FPC is described in Sec. 11.3 and those features relevant to the maintenance operation are emphasized. The procedure for removing the FPC modules is presented in Sec. 11.4 and alternative maintenance schedules are discussed. A summary and conclusions are given in Sec. 11.5.

11.2. MAINTENANCE PHILOSOPHY

The maintenance procedure for commercial fission power plants, other conceptual fusion-reactor designs [1-6], and existing experimental fusion facilities were reviewed in order to guide the maintenance approach for the ARIES-I design. In particular, the proposed plan for replacing one of the JET toroidal-field (TF) coils during the 1989-1990 shutdown [7], the proposed plan for replacing a superconducting TF coil in Tore Supra [8], and the proposed plan for replacing a TF coil of the compact ignition experiment (CIT) [9] were studied. This exercise illuminated key areas and issues for the maintenance of commercial fusion reactors.

11.2.1. Machine Design

The complexity of the maintenance operation and the required time for its completion are strongly influenced by the machine design and plant layout. For example, experimental fusion facilities are designed for research and, therefore, require numerous ports and windows to provide access for diagnostics and experiments. Window removal and port closure alone are estimated to take more than two weeks for the JET tokamak with equal or greater time needed for reinstallation. A commercial reactor does not need such windows and ports. Furthermore, experimental facilities are constantly modified for further research and the new equipment added to a facility, unforeseen in the initial design, further complicates the maintenance task. Lastly, changes in the machine design in order to facilitate maintenance operations may increase the initial cost of the system. An obvious example is that to provide ample work and transport area around the machine for maintenance operation, the size and cost of the building should be increased. Unfortunately, this investment is not usually made and results later in higher maintenance costs and/or lengthy maintenance.

By reviewing plans for various maintenance operations for existing experimental facilities, the following observations have been made, which can lead to drastic reduction in the maintenance time for a fusion facility. Most of these observations simply allow for ready access to components that have to be replaced.

- Avoid the need to remove other components to access the component that must be replaced.
- Make components structurally independent of any neighboring components that may be removed. This will eliminate any need for temporary support for components that do not have to be replaced.
- Minimize the number of welds to be cut and re-welded. Eliminate complex welds and provide easy access to components to be welded.
- Minimize the number of coolant supplies that have to be connected and disconnected; coolant leaks, especially at coolant joints, are major sources of failures.
- Minimize the number of connects and disconnects for electric power leads. Locate all power leads close to each other so that the appropriate jumpers can be removed simultaneously.

- Provide ample work and transport area for manipulators (or robots) and transport equipment. Locate ancillary equipment away from these areas.
- All components are subject to failure, hence, the procedure and the necessary tools for replacing every component should be included in the design.
- The machine design and maintenance procedures should allow for modifying and upgrading components without impacting maintenance time and availability.

11.2.2. Remote Maintenance and Robotics

Currently, remote maintenance and robotics in some of the existing (and planned) fusion facilities and commercial fission reactors is mostly limited to remote manipulators controlled by a human operator. Experience indicates that the remote manipulator takes from 3 to 10 times longer than hands-on operation by humans to perform the same task. This difference should be expected since the manipulator performs the maintenance operation in series (one at a time) and, at best, can only match the speed of a human operator. The limitations in the capability and flexibility of the manipulators reduce the speed of maintenance operation, with the fastest speed (threefold increase over hands-on) accomplished by modifying the machine design and by extensive mock-up testing before the machine is constructed. Because of this increased maintenance time (and cost), the remote manipulators are currently used only for operations that are hazardous to human workers.

Contrary to the above experience is the explosion in the use of robots in factories during the last decade. For example, assembly lines for automobile manufacturing use robots for welding, painting, *etc.* These robots perform faster, cheaper, and with better quality control than human workers because: (1) robots perform repetitive jobs and different robots perform different jobs, (2) the work can be performed automatically because it is repetitive, (3) many robots can work simultaneously to finish the work faster.

The above observations indicate that, rather than using manipulators with human operators, the maintenance operations for a fusion facility should be standardized and highly automated so that robots can be utilized. The maintenance approach to unscheduled events should be similar to that for scheduled events, and work in the reactor vault should be limited to replacing components. Repairs to failed components, if desired, should be made afterward and outside of the reactor vault.

11.2.3. ARIES-I Maintenance Philosophy

The observations from the previous two subsections were included in the machine design and plant layout. The ARIES-I maintenance philosophy is based on high degrees of standardization and automation. Therefore, the ARIES-I FPC is composed of 16 large-scale modules that are identical. The FPC modules are self-contained and structurally independent of any neighboring component.

The large-scale modularity and standardization allows the maintenance of the FPC for both scheduled and unscheduled events to be similar, basically by replacing a complete module. The only exception is the divertor system, which is under considerable thermal and particle loads and may need frequent replacement. For this case, ports are provided to replace the divertor system unit only, instead of replacing the complete FPC module containing that specific divertor module. In order to facilitate the maintenance procedure, several FPC modules, all pretested to full operational condition, are kept on site for immediate installation in the reactor vault in case of unscheduled events. Lastly, the large-scale modularity of the system allows modification in the design of each FPC module since each is self-contained.

A detailed description of the ARIES-I design and layout is given in the next section. The maintenance procedure is described in Sec. 11.4.

11.3. DESIGN DESCRIPTION/INTEGRATION

The ARIES-I FPC comprises 16 self-contained modules. Modularity has been used in other reactor design studies to obtain high reliability due to extensive module pretesting and high availability through reduced downtime for scheduled and unscheduled component replacement [1-3]. Each of the ARIES-I FPC modules consists of one toroidal-field (TF) coil, two inboard and two outboard first-wall, blanket, and shield sub-modules, two upper and lower divertor targets with support structure, and a section of the vacuum vessel. One of the FPC modules must have a modified outboard first-wall and blanket sub-module to accommodate the installation of the folded-waveguide RF launching structure. The bottom of the launching structure sits at the outboard mid-plane of the reactor and extends vertically about 1.2 m. An elevation view of the ARIES-I reactor is shown in Fig. 11.3-1. The self-contained FPC module is shown in Fig. 11.3-2. A mid-plane radial build with reference dimensions is shown in Fig. 11.3-3.

Each module contains primary coolant, tritium purge, and diagnostic systems in order to minimize the number of inter-module connections. The only interfaces between

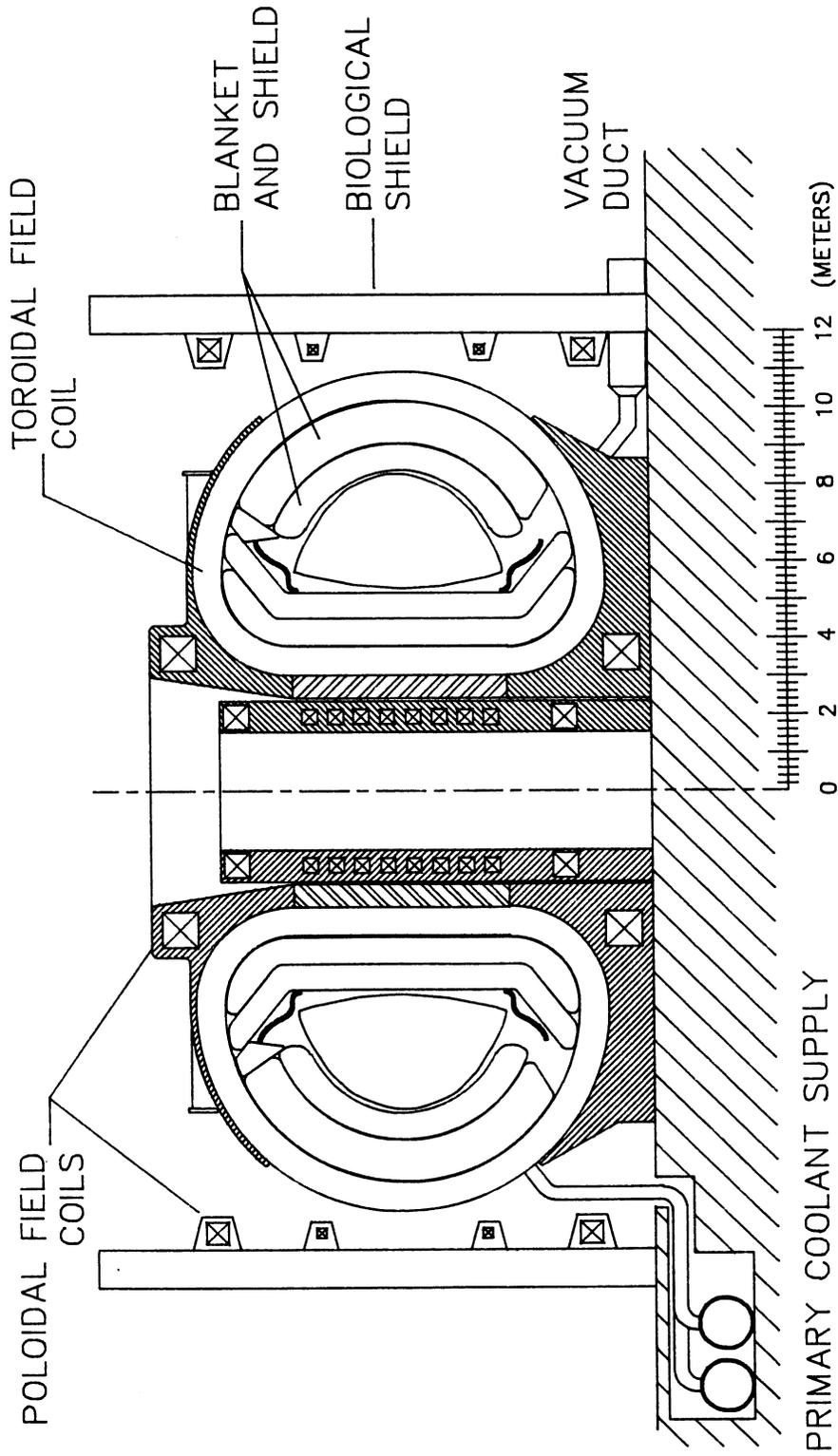


Figure 11.3-1. Elevation view of the ARIES-I fusion power core.

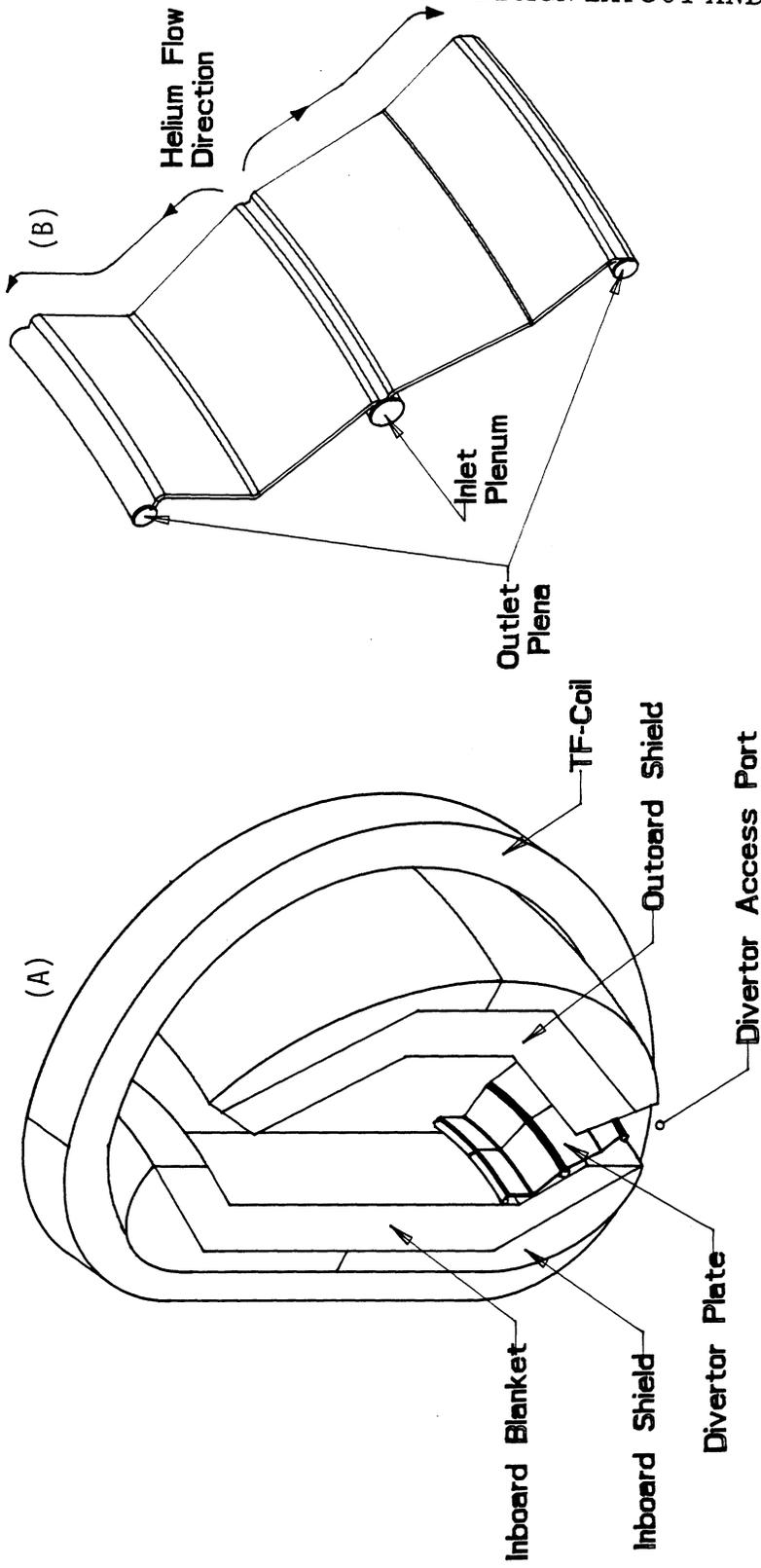


Figure 11.3-2. (A) The ARIES-I self-contained FPC module and (B) the divertor system.

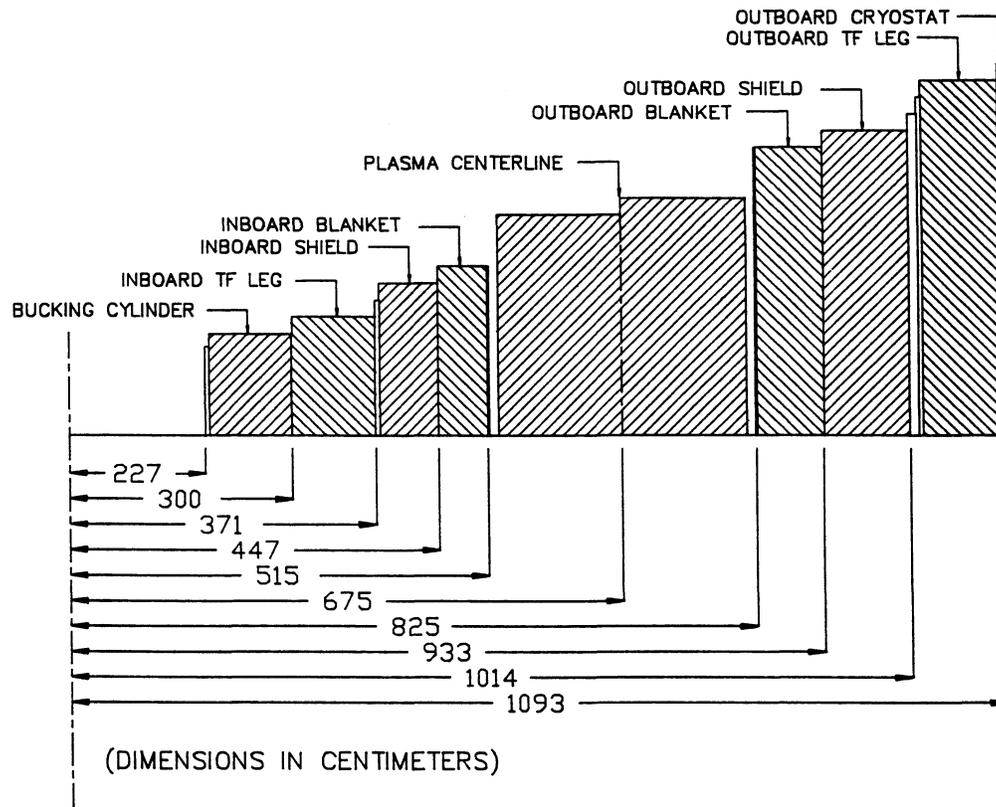


Figure 11.3-3. Mid-plane radial build of the ARIES-I fusion power core.

modules are the welds in the vacuum vessel located behind the shield, and the alignment and support structure for module installation. The vacuum boundary for the cryostat of the TF coil mates with the cryostats of the bucking cylinder and the torque shells. This configuration reduces size and heat leakage because the magnetic loads are carried from the coil to the support structure via cold-to-cold interfaces. Located away from the FPC, but still in the reactor building, the primary coolant circuits from each module are connected to large ring headers that supply the primary coolant to the remainder of the primary loop (*e.g.*, coolant circulators, steam generators, *etc.*). Similarly, the tritium purge streams are grouped together to supply the tritium recovery system. Remotely actuated connect/disconnects are provided on each module to facilitate module removal without interfering with the neighboring modules.

The detailed description of the ARIES-I first-wall, blanket, and shield design is given in Sec. 8. The ARIES-I FPC design uses silicon-carbide/silicon-carbide (SiC) composite as the structural material, 10-MPa helium as the coolant, Li_2ZrO_3 as the solid tritium breeder, and beryllium metal sphere-pac pellets as the neutron multiplier. The blanket is segmented toroidally into 32 inboard and 32 outboard poloidal modules. Each poloidal

module comprises 17 nested, U-shaped, SiC-composite shells. The sphere-pac solid-breeder and Be neutron-multiplier mixture is located between the shells. The cylindrical helium-coolant channels are embedded in each of the 17 SiC-composite shells. The helium coolant enters the blanket from the inlet plena which are located in the shield behind the blanket and reflector. It then flows radially inward through the shells. It cools the shells while flowing in the toroidal direction before it turns and flows radially back into the coolant outlet plena. This routing configuration was selected to provide adequate cooling of the blanket materials and to minimize the blanket pressure drop. The maximum blanket pressure drop of 22 kPa is at the first wall. The corresponding total blanket internal- and external-loop pumping power is a completely acceptable 19 MW.

The shield incorporates multiple layers of aluminum sheets sandwiched between He-cooled, SiC shells to provide passive stabilization against vertical motion of the plasma. There are 40 layers of 1-mm-thick aluminum sheets and 40 layers of 19-mm-thick SiC shells for an overall shield thickness of 0.8 m. The SiC shells, with internal passages for helium flow, are manufactured by using the same method as is used for the blanket shells. All of the aluminum sheets within a module are electrically connected together at the back of the shield. Neighboring shield modules are also electrically connected together with a detachable jumper to provide a complete toroidal circuit.

An important design criteria for any tokamak reactor is that the FPC should survive plasma disruptions. Since the ARIES-I FPC is made of SiC composite, the only electrically conducting materials in the FPC are the passive-stabilization aluminum sheets and the vacuum vessel. Analysis shows that most of the electromagnetic forces generated by a plasma disruption appear on the aluminum sheets and, in effect, the aluminum shells shield the vacuum vessel from disruption forces. The disruption-induced electromagnetic forces generated in each of the aluminum sheets are restrained by the neighboring SiC shells.

The ARIES-I FPC design provides an ideal solution for supporting disruption forces: no forces appear on the delicate first-wall and blanket components, and the forces are distributed more or less uniformly in the shield where they are absorbed and reacted by a massive structure. Very detailed analyses are needed to confirm this attractive feature of the ARIES-I design. The cumulative thickness of the aluminum layers is 40 mm, albeit the conductor is distributed as 40 layers over the entire 0.8-m-thick shield and connected toroidally behind the shield between neighboring modules. Additional analysis of this configuration is necessary to verify its exact performance in providing passive stabilization. Analysis is also needed to confirm the location and magnitude of the disruption-induced forces and to ensure that these forces are not localized.

The vacuum vessel is outside of the shield and is made of a low-activation steel. When an individual FPC module is to be removed (or installed), welds in the vacuum vessel must be either cut (or re-welded). This procedure must be performed with remote maintenance equipment. The top, bottom, and outboard weld seams have relatively good access for remote welding tools, cutters, *etc.* The inboard vertical leg of the vacuum vessel, however, lies very near the straight leg of the TF coil and a vertical access tunnel must be provided so that tools can be manipulated to seal or cut this weld seam. If neutron shielding is unacceptably reduced by this access tunnel, a shield plug must be installed after the welding procedure is complete.

Although no appreciable disruption-induced forces are expected to load the vacuum vessel, it must still support and carry the weight of the FPC module components (except the TF coils) and any electromagnetic forces that are absorbed by the shield and transferred to the vacuum vessel. These forces are then carried to support pads in the lower torque shell and the total weight of the assembly is subsequently transferred to the foundation of the reactor building.

The large-scale modular maintenance procedure for ARIES-I requires the TF coils to be removable. This maintenance constraint is included in the TF-coil design. Support of the electromagnetic forces acting on the TF coils is provided by three structural members: two torque shells and a bucking cylinder (Fig. 11.3-1). The torque shells are axisymmetric toroidal caps that counteract the overturning forces in the upper and lower hemispheres. The arrangement of loads is such that comparatively small forces have to cross the machine mid-plane, most being balanced in their own hemisphere. The small overturning forces at the outboard mid-plane are constrained by stiffness of the leg of the TF coil. The bucking cylinder restrains the inward radial forces of the TF coil, as well as a small overturning force on the inner leg of the coil. There is zero torque on the components where the top and bottom of the bucking cylinder meet the torque shells. There is little or no force transmitted between the cylinder and the shells and, therefore, very little interconnecting structure is required. Because of this structural arrangement, only removal of the upper torque shell is needed in order to access and replace each FPC module. The detailed structural analysis for this design is given in Sec. 7.

Another important component from the maintenance point of view is the cryostat for the TF coils. Instead of a large cryostat for the entire device, each coil has its own cryostat with two kinds of exterior surfaces. The first, occurring over the entire bore surface and some of the sides and outer surface, is the conventional type and the vacuum vessel is the visible component. The inward progression is the super-insulation and heat-shield layers within the vacuum, followed by a structural helium vessel and conductor

matrix (or a matrix containing small-scale helium confinements such as tubes with the case being only structural).

The second type of exterior surface is visible and exposes the face, completely unin-sulated, of the helium vessel or other major structural case. At the periphery of this face, a G10 plate connects the edges of the conventional exterior surface and the visible cryogenic components, forming a continuous flat face. Although this face is vacuum sealed, the magnet is not operable in this face-exposed condition because the matrix is not coolable with one face of its casing exposed to air. For magnet operation, each of these exposed faces must butt against an identical face in an adjacent FPC module, the bucking cylinder, or the torque shells. After the faces are aligned, the cryostat is evacuated and cool-down can begin. A typical TF coil with the interface surface is shown in Fig. 11.3-4.

Application of this new, cold-face concept eliminates the need to carry very large loads from cold to warm structural elements. When the heat leakage resulting from out-of-plane forces is calculated on a basis of cold-to-warm structure requirements, it is 10 times higher for a conventional design than for the proposed ARIES-I cold-face cryostat system. Moreover, because the cryostat system also deals with the center-post butting forces, the total benefit would be several times larger (*i.e.*, a factor of 50 over conventional design). Additionally, at least 0.15 m of space on each of the coil cross-section dimensions is saved. The use of the cold-face cryostat gives a new capability to avoid heat leak and allow for TF-coil removal. This cold-face interface concept, however, requires the machining of large components with more precision than is necessary for a conventional design.

The poloidal-field (PF) coil set forms an annulus (with inner and outer solenoids of, respectively, six and four coils) surrounding the FPC. Two additional shaping coils are required near the \times -point of the divertor. The upper torque shell and the upper shaping coil must be removed to access the FPC modules. The lower shaping coil is "trapped" beneath the FPC assembly and the lower torque shell. Direct access to the lower coil can be provided with a below-grade vault in the basement of the reactor building. However, if the combination of dead weight and operating forces of the FPC preclude the use of cavities in the basement of the reactor vault, then access to the lower shaping coil will require removal of the FPC assembly and both torque shells. Fortunately, all of the PF coils are designed to perform for the lifetime of the plant and access is not expected to be necessary.

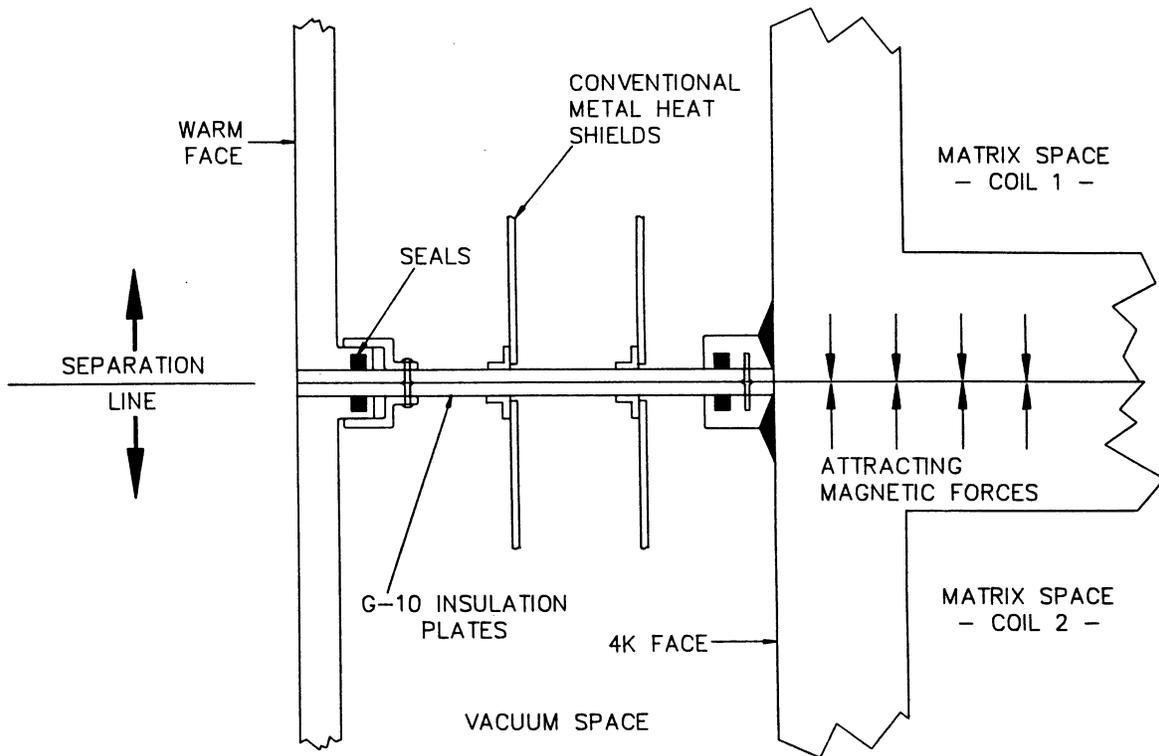


Figure 11.3-4. Cold-face cryostat showing cold-to-cold surface interface.

11.4. ARIES-I MAINTENANCE PROCEDURE

The ARIES-I maintenance procedure for both scheduled and unscheduled events centers around FPC module replacement. Although the list of tasks to be performed during the maintenance of the FPC is extensive, the major tasks for ARIES-I FPC module removal and replacement are:

1. Shut down the plasma in an orderly fashion by slowly reducing the plasma fueling rate.
2. Prepare the FPC components for maintenance operation (the following activities are done in parallel):
 - A. Continue primary coolant flow at reduced rate, as required, to remove decay afterheat;
 - B. Continue tritium purge flow. Control the primary-coolant flow rate and inlet and outlet temperatures and tailor the temperature distribution in the breeder to hasten the removal of tritium;

- C. Continue vacuum pumping, as necessary, to remove tritium from the plasma chamber;
 - D. Discharge the magnets and begin to warm up the cryogenic systems associated with the necessary maintenance (the external PF coils can remain cold during maintenance of the FPC modules).
3. Valve-off and disconnect supply lines for cryo-fluids, primary coolant, and electrical power. Only service to affected modules and components should be removed. Because rapid removal of the FPC modules relies on "grouping," as many supply lines as possible will be grouped together into a single remote connect/disconnect. Similarly, when a single supply splits into several sub-feeds on one module, the remote connect/disconnect will be located on the single main supply.
 4. Break the vacuum in the plasma chamber and cut the welds of the module(s) to be removed.
 5. Lift the upper superstructure [Fig. 11.4-1(A)] and transport it to a temporary storage area.
 6. Lift the modules that are to be replaced and transport them to a hot cell where they can be serviced after the reactor is back on line [Fig. 11.4-1(B)].
 7. Install new, pretested modules and re-weld the plasma chamber vacuum vessel.
 8. Reinstall the TF-coil superstructure.
 9. Connect the vacuum systems to the plasma chamber and cryostat and begin pump-down. Concurrently, the coolant, electric power, and cryo-fluids supplies are reconnected.
 10. Test reactor systems and begin start-up activities.

This procedure is used for both scheduled and unscheduled events. The FPC modules are tested to full operational capability so that undetected defects may become evident. A few pretested modules are kept on site at all times for immediate installation in the reactor vault. Minimum repair is performed in the reactor vault. Instead, the module containing the failed component is removed and replaced with a new module. After the reactor is back on line, the modules that have been removed can be serviced for later use and/or prepared for recycling and waste disposal.

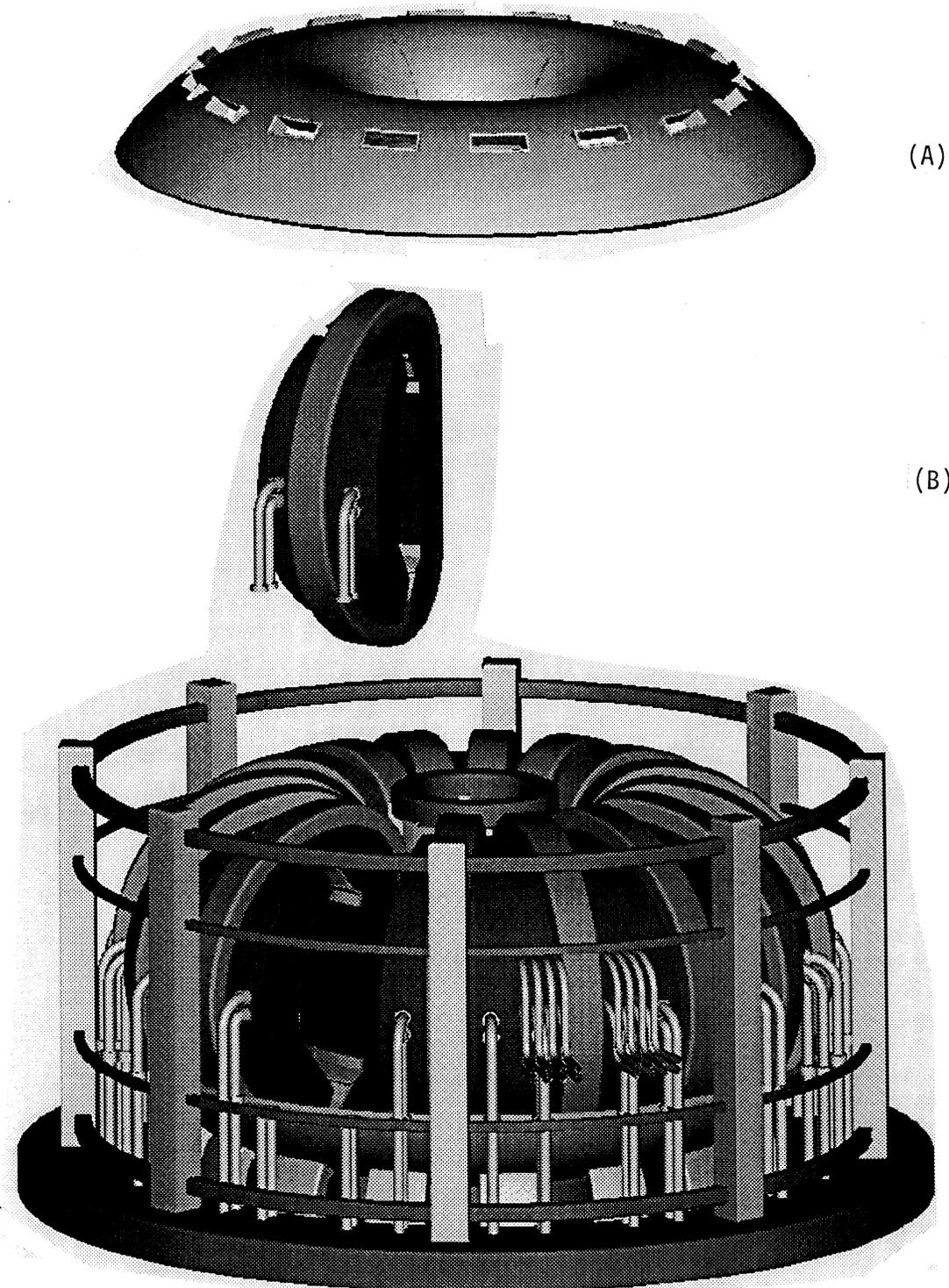


Figure 11.4-1. Schematic of the movement of components during removal and replacement of an ARIES-I FPC module: (A) Removal of the upper superstructure and (B) Removal of a complete FPC module.

The scheduled maintenance of the ARIES-I reactor consists of yearly maintenance of the balance of plant ($t_{BOP} = 28$ d) and replacement of the first-wall and blanket modules. The lifetime of the first wall and blanket is estimated to be 20 MWy/m², based on radiation damage to the SiC-composite structure. Therefore, with a peak neutron wall load of 3.7 MW/m² and a plant availability of 76%, the first-wall and blanket lifetime is about 7 years. Several scenarios were devised for the module replacement program, all of which result in complete replacement of all modules over a 7-year period:

1. Replace 2 modules every year for 5 years and replace 3 modules during each of the next 2 years, for a total replacement of all 16 modules in 7 years.
2. Replace 4 modules (one-quarter of the FPC) every other year.
3. Replace 8 modules (one-half of the FPC) every 4 years.
4. Replace all 16 of the modules at the end of life (every 7 years).

Of the four above options, the one that yields the highest availability is preferable. A simple model was constructed to analyze these options. The availability of the reactor, p_F can be written as

$$p_F = 1 - \frac{t_s + t_u}{365}, \quad (11.4-1)$$

where t_s and t_u are, respectively, the yearly scheduled and unscheduled maintenance times. During the yearly scheduled period, maintenance of both the balance of plant (BOP) and the FPC is performed. Therefore, t_s is the maximum time for BOP maintenance (t_{BOP}) and for FPC maintenance (t_{FPC}):

$$t_s = \begin{cases} t_{BOP} & t_{BOP} > t_{FPC} \\ t_{FPC} & t_{BOP} < t_{FPC} \end{cases}. \quad (11.4-2)$$

The replacement procedure for the ARIES-I FPC modules contains certain tasks that are common and independent of the number of modules that have to be replaced (items 1, 2, 5, 8, and 10 of the ARIES-I module replacement list, p. 11-11). Denoting t_{com} as the duration of these common tasks, t_{mod} as the time to replace the first module, αt_{mod} as the time to replace subsequent modules, the time to replace n_{mod} modules is

$$t_{FPC} = t_{com} + t_{mod} [1 + \alpha(n_{mod} - 1)]. \quad (11.4-3)$$

If $\alpha = 1$, the maintenance of modules is performed in series (*i.e.*, maintenance operation on a subsequent module starts after the previous module is completely removed). However, most of module-removal tasks can be performed concurrently (*i.e.*, the coolant and electrical supplies to the next module can be disconnected while the first module is being removed). For these cases, $\alpha < 1$. Even a value of $\alpha = 0$ can be achieved if each module has its own dedicated set of equipment.

In order to simplify the analysis, it is assumed that the lifetime of the FPC modules is 8 years (instead of 7 years for ARIES-I). The scenarios examined are: replace 2 modules each year, 4 modules every 2 years, 8 modules every 4 years, and 16 modules every 8 years ($t_{FPC} = 0$ for those years that no modules are replaced). Values of $t_s = 28$ d and $t_u = 60$ d are used, which are the reference parameters for the ARIES-I design. A total of 8 years of operations is considered and the availability of the reactor is averaged over these 8 years. Because of lack of data regarding t_{com} , t_{mod} , and α , the impact of these variables was examined parametrically. Table 11.4-I summarizes the results of this analysis for $t_{com} = 7, 14, \text{ and } 28$ d, $t_{mod} = 2, 7, \text{ and } 14$ d, and $\alpha = 1$ and 0.5. For those cases with $t_{FPC} < t_{BOP}$, the availability is determined by yearly scheduled BOP maintenance and is 0.759.

The results from Table 11.4-I indicate that the ratio of t_{com}/t_{BOP} is the major deciding factor in choosing among various module-replacement options. Examining cases with $\alpha = 1$, if $t_{com} = t_{BOP}$ (28 d for ARIES-I), the maintenance time for the FPC is always longer than t_{BOP} and the difference is the time needed for module change out. For this case, all four module changeout options yield the same availability. If $t_{com} < t_{BOP}$, it is beneficial to replace the modules gradually (*i.e.*, replacing 2 modules each year yields higher availability). On the other hand, cases with $t_{com} > t_{BOP}$ are expected to favor replacement of all modules simultaneously.

Reducing parameter α results in an improvement in availability for all cases. Lower values of α also reduce the ratio of t_{com}/t_{BOP} that distinguishes between yearly and complete module replacement (16 modules every 8 years). This observation underlines the importance of performing maintenance tasks in parallel.

Lastly, even with long t_{com} and t_{mod} , the minimum availability value is 0.682 (0.718 for $\alpha = 0.5$ and replacement of all modules). This rather small drop in the availability reflects the fact that unscheduled maintenance time is dominant in setting the availability values. Analysis of unscheduled maintenance time, t_u , requires data on mean time-to-failure and mean time-to-repair for various components. Because of the lack of data, this analysis was not performed. Rather, attempts have been made to standardize maintenance operations so that unscheduled events can be handled by the scheduled

Table 11.4-I.
Average Plant Availability as a Function of
Number of Modules Replaced Every Number of Years

t_{com} (d) ^(a)	t_{mod} (d) ^(b)	2 mod/y	4 mod/2 y	8 mod/4 y	16 mod/8 y
<u>For $\alpha = 1$^(c)</u>					
7	2	0.759	0.759	0.759	0.755
7	7	0.759	0.749	0.735	0.728
7	14	0.740	0.711	0.697	0.689
14	2	0.759	0.759	0.758	0.753
14	7	0.759	0.740	0.730	0.725
14	14	0.721	0.701	0.692	0.687
28	2	0.748	0.748	0.748	0.748
28	7	0.721	0.721	0.721	0.721
28	14	0.682	0.682	0.682	0.682
<u>For $\alpha = 0.5$^(c)</u>					
7	2	0.759	0.759	0.759	0.759
7	7	0.759	0.759	0.752	0.746
7	14	0.759	0.740	0.730	0.725
14	2	0.759	0.759	0.759	0.758
14	7	0.759	0.754	0.747	0.743
14	14	0.740	0.730	0.725	0.723
28	2	0.751	0.752	0.753	0.753
28	7	0.730	0.735	0.737	0.739
28	14	0.701	0.711	0.716	0.718

^(a) t_{com} is the time required to perform common tasks regardless of the number of modules to be replaced.

^(b) t_{mod} is the time required to replace the first FPC module.

^(c) αt_{mod} is the time required to replace the second (& subsequent) FPC module.

maintenance methods and equipment. It is expected that pretesting the FPC modules and standardizing maintenance procedures will reduce unscheduled maintenance time.

The reference maintenance scenario for the ARIES-I reactor is based on replacing two modules every year, because it is anticipated that two weeks is sufficient time to perform common FPC maintenance tasks ($T_{mod} = 14$ d). As a result, the yearly FPC maintenance can be performed within the allotted 28 d for BOP maintenance. If t_{com} exceed 28 d, then a less frequent replacement schedule would become preferable for achieving the highest availability possible. The dramatic impact of reactor maintenance and availability to reactor economics should be emphasized. For a 1000-MWe power plant with a cost of electricity of 70 mill/kWh, a decrease of plant availability from 76% to 75% costs the utility company \$6 M every year.

11.5. CONCLUSIONS

The complexity of the maintenance operation and the required time for its completion are strongly influenced by the machine design and plant layout. Because of this interconnection, operational and maintenance aspects of the ARIES-I reactor have been incorporated into the design process from the beginning. The maintenance philosophy of the ARIES-I reactor was developed through our examination of the maintenance procedures for commercial fission power plants, other conceptual fusion-reactor designs, and existing experimental fusion facilities.

The ARIES-I maintenance philosophy is based on a high degree of standardization and automation. Therefore, the ARIES-I FPC comprises 16 large-scale, identical modules. The FPC modules are self-contained and structurally independent of any neighboring component. Each of the modules consists of one toroidal-field (TF) coil, two inboard and two outboard first-wall, blanket, and shield sub-modules, two (upper and lower) divertor targets with support structure, and a section of the vacuum vessel. The limit to the number of components within a module is principally determined by the total mass of the module to be transported. Since the TF coils are removed during module replacement, a removable cryostat seal is used which does not require the cutting and joining of welds to remove cryogenic structures, further reducing the time required for maintenance.

Each module is replaced as a single unit during both scheduled and unscheduled events. Furthermore, all modules are pretested prior to installation in the reactor vault so that undetected defects become evident and high reliability can be achieved. As a

result, new modules are always available for immediate installation in the reactor vault. Minimum repair is performed in the reactor vault. Instead, the module containing the failed component is removed and replaced with a new module. After the reactor is back on line, the modules that have been removed can be serviced for later use and/or prepared for recycling and waste disposal.

Several different maintenance schedules have been evaluated. Consideration has been given to whether annual, two-module replacement or replacement of all 16 modules every 8 years is preferable. Since the modules are self-contained, the interfaces with neighboring modules and support structure should be few. It is anticipated that two modules can be replaced within the allocated 28-day annual scheduled maintenance period. The schedule allows for one week each to remove and replace the two modules and two weeks for common maintenance activities, resulting in an overall plant availability of 76% (including 60 days for unscheduled maintenance). If module replacement and other associated activities require much more than the allocated 28 days per year, then a less frequent replacement schedule may be preferable to achieve the highest availability possible.

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