20. TITAN-II MAINTENANCE PROCEDURES

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20.1. INTRODUCTION

The TITAN reactors are compact, high-power-density designs. The small physical size of these reactors permits each design to be made of only a few pieces, allowing a single-piece maintenance approach [1,2]. Single-piece maintenance refers to a procedure in which all of components that must be changed during the scheduled maintenance are replaced as a single unit, although the actual maintenance procedure may involve the movement, storage, and reinstallation of some other reactor components. In TITAN designs, the entire reactor torus is replaced as a single unit during scheduled maintenance. Furthermore, because of the small physical size and mass of the TITAN-II FPC, the maintenance procedures can be carried out through vertical lifts, allowing a much smaller reactor vault. The advantage of using fully toroidal units with vertical lifts for maintenance has been verified in some fusion experiments [3].

The single-piece maintenance procedure is expected to result in the shortest period of downtime during the scheduled maintenance period because: (1) the number of connects and disconnects needed to replace the components will be minimized and (2) the installation time is much shorter because the replaced components are pretested and aligned as a single unit before committment to service. Furthermore, recovery from unscheduled events will be more standard and rapid because complete components are replaced and the reactor is brought back on line. The repair work will then be performed outside the reactor vault.

A single-piece maintenance of the entire reactor torus (including the first wall, blanket, and divertor modules) will have the additional benefits of: (1) no adverse effects resulting from the interaction of new materials operating in parallel to radiation-damaged material; (2) complete and extensive testing of the entire torus assembly can be performed before commitment to service, which is expected to result in increased reliability; and (3) it will be possible to continually modify the torus assembly as may be indicated by the reactor performance and technological developments and to fully exploit the learning curves.

In this section, the layout of the main power-plant buildings (Section 20.2) and the proposed maintenance procedures for the TITAN-II reactor (Section 20.3) are presented. A comparison of the TITAN-II single-piece maintenance procedure with a modular approach is difficult because: (1) the TITAN-II fusion power core (FPC) is designed so that the advantages of a single-piece approach are fully utilized and a different design should have been produced to compare and quantify the benefits of single-piece maintenance procedures, (2) little data is available on times that would be required for each step during the maintenance procedure, and (3) data are needed on "mean time-to-failure" and "mean time-to-repair" of various components in order to quantify the impact of the maintenance procedure on the overall plant availability. Therefore, only those steps that are likely to be different between single-piece and modular approaches have been identified. Pretesting of the reactor torus to full operating condition is one of the potential advantages of the TITAN-I and TITAN-II single-piece approach. Pretesting of TITAN reactors is discussed in Section 14.4 and, thus, is not reported here.

20.2. TITAN-II PLANT LAYOUT

The elevation view of the TITAN-II design is shown in Figures 20.2-1 and 20.2-2. All of the TITAN-II maintenance procedures are performed with vertical lifts. As a result, the reactor vault and reactor building are smaller. The vertical lift of various components is performed by a moveable bridge crane. The heaviest components are the reactor torus weighing about 180 tonnes and the moveable upper OH-coil set (120 tonnes). Vertical lift of these components is easily manageable by existing cranes (conventional bridge cranes have a lift limit of about 500 tonnes and special-order cranes are available with lift limits exceeding 1000 tonnes).

The lifetime of the TITAN-II reactor torus (including the first wall, blanket, shield, and divertor modules) is estimated to be in the range of 15 to 18 MW y/m^2, and the more conservative value of 15 MW y/m^2 will require the change-out of the reactor torus (including the toroidal-field coils) on a yearly basis for operation at 18 MW/m^2 of neutron wall loading with 76% availability. The toroidal-field coils would be reused at a later date.

The TITAN-II reactor is a "loop-in-pool" design which is cooled with an aqueous solution of a dissolved lithium salt, $LiNO_3$. The major feature of the TITAN-II reactor is that the entire primary loop is located the bottom of a low-temperature, atmospheric-pressure, pure-water pool (Figure 20.2-1). Detailed safety analyses have been performed (Section 19) which show that the TITAN-II pool can contain the afterheat energy of the FPC and will remain at a low enough temperature such that tritium or other radioactive material in the primary-coolant system will not be released.

The first wall and blanket of the TITAN-II design consist of stamped side plates made of the low-activation, high-strength ferritic steel alloy, 9-C [4]. These plates, called

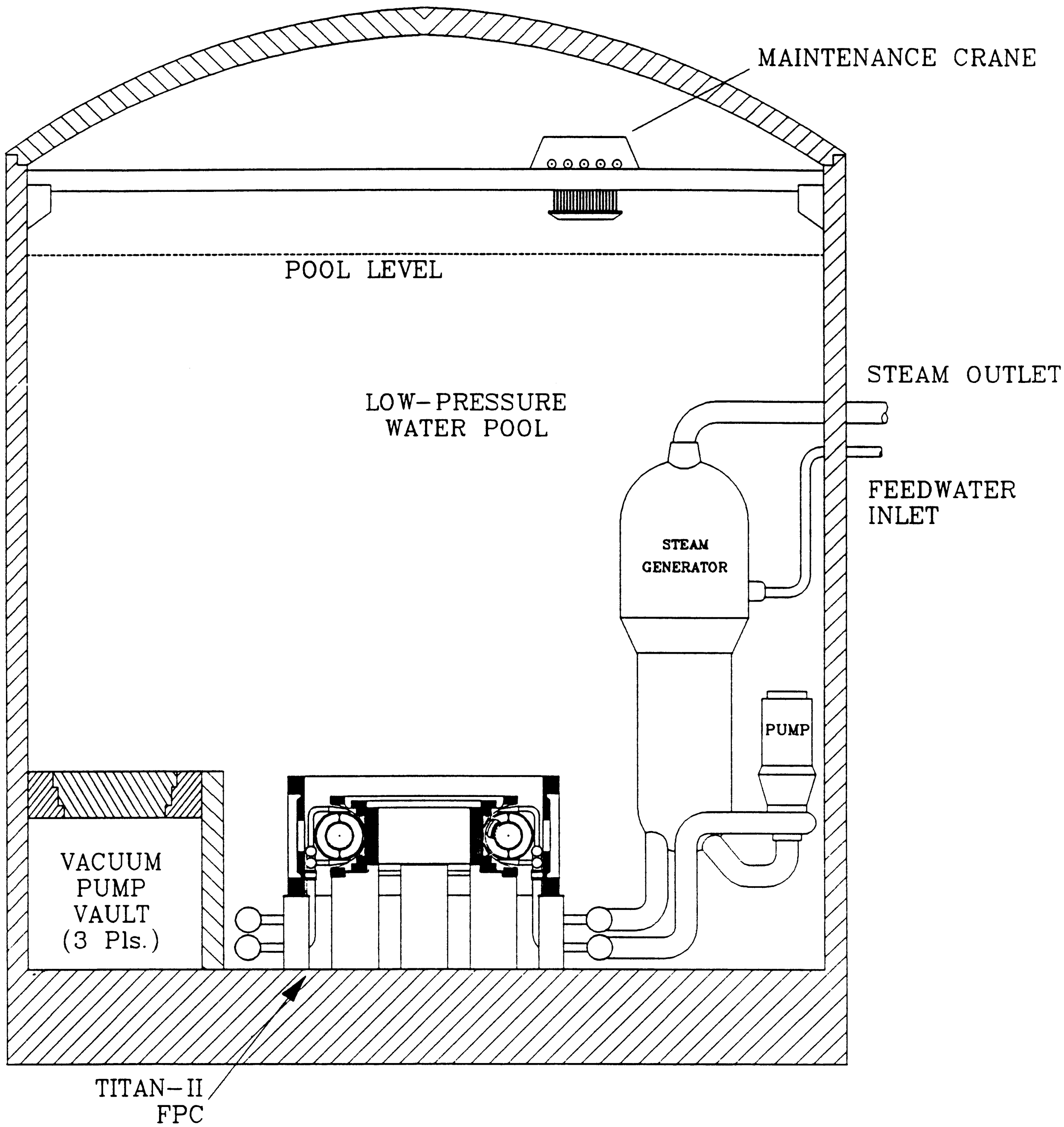

Figure 20.2-1. Elevation view of the TITAN-II reactor building through the reactor centerline showing the FPC, water pool, and maintenance crane.

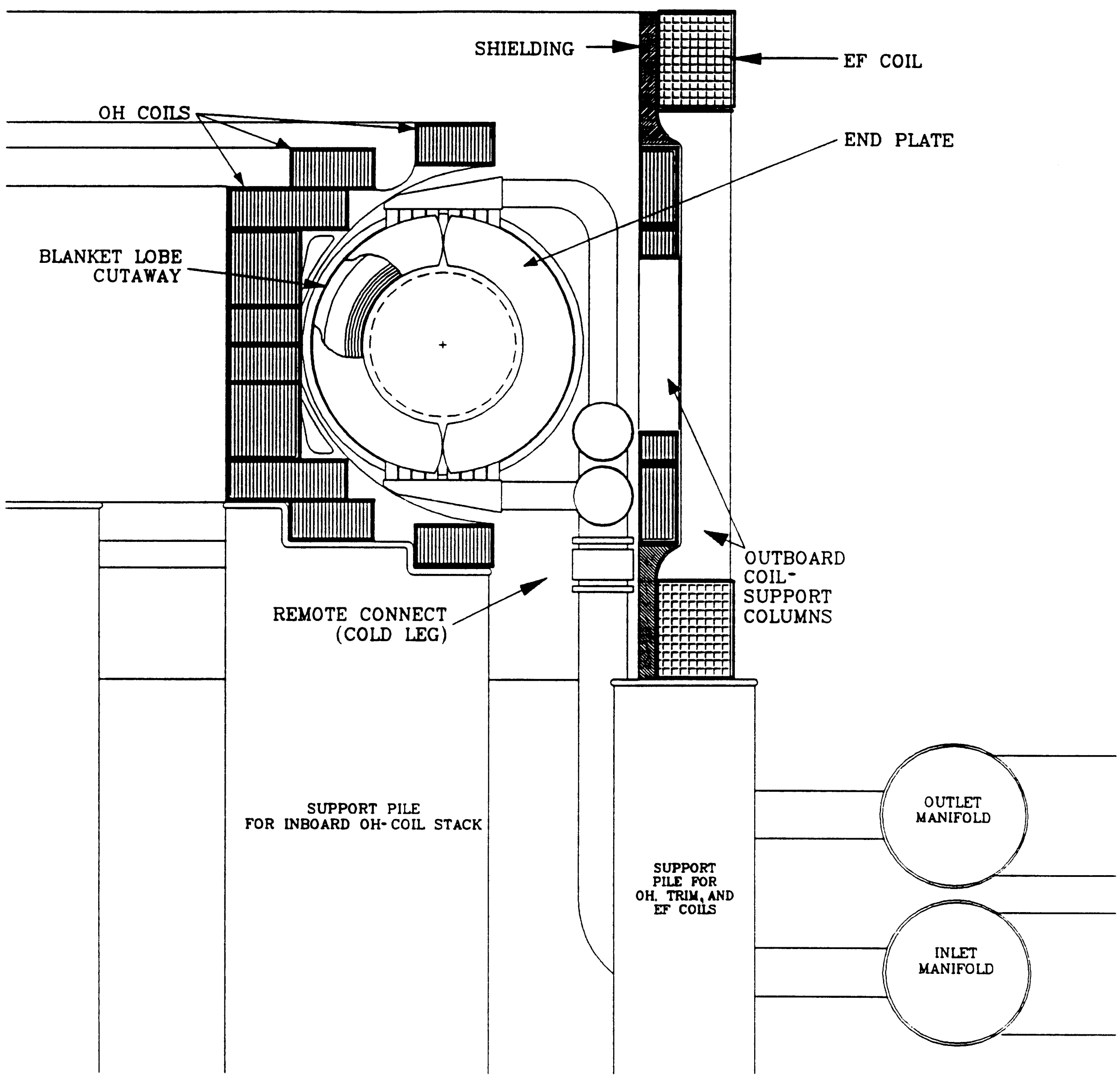

Figure 20.2-2. Poloidal cross section of the TITAN-II fusion power core illustrating the major components and coolant flow paths.

"J-plates" because of their cross section, are assembled into blanket lobes as shown in Figure 20.2-3. Inside each of the lobes are 9-C-clad beryllium rods which occupy the first 20 cm behind the first wall. The blanket lobes are stacked side-by-side to form a blanket module. The shield is used as a clamp to restrain the lobes from any movement. A cross section and an isometric view of a blanket module are shown, respectively, in Figures 20.2-4 and 20.2-5. Twelve blanket modules and three divertor sections are assembled into a single reactor torus in preparation for installation into the reactor chamber.

The vacuum boundary for the FPC, located outside the toroidal-field (TF) coils, acts as a boundary between the pool and the hot torus. The TF coils occupy the space between the back of the shield and the vacuum shell (Figure 20.2-4). Vacuum-duct penetrations through the vacuum shell are located in the regions near the divertors. Isolation valves, as illustrated in Figure 20.2-6, are required at all of the underwater connections (hydraulic, electrical, and vacuum). The vacuum-tank concept of TITAN-I was not used here because it would provide excessive thermal insulation between the pool and the FPC and the pool could not act as a heat sink for the decay heat during off-normal events.

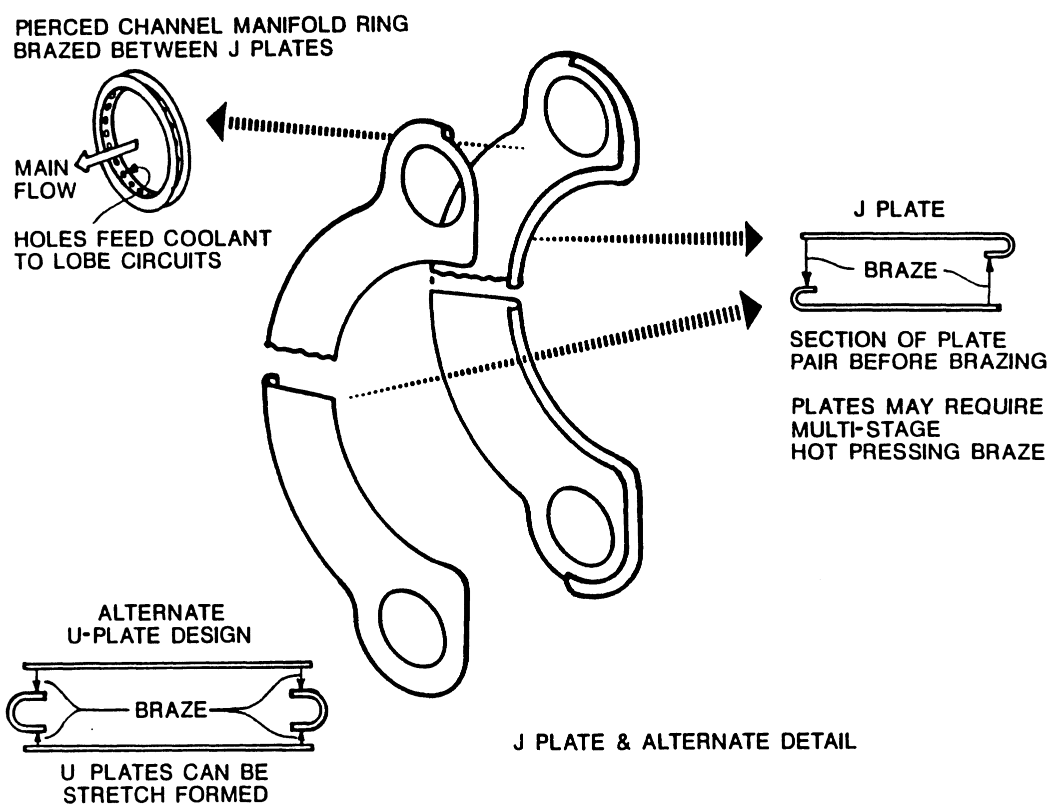

Figure 20.2-3. The TITAN-II blanket lobe, J-plate design.

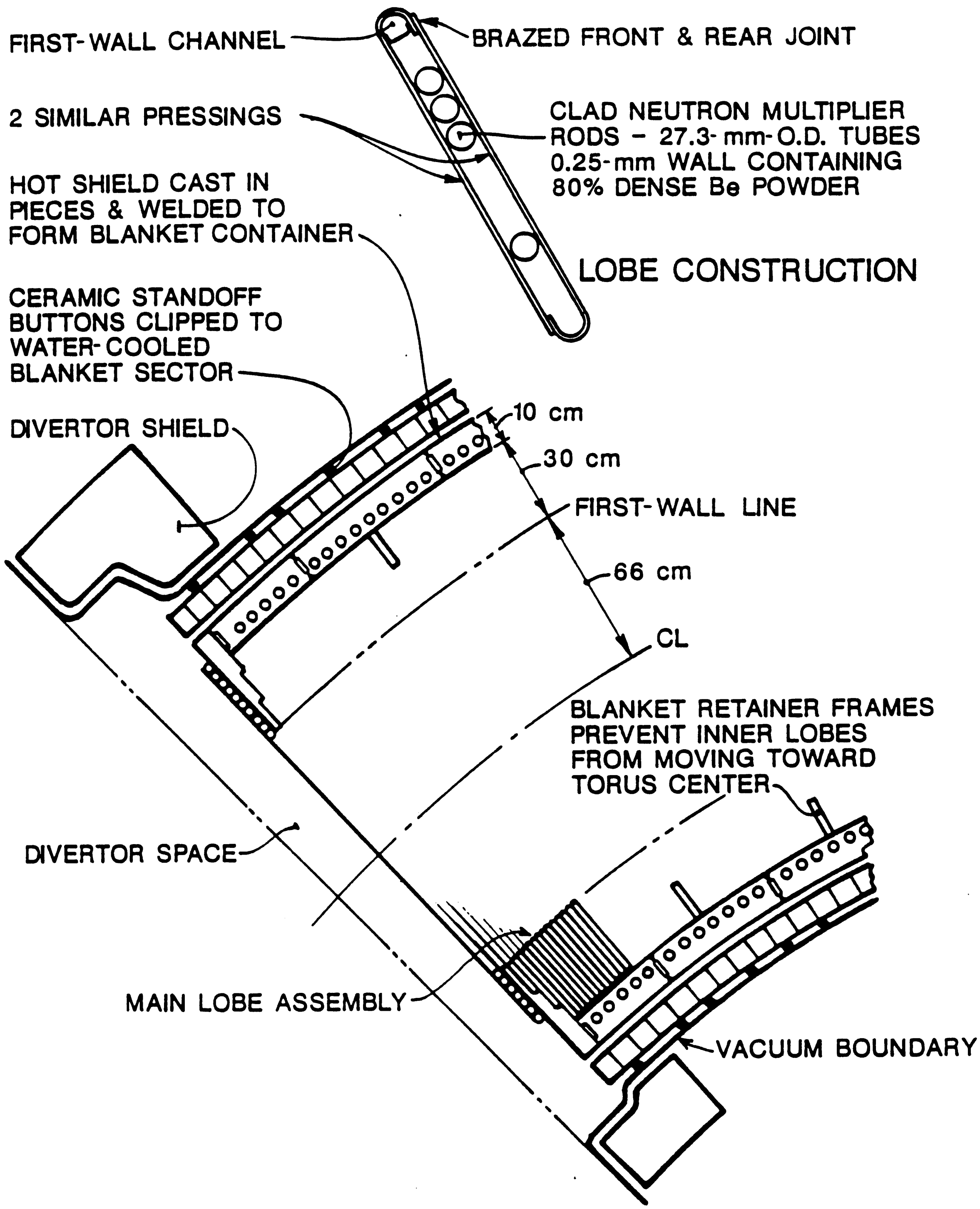

Figure 20.2-4. Cross section of a TITAN-II blanket module.

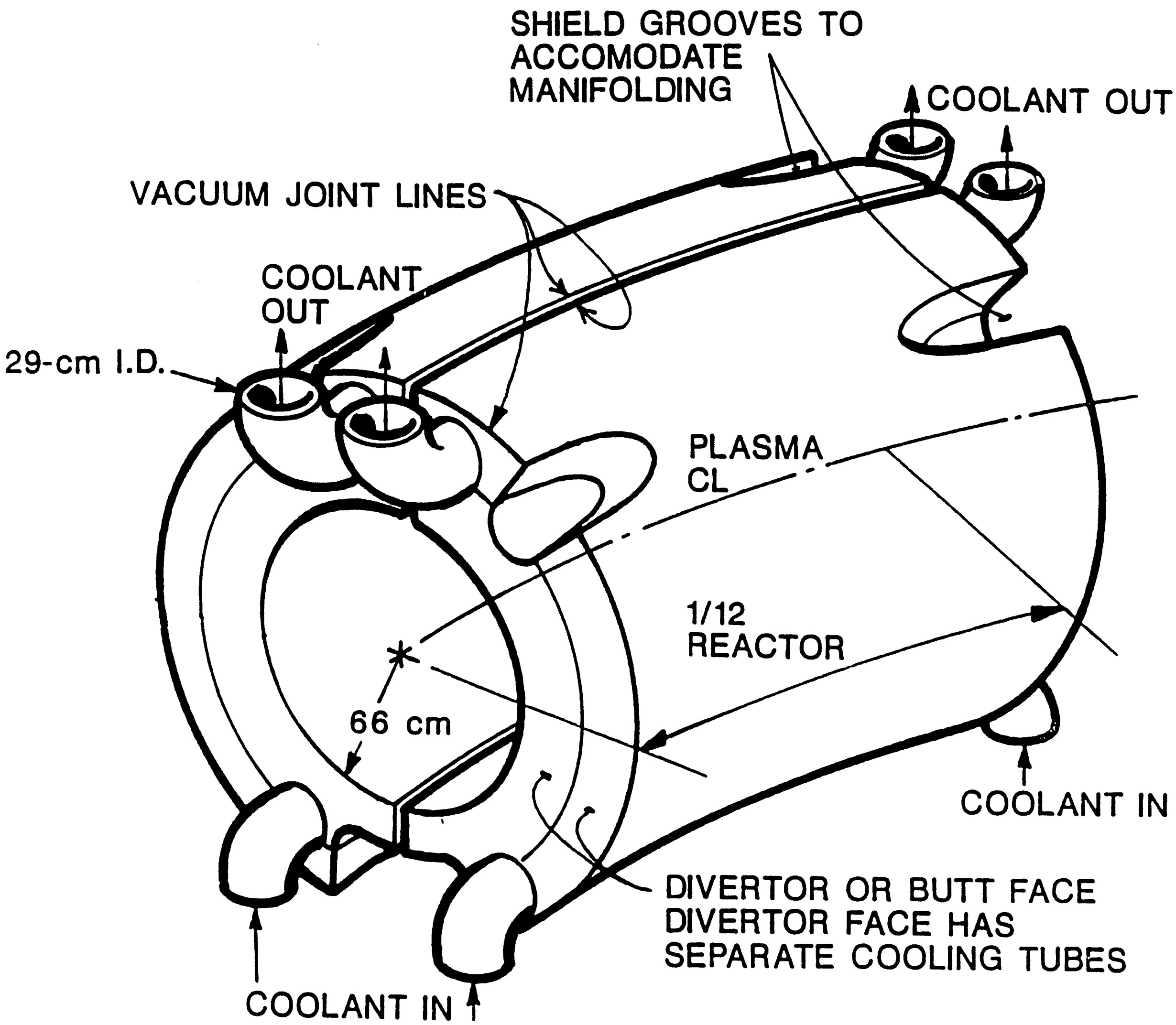

Figure 20.2-5. Isometric view of a TITAN-II blanket module.

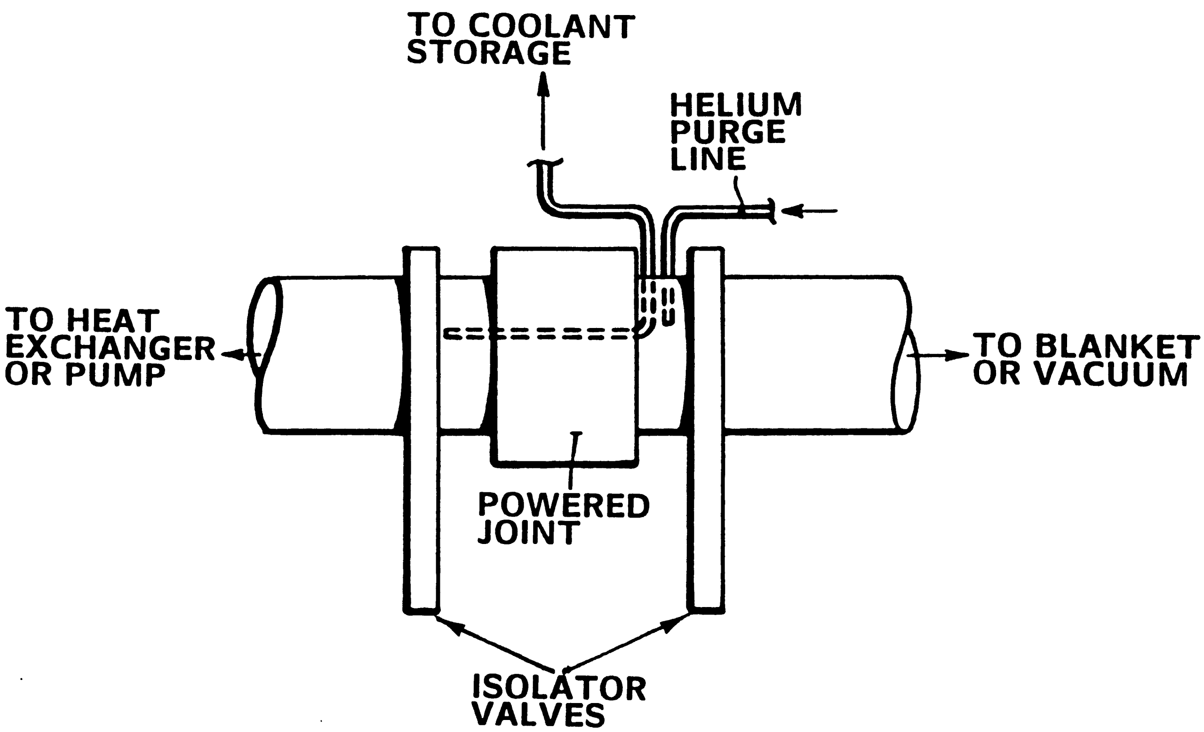

Figure 20.2-6. Illustration of a proposed isolation valve for the TITAN-II vacuum ducts.

20.3. MAINTENANCE PROCEDURES

A key assumption for the TITAN maintenance program, as in other fusion reactor studies, is that a high degree of automation is available. In the TITAN-II design, powered joints are used extensively for hydraulic and electrical connect/disconnects. The use of powered joints allows many tasks to be done quickly and in parallel. Together with the single-piece maintenance scheme, which reduces the number of joints to a minimum, this approach is expected to result in a dramatic reduction in the required time to perform the maintenance operations and to increase the overall reliability. The powered joints for the coolant circuits are located on the hot and cold legs of the aqueous-solution supplies as is shown in Figure 20.2-2. Additional connect and disconnect powered joints are also provided for the upper OH-coil-set electrical and cooling circuits. Examples of powered joints [2] are shown in Section 14.3.

One of the unique aspects of the TITAN-II maintenance procedures is the presence of the large water pool surrounding the FPC. Three maintenance options are available:

1. Perform all required maintenance under water without draining the pool. This option maintains the pool as a safety barrier until the torus assembly is removed from the pool. Also, the pool drain time does not affect the scheduling of the maintenance.

2. Drain the entire pool prior to maintenance operations. A benefit is that double valves to prevent water infiltration into the vacuum and electrical systems are not required. Pool drain time and cost for pool-water storage need to be considered.

3. The third approach, a hybrid of the above two approaches, provides an intermediate cylinder around the FPC. In this case, only the central portion of the pool would be pumped out prior to maintenance. This approach also does not require double valves to prevent water infiltration into the vacuum and electrical systems. Compared to second approach, the pumping time is reduced and water storage requirements are smaller. However, this approach requires additional structure.

Because of the perceived safety advantages and simplicity, the TITAN study adopted maintenance method number one: to perform the maintenance procedures under water. Fourteen principal tasks must be accomplished for the annual, scheduled maintenance of the TITAN-II fusion power core. These steps are listed in Table 20.3-I. Tasks that will require a longer time to complete in a modular design are also identified in Table 20.3-I (assuming the same configuration for the modular design as that of TITAN-II). Another potential benefit of the single-piece maintenance approach is that the recovery from any unscheduled event will be standard and similar to the procedures of Table 20.3-I for the scheduled maintenance. It should be noted that the economic impact of a disabled FPC is dominated by the downtime of the plant and not by the capital cost of a new FPC.

Vertical lifts have been chosen for the component movements during maintenance. Vertical lifts allow a more compact reactor building, consistent with the TITAN-II design goal. In addition, if one to provide horizontal access near the bottom of the pool, the design of the pool surrounding the FPC would be very complicated and the integrity of the pool would be questionable. Vertical lifts of the components are performed by a moveable bridge crane as shown in Figure 20.2-1. Lift limits for conventional bridge cranes is around 500 tonnes, with special-order crane capacities in excess of 1000 tonnes. The most massive components lifted during TITAN-II maintenance are the reactor torus

Table 20.3-I.

PRINCIPAL TASKS DURING THE TITAN-II MAINTENANCE PROCEDURE

1. Orderly shutdown of the plasma and discharge of the magnets;
2. Continue cooling the FPC at a reduced level until the decay heat is sufficiently low to allow natural convection cooling in the atmosphere;
3. During the cool-down period:
   a. Continue vacuum pumping until sufficient tritium is removed from the FPC,
   b. Valve-off all systems which will be disconnected during maintenance (*i.e.,* vacuum and electrical systems) and, depending on the maintenance method, drain the water pool above the FPC,
   c. Disconnect electrical and coolant supplies from the upper OH-coil set,
   d. Break vacuum;
4. Drain primary coolant from FPC;
5. Lift OH-coil set and store in the lay-down area;
6. Disconnect primary-coolant supplies at ring headers;[a]
7. Lift the reactor torus and move to the hot cell;[a]
8. Inspect FPC area;
9. Install the new, pretested torus assembly;[a]
10. Connect primary-coolant supplies, TF-coil electrical supplies, and re-weld all vacuum ducts;[a]
11. Replace the upper OH-coil set and connect electrical and coolant supplies;
12. Hot test the FPC;[b]
13. Pump-down the system;
14. Initiate plasma operations.

(*a*) The time required to complete these tasks is likely to be longer for a modular system than for a single-piece system, assuming similar configuration.

(*b*) The new torus assembly is pretested and aligned before committment to service. Only minimum hot testing would be required.

(180 tonnes) and the upper OH-coil set (OH coils 2 through 4) and its support structure (120 tonnes), which are easily manageable by the conventional cranes. The OH coils are reinstalled following the installation of the new torus assembly. Once the new torus is lowered into position, vertically oriented remote connects attach the torus to the stationary primary-coolant supplies.

A simple comparison of modular and single-piece maintenance approaches can be made using Table 20.3-I by assuming a modular design for TITAN-II with the same dimensions and wall loading but with toroidal segmentation which separates the reactor torus into three or more units for maintenance purposes. Examination of the maintenance steps listed in Table 20.3-I indicates that 5 of the 14 tasks (6, 7, 9, 10, and 12) would likely be more time consuming for a modular reactor. Some of the differences are associated with those steps that involve interfaces between modules and lifting of individual modules. Since the lifting of individual modules is done in series rather than in parallel, the total number of module transfers requires more time even though the lighter, modular unit may be transported somewhat faster than the complete reactor torus.

One of the crucial steps in Table 20.3-I is the installation of the new reactor torus at the bottom of the TITAN-II pool (step 9). A modular design will require additional time in order to align the modules into a full torus (depending on the required degree of precision). Another important difference between the modular and single-piece approaches is the degree of pretesting that can be performed outside of the reactor vault. A comprehensive set of pretests are envisioned for the TITAN reactors (Section 14.4). For a modular design, those pretests that require a fully assembled torus should be performed after the installation of the modules into the reactor vault as a complete torus, which will increase the maintenance period and the downtime.

Similar to the maintenance procedures for the TITAN-I design, a self-consistent comparison of the TITAN-II single-piece maintenance procedure with a modular approach is difficult because very little information is available on the time needed to perform each of the maintenance tasks listed in Table 20.3-I. Furthermore, the TITAN-II FPC is designed such that the advantages of a single-piece approach are fully exploited and a different modular-type design should have been produced for a self-consistent comparison.

The comparison between the single-piece and modular maintenance procedures is even more difficult for unscheduled events because such a comparison would require an extensive data base on the mean time-to-failure and the mean time-to-repair of various components of the reactor. Recovery from a major event will be shorter with the single-piece maintenance approach. It is possible that for minor events, the mean time-to-repair for a modular approach will be shorter. However, for a modular approach, recovery from unscheduled events requires additional equipment, each designed to handle and repair certain failure modes. In a single-piece approach, recovery from unscheduled events will be, in principle, standard and similar to a scheduled maintenance procedure. One should also note that the sector-to-sector interfaces in a modular design add to the number of possible fault areas, hence, possibly reducing overall reliability.

20.4. SUMMARY

The TITAN reactors are compact, high-power-density designs. The small physical size of these reactors permits each design to be made of only a few pieces, allowing a single-piece maintenance approach. Also, because of the small physical size and mass of the TITAN-II FPC, the maintenance procedures can be carried out through vertical lifts, allowing a much smaller reactor vault.

The major tasks required for annual maintenance of the TITAN-II FPC have been identified. Single-piece maintenance of the reactor torus (including the first wall, blanket, shield, TF coils, and divertor modules) appears feasible and must be performed yearly. Following the removal of the old torus, a new, fully pretested assembly is installed.

Potential advantages of single-piece maintenance procedures are identified:

1. Shortest period of downtime resulting from scheduled and unscheduled FPC repairs;
2. Improved reliability resulting from integrated FPC pretesting in an on-site, non-nuclear test facility where coolant leaks, coil alignment, thermal-expansion effects, *etc.* would be corrected by using rapid and inexpensive hands-on repair procedures prior to committing the FPC nuclear service;
3. No adverse effects resulting from the interaction of new materials operating in parallel to radiation-exposed materials;
4. Ability to modify continually the FPC as may be indicated or desired by reactor performance and technological developments; and
5. Recovery from unscheduled events would be more standard and rapid. The entire reactor torus is replaced and the reactor is brought back on line with the repair work being performed, afterwards, outside the reactor vault.

A high level of pretesting ensures that the new torus will behave as designed, and will have a higher reliability than individual modules that have not been tested together as a single operating unit under reactor-like conditions. It appears that the single-piece maintenance approach, together with a detailed pretesting program, can substantially improve the availability of the TITAN-II reactor.

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