

# **14. TITAN-I MAINTENANCE PROCEDURES**

Steven P. Grotz

Richard L. Creedon

Patrick I. H. Cooke

William P. Duggan

Robert A. Krakowski

Farrokh Najmabadi

Clement P. C. Wong

## Contents

14.1. INTRODUCTION . . . . .	14-1
14.2. TITAN-I PLANT LAYOUT . . . . .	14-2
14.3. MAINTENANCE PROCEDURES . . . . .	14-6
14.4. FUSION POWER CORE PRETESTING . . . . .	14-12
14.5. SUMMARY . . . . .	14-14
REFERENCES . . . . .	14-16

## 14. TITAN-I MAINTENANCE PROCEDURES

### 14.1. 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-I 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 commitment 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 14.2) and the proposed maintenance procedures for the TITAN-I reactor (Section 14.3) are presented. A comparison of the TITAN-I single-piece maintenance procedure with a modular approach is difficult because: (1) the TITAN-I fusion power core (FPC) is designed so that

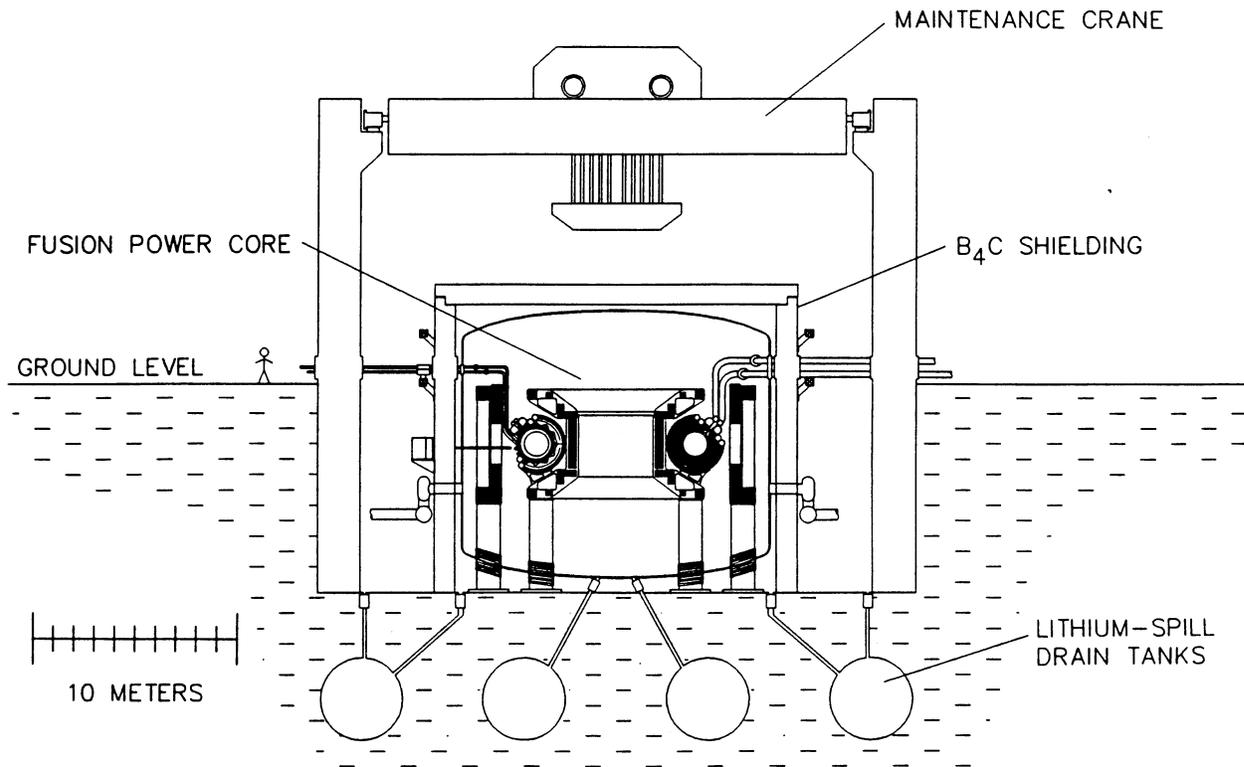
the advantages of a single-piece approach are fully utilized and a different design should have been produced to compare and quantify the benefits of single-piece maintenance procedures, (2) little data is available on times that would be required for each step during the maintenance procedure, and (3) 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 single-piece approach and is discussed in Section 14.4.

## 14.2. TITAN-I PLANT LAYOUT

The elevation view of the TITAN-I design is shown in Figures 14.2-1 and 14.2-2. All of the TITAN-I 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 moveable upper ohmic-heating (OH) coil set and the upper hot shield, each weighing about 150 tonnes, which can be easily lifted 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-I reactor torus (including the first wall, blanket, and divertor modules) is estimated to be in the range of 15 to 18 MW y/m<sup>2</sup>, and the more conservative value of 15 MW y/m<sup>2</sup> will require the change-out of the reactor torus on a yearly basis for operation at 18 MW/m<sup>2</sup> of neutron wall loading at 76% availability. The lifetime of the hot shield is estimated to be five years. To reduce the quantity of the rad-waste, the TITAN-I hot shield is made of two pieces, with the upper hot shield removed during the maintenance procedures and then reused following replacement of the reactor torus. It should be noted that because of the smaller mass of the FPC of a compact reactor, the total replaced mass during the life of the plant is comparable to that of a low-neutron-wall-loading design.

One of the unique features of the TITAN-I design is that the entire FPC operates inside a vacuum tank, again made possible because of the small physical size of the reactor. The vacuum tank concept moves the vacuum boundary well away from the harsh radiation and thermal environment, allowing for a more robust and reliable design. During maintenance of the FPC, the weld at the lid of the vacuum tank must be cut



**Figure 14.2-1.** Elevation view of the TITAN-I reactor building through the reactor centerline showing the reactor vault and the maintenance crane.

and then rewelded after the maintenance is complete. Although a design with individual vacuum ducts leading to each of the three divertor chambers is possible, remote cutting and welding of that complex geometry is expected to be much more difficult. The vacuum tank of TITAN-I provides an additional safety barrier in the event of an off-normal incident (Section 13). Drain tanks are provided below the FPC to recover and contain any spilled lithium in the vacuum tank or the reactor building. The drain tank system connected to the vacuum tank is also evacuated during the normal operation.

The major plant facilities and the plant layout of the TITAN-I reactor are illustrated in Figure 14.2-3. The entire reactor building has an argon atmosphere to prevent and contain lithium-fire accidents in the event of a lithium spill. All of the systems containing the tritiated, primary-lithium coolant are surrounded by this argon atmosphere. New, pretested torus assemblies are also stored in inert argon. In addition, all maintenance operations are performed in this argon atmosphere. This approach reduces the out-gassing and pump-down time when the reactor torus is installed into the vacuum tank.

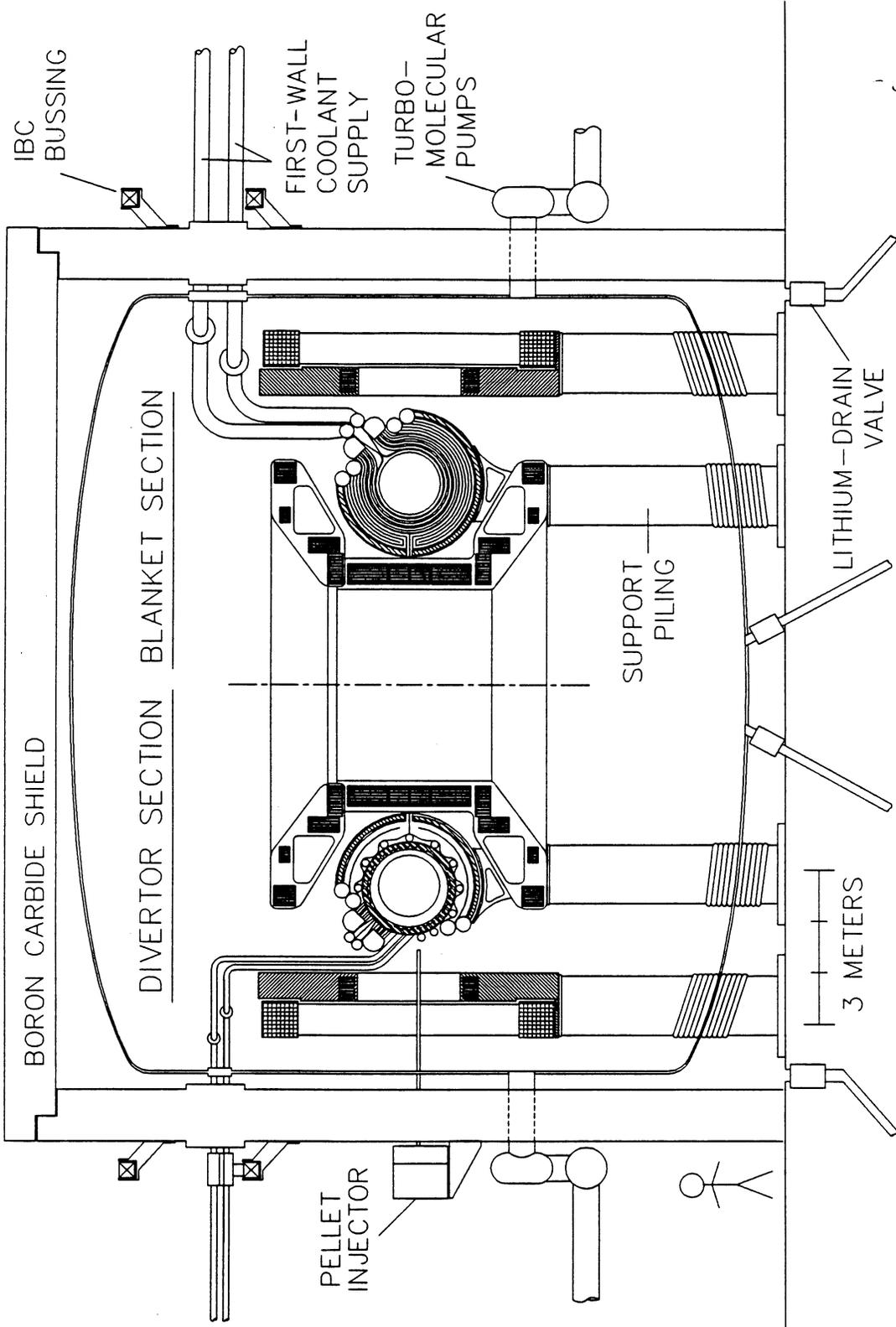


Figure 14.2-2. Elevation view of the TITAN-I reactor showing the vacuum tank and the FPC.

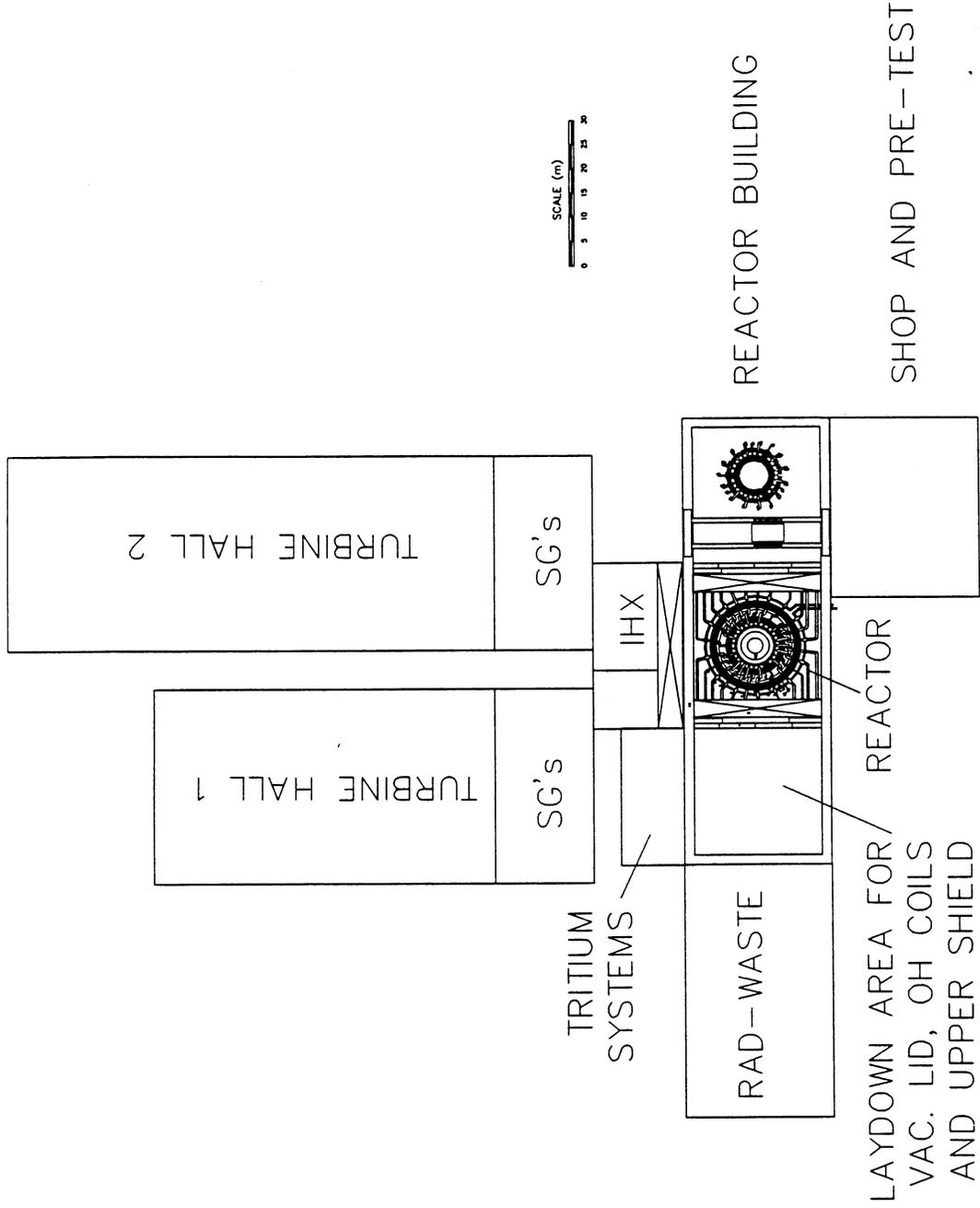


Figure 14.2-3. Proposed layout of the TITAN-I major plant facilities.

A plan-view of the confinement building is given in Figure 14.2-4 and illustrates the lay-down areas for the components which have to be moved during maintenance, as well as the storage area for the new reactor torus assemblies.

### 14.3. 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-I 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 lithium supplies, above the torus, as is shown in Figure 14.2-2. 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 Figure 14.3-1.

Seventeen principal tasks must be accomplished for the annual, scheduled maintenance of the TITAN-I FPC. These steps are listed in Table 14.3-I. Tasks that will require a longer time to complete in a modular design are also identified in Table 14.3-I (assuming the same configuration for the modular design as that of TITAN-I). 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 14.3-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-I design goal. Vertical lifts of the components are performed by a moveable bridge crane as shown in Figures 14.2-1 through 14.2-4. 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-I maintenance are the upper OH-coil set (OH coils 2 through 5) and the upper hot shield, each weighing about 150 tonnes. Vertical lift of these components is easily manageable by conventional cranes. The four major component lifts are illustrated in Figure 14.3-2. Temporary storage for the vacuum lid, upper OH-coil set, and upper hot shield are provided, as shown in Figure 14.2-4. These

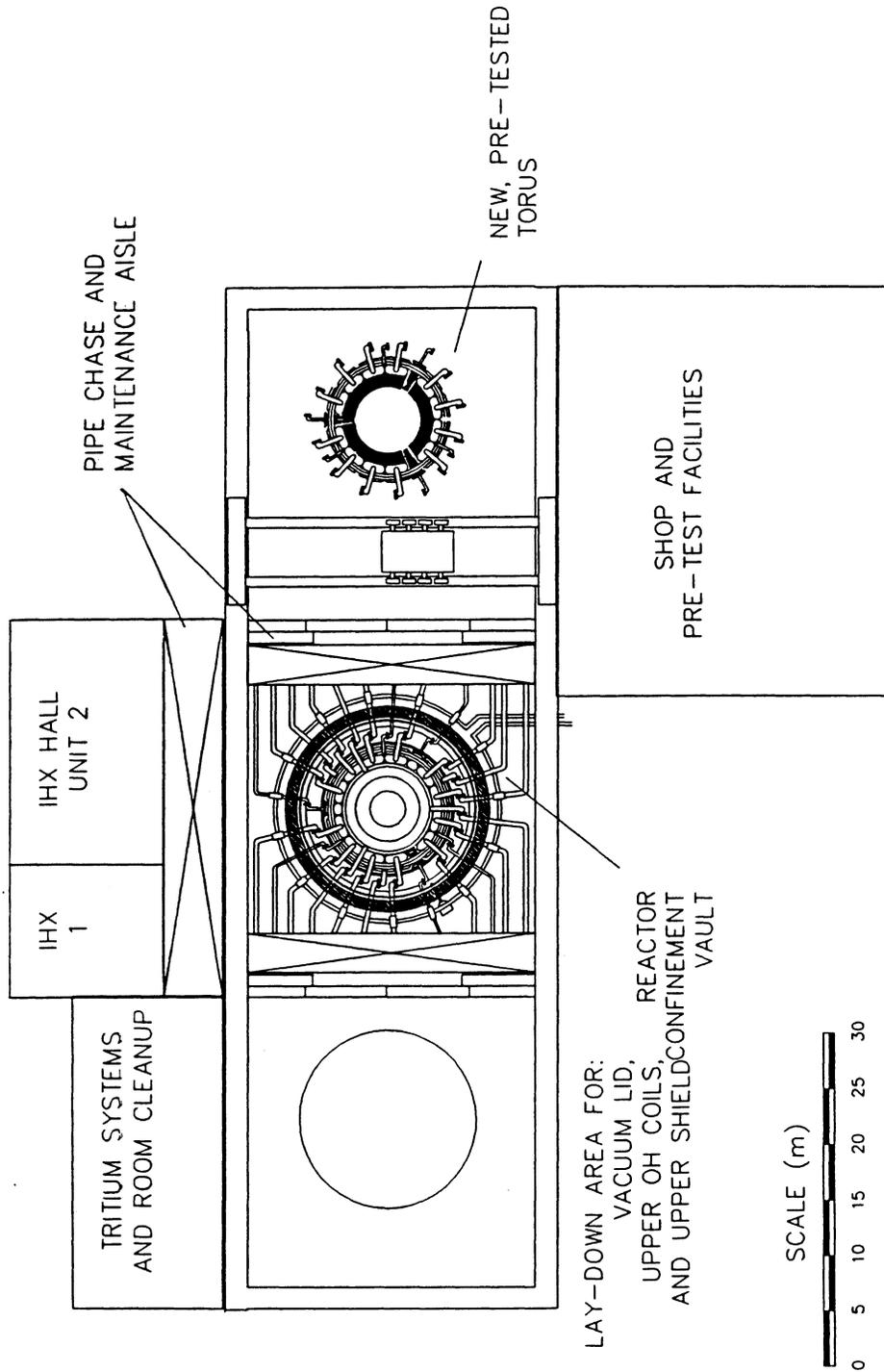
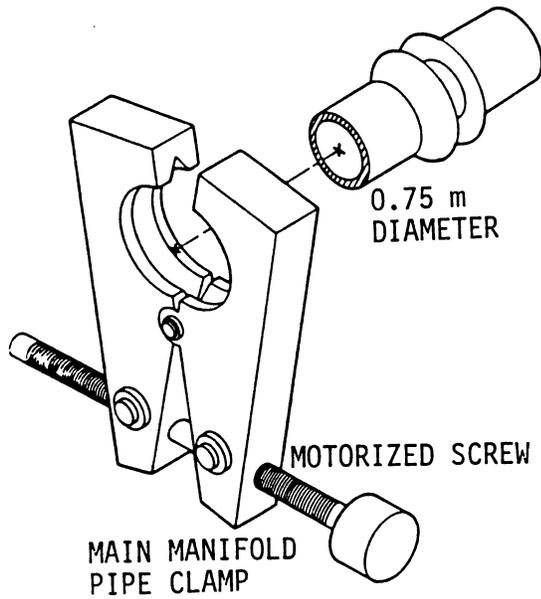
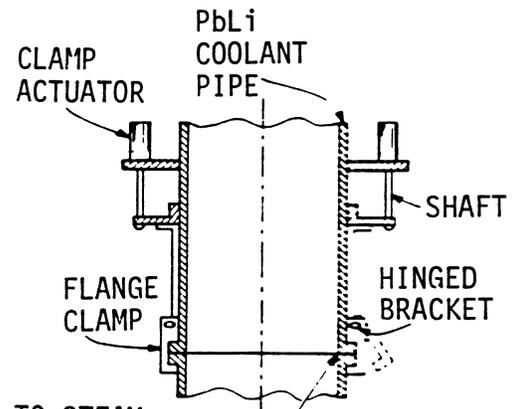


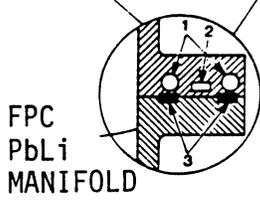
Figure 14.2-4. Plan-view of the TITAN-I reactor building.



Clamp for remotely disconnecting main PbLi headers.

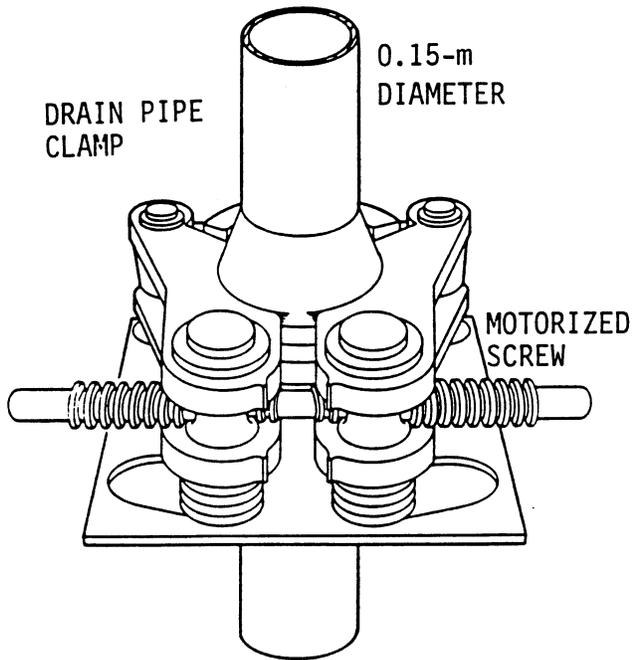


TO STEAM GENERATORS



FPC PbLi MANIFOLD

- 1. Helium coolant circuits (2 for redundancy)
- 2. Seal-verification and leak-monitoring channel
- 3. Frozen PbLi zones



Clamp for remotely disconnecting PbLi drain plug.

Figure 14.3-1. Examples of remote connect/disconnect, powered joints [2].

**Table 14.3-I.**  
**PRINCIPAL TASKS**  
**DURING THE TITAN-I 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 cooling by natural convection in the argon atmosphere;
  3. During the cool-down period:
    - a. Continue vacuum pumping until sufficient tritium is removed from the FPC,
    - b. Break vacuum (valve-off vacuum pumps and cut weld at vacuum tank lid),<sup>(a)</sup>
    - c. Remove vacuum-tank lid to the lay-down area,
    - d. Disconnect electrical and coolant supplies from the upper OH-coil set;
  4. Drain lithium from the FPC;
  5. Lift OH-coil set and store in the lay-down area;
  6. Disconnect lithium-coolant supplies;<sup>(a)</sup>
  7. Lift upper shield and store in the lay-down area;
  8. Lift the reactor torus and move to the hot cell;<sup>(a)</sup>
  9. Inspect FPC area;
  10. Install the new, pretested torus assembly;<sup>(a)</sup>
  11. Connect lithium supplies;<sup>(a)</sup>
  12. Replace upper shield and connect shield-coolant supplies;
  13. Replace the upper OH-coil set and connect electrical and coolant supplies;
  14. Hot test the FPC;<sup>(b)</sup>
  15. Replace vacuum-tank lid and seal the vacuum tank;<sup>(a)</sup>
  16. Pump-down the system;<sup>(c)</sup>
  17. Initiate plasma operations.
- 

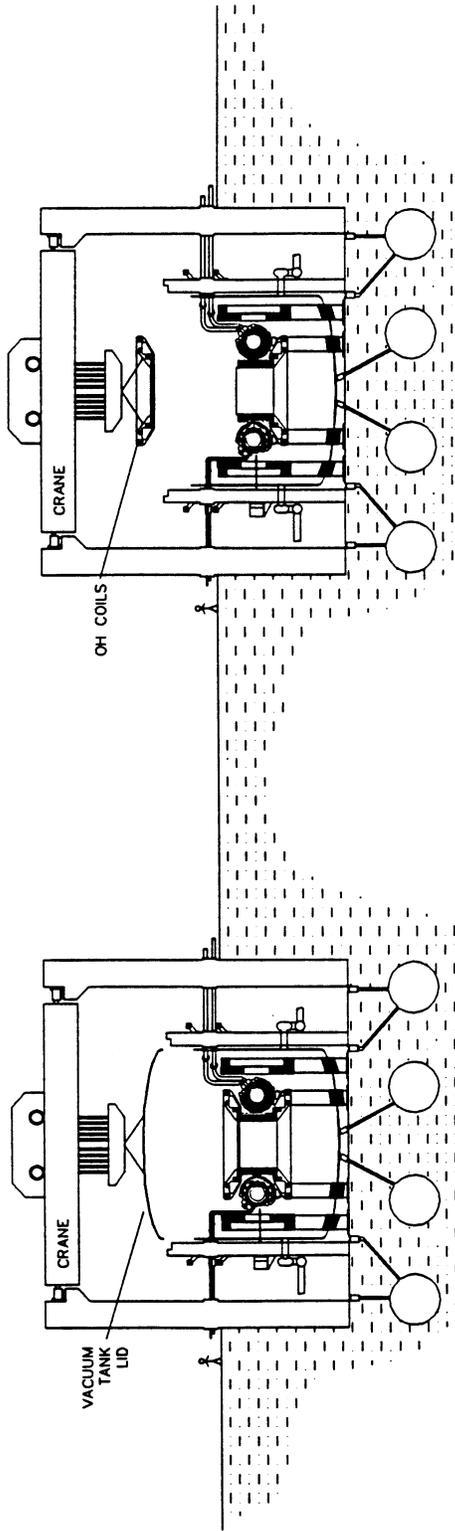
(a) The time required to complete these tasks is likely to be longer for a modular system than for a single-piece system, assuming similar configuration.

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

(c) The TITAN-I reactor building is filled with argon gas and the replacement torus is also stored in argon atmosphere. Therefore, the pump-down time would be short.

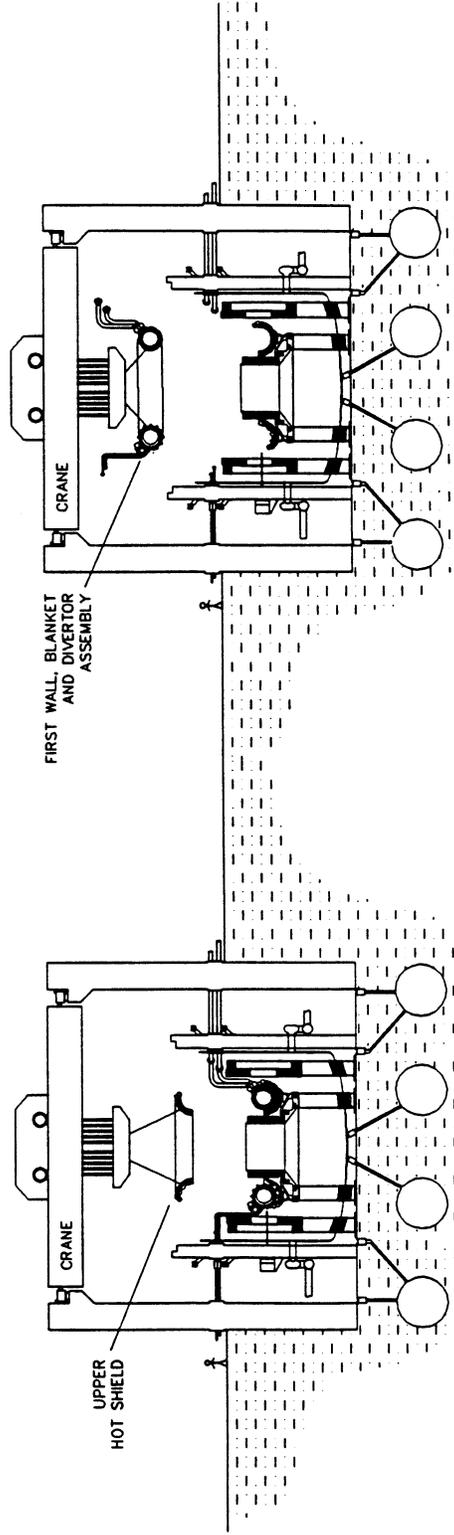
(1) VACUUM TANK LID

(2) UPPER OH COILS



(3) UPPER HOT SHIELD

(4) TORUS ASSEMBLY



FIRST WALL, BLANKET AND DIVERTOR ASSEMBLY

Figure 14.3-2. Four major crane lifts required for TITAN-I maintenance.

three components are reinstalled following the installation of the new torus assembly. Once the new torus is lowered into position, horizontally oriented remote connects attach the torus to the stationary primary-lithium supplies.

A simple comparison of modular and single-piece maintenance approaches can be made using Table 14.3-I by assuming a modular design for TITAN-I 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 14.3-I indicates that 5 of the 17 tasks (6, 8, 10, 11, and 14) 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 14.3-I is the installation of the new reactor torus in the reactor vault (step 10). A modular design will require additional time in order to align the modules into a full torus (depending on the required degree of the 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-I design and are discussed in 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.

A self-consistent comparison of the TITAN-I 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 14.3-I. Furthermore, the TITAN-I 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.

#### 14.4. FUSION POWER CORE PRETESTING

An important feature of the TITAN design is the pretest facility. This facility allows the plant personnel to test fully the new torus assemblies in a non-nuclear environment prior to committing it to full-power nuclear operation in the reactor vault. Any faults discovered during pretesting can be quickly repaired using inexpensive hands-on maintenance. Furthermore, additional testing can be used as a shakedown period to reduce the “infant-mortality” rate of the new assemblies. A comprehensive pretest program can greatly increase the reliability of the FPC, hence increasing the overall plant availability.

A detailed list of pretests for the TITAN-I design is included in Table 14.4-I. The tests are categorized by the level of assembly and by the type of test. Three levels of assembly are identified: sub-modules, modules, and full torus. Sub-modules are such items as first-wall pipes, blanket pipes, and ring headers. Modules are the assembled blanket units as shipped from the factory to the site (12 per torus). The full torus is the unit that is installed into the reactor vault (12 blanket modules and 3 divertor modules mechanically attached together). Pretesting of the complete torus is further subdivided into plasma and no-plasma tests.

The benefits of pretesting (higher reliability, higher availability) must be balanced with the additional cost associated with the pretest facility. The more representative the pretests are of the actual operation, the more duplication of the primary-loop components is required. For example, vacuum-field mapping and divertor-plate alignment will require a vacuum system, simulated toroidal and divertor magnetic fields, and the diagnostics for the tests. Furthermore, since the toroidal-field and divertor coils are IBC-type coils (*i.e.*, the poloidally flowing lithium-coolant is used as the electrical conductor for the coil), a lithium circuit will be required for pretest. If the only requirement for pretesting is to perform hot, functional tests, then the only major facility is a hot-gas circulation system. The optimum level of pretesting can be determined with a detailed trade-off study to compare the benefits of the higher reliability and availability against the cost penalties associated with the pretest equipment. The lack of operating experience and data on the new technologies and configurations proposed for fusion systems will lead to

Table 14.4-I.

## MAIN PRE-OPERATIONAL TESTING OF THE TITAN-I FPC

Test	Sub-Module <sup>(a)</sup>	Module <sup>(a)</sup>	Full Torus <sup>(b)</sup>	
			No Plasma	Plasma <sup>(c)</sup>
<b>Mechanical</b>				
• Tube-bank vibration (first wall, blanket)	X	X	X	
• Tube-bank expansion (first wall, blanket)	X	X	X	
• Inter-module and full-torus deflection			X	
• Plasma chamber (shell)/coil displacement			X	
<b>Thermal Hydraulic</b>				
• Flow rates, pressure drops, leaks, ... :			X	
* First wall, divertor, blanket, shield	X			
* Coils			X	
* Manifolds, headers			X	
• "Hot" FPC test, (pressure drops, vibrations, ...)			X	
* Electrically heated coolant			X	
* Plasma-driven heat fluxes				X
• Remote coupling, disconnects	X	X	X	
<b>Electrical</b>				
• Magnet test (forces, deflection, voltages, ...)			X	X
• Vacuum-field mapping (TF ripple, vertical field, ...)			X	
• Plasma transients				
* RFP formation			X	X
* Fast-ramp phase			X	X
* Slow-ramp phase				X
• Current-drive (steady-state) phase				X
• Active feedback control			X	X
• Eddy currents (start-up, OFCD)				
* First wall and shell			X	X
* Blanket and shield			X	X
* Coil casing, structure, pumps, ...			X	X
• Termination control/response				X
<b>Vacuum, Fueling, and Impurity-Control Systems</b>				
• Base vacuum			X	
• Full gas-load test			X	
• Pellet injection				X
<b>Neutronics</b>				
• Breeding efficiency				X
• Energy-recovery efficiency				X
• Shielding effectiveness, streaming				X

(a) Performed at factory site.

(b) Performed at plant site during operational year.

(c) Performed in the reactor vault during the scheduled maintenance.

a great degree of uncertainty in that type of trade-off study at present. Simple models of availability have been developed [4] and could be used to show relative benefits of increased reliability. In situations where several reactors are clustered together, the cost of a single pretest facility could be shared, leading to a lower average cost per reactor.

## 14.5. 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-I 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-I FPC have been identified. Single-piece maintenance of the reactor torus (including the first wall, blanket 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-I reactor.

**REFERENCES**

- [1] R. L. Hagenson, R. A. Krakowski, C. G. Bathke, R. L. Miller, M. J. Embrechts, *et al.*, "Compact Reversed-Field Pinch Reactors (CRFPR): Preliminary Engineering Considerations," Los Alamos National Laboratory report LA-10200-MS (1984).
- [2] C. Copenhaver, R. A. Krakowski, N. M. Schnurr, R. L. Miller, C. G. Bathke, *et al.*, "Compact Reversed-Field Pinch Reactors (CRFPR)," Los Alamos National Laboratory report LA-10500-MS (1985).
- [3] D. W. Graumann, "Experience with the Modular Concept of the OHTE Experimental Device During Initial Assembly, Operations, and the Mid-Experiment Upgrade," General Atomics report GA-A17077 (1983).
- [4] J. Sheffield, R. A. Dory, S. M. Cohn, J. G. Delene, L. F. Parsley, *et al.*, "Cost Assessment of a Generic Magnetic Fusion Reactor," Oak Ridge National Laboratory report ORNL/TM-9311 (1986) 103.