CONF-870301--10 Draft

CONF-870301--10

DE87 004062

MAINTENANCE FEATURES OF THE COMPACT IGNITION TOKAMAK FUSION REACTOR*

P. T. Spampinato
Fusion Engineering Design Center/
Grumman Corporation
P.O. Box Y, FEDC Bldg.
Oak Ridge, Tennessee 37831
(615)576-5475

E. R. Hager
GA Technologies, Inc.
P.O. Box 85608
San Diego, California 92138
(619)455-4319

ABSTRACT

The Compact Ignition Tokamak (CIT) is envisaged to be the next experimental machine in the U.S. Fusion Program. Its use of deuterium/tritium fuel requires the implementation of remote handling technology for maintenance and disassembly operations. The reactor is surrounded by a close-proximity nuclear shield which is designed to permit personnel access within the test cell, one day after shutdown. With the shield in place, certain maintenance activities in the cell may be done hands-on. Maintenance on the reactor is accomplished remotely using a boom-mounted manipulator after disassembling the shield. Maintenance within the plasma chamber is accomplished with two articulated boom manipulators that are capable of operating in a vacuum environment. They are stored in a vacuum enclosure behind movable shield plugs.

INTRODUCTION

The primary mission of the CIT is to operate utilizing the deuterium-tritium (D-T) fuel cycle in order to extend the knowledge of plasma physics to power-producing reactors. This device is to be located at the Princeton Plasma Physics Laboratory (PPPL) where the use of existing peripheral systems (i.e., motor-generators and power supplies) will minimize capital cost. However, new facilities such as the shielded test cell and hot cell will be constructed to confine neutron-induced activation of reactor structures. The experimental nature of this machine requires the installation of numerous diagnostics, and budgetary constraints for capital funds have led to a very compact design. These two features present a challenge in developing a tokamak configuration that is maintainable; hence, considerations for disassembly and maintenance have been a key factor in the design.

The reactor will initially operate in a nonactivated hydrogen phase for approximately two years. This permits verification of the integrity of the total system and allows hands-on repair to any equipment that has experienced shakedown and early operation failures. Once D-T operations commence, reactor maintenance will require remote handling techniques. A close-proximity (igloo) shield is installed around the device in order to permit personnel access into the test cell 24 h after shutdown. The shield surrounds the reactor and encloses much of the auxiliary equipment that is mounted to the plasma chamber ports. Figure 1 is an elevation view of the machine.

MAINTENANCE PHILOSOPHY

General Approach

The CIT maintenance strategy is to maintain all in-vessel components by remote maintenance (R/M) and to utilize the igloo shield to maximize the hands-on approach to systems outside the shield, after a 24-h cool-down period. CIT components outside the plasma chamber, but inside the shield [for example, toroidal field (TF) and poloidal field (PF) coils, magnet structure, etc.] will be hands-on maintained during the initial hydrogen phase, but their repair and maintenance are not included in R/M strategies or costs following the start of D-T operation. Components such as these which are not affected by "wearout" will undergo extensive quality assurance measures during fabrication and installation, and operational testing during the hydrogen phase will verify their reliability.

*Research sponsored by the Office of Fusion Energy, U.S. Department of Energy, under Contract No. DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

Operations within the penetrations of the shield for port flanges, rf, and diagnostic connections are planned as R/M operations along with operations to replace graphite tiles within the plasma chamber.

Personnel Access

The limitations and safety aspects of maintenance operations that deal with personnel access are governed by Chapter XI of the U.S. Department of Energy "Environmental Protection, Safety, and Health Protection Program for DOE Operations," DOE 5480.1. This document is based on the Code of Federal Regulations, 10CFR20, "Standards for Protection Against Radiation." Basically, these limit doses to radiation workers to less than 5 rem/year, with a quarterly dose not exceeding 3 rem. In addition, both of these codes stipulate implementing the concept of "as low as reasonable achievable" (ALARA) in the design. The general interpretation of ALARA is a dose equal to 1/5 of the limit, or 1 rem/year. The igloo shield is designed to limit the dose rate at the shield boundary to 1 mrem/h, 24 h after shutdown. Therefore, a worker who is constantly at the shield boundary (1 day after reactor shutdown), may spend up to 1000 h in the test cell. On average, this means a worker may spend 20 h per week in the test at the shield boundary, or more than 20 h per week if his activities are away from the shield.

MAINTENANCE OPERATIONS

A preliminary evaluation has been completed to determine the scope of maintenance operations that must be performed on the CIT. In-vessel operations are always accomplished remotely, while ex-vessel operations may consist of a mix of hands-on and remote activities. Repairs, adjustments, and modifications to equipment outside the shield are accomplished by personnel. In addition, personnel will disassemble interfaces and set up remote equipment while the shield is in place in preparation for remote operations. Maintenance activities that require disassembling the igloo shield will be accomplished remotely using teleoperator manipulators. Ex-vessel inspections are accomplished either with personnel or with a surveillance robot, depending upon the state of the shield. In-vessel inspections are accomplished remotely through a vacuum interlock, thereby permitting timely inspections without venting the plasma chamber. A list of representative maintenance tasks is shown below.

- Inspect and replace graphite armor tiles and limiter/divertor plates using remote equipment.
- Inspect and repair the hydraulic preload system using remote equipment.
- Uncouple diagnostic, rf, and fueling interfaces using personnel/remote equipment.
- Remove port covers using remote equipment.
- Replace vacuum windows and certain optical mirrors using remote equipment.
- Accomplish ex-vessel inspections using personnel and remote equipment.
- Perform diagnostic equipment adjustments and modifications using Personnel or remote equipment, depending upon the location of the diagnostics.
- Accomplish vacuum/coolant leak repairs using personnel or remote equipment, depending upon the location of those repairs.

IN-VESSEL OPERATIONS

During D-T operation of the tokamak, activation of vacuum vessel components and retained tritium will preclude personnel access. All maintenance operations must therefore be accomplished remotely through the oblong, radial midplane ports or the smaller vertical ports. The midplane ports are 300 mm wide and 800 mm high and the pairs vertical ports are 50 mm and 100 mm inside diameters.

Two of the midplane ports which are 180 degrees from each other have been dedicated to in-vessel remote maintenance. Figure 1 shows the arrangement of the system. Two of the 100 mm vertical ports, one above each midplane port, are also utilized for maintenance operations. The major maintenance tasks include the following:

- First wall protective tile inspection,
- Tile replacement and height adjustment,
- Leak detection and repair,
- Divertor plate inspection and replacement,
- Divertor or first wall modifications,
- Port bellows replacement,
- RF launcher inspection,
- Diagnostic inspection (in-vessel), and
- Diagnostic repair (in-vessel).

The equipment required to accomplish the tasks above may be grouped into the following categories:

(a) Manipulator Systems
(b) Transport Systems
(c) Inspection/Viewing/Testing Systems
(d) Cutting/Welding/Machining Systems
(e) Mockup Equipment
(f) Miscellaneous Tools

All of this equipment except for the Transport Systems and some Mockup Equipment is designed to operate remotely within the vacuum vessel.

Manipulator Systems. The primary in-vessel remote maintenance devices are a pair of articulated boom manipulators (ABMs), with each having a bilateral servomanipulator. Provisions are made to interchange these manipulators with other (robotic) mechanisms, including the First Wall Tile Installation/Removal machine tool. Interchangeable end effectors on the servomanipulators allow the use of general purpose wrenches and tools. TV cameras and lighting will be carried on each ABM to provide viewing and operator guidance during operations.

The ABMs are housed in vacuum enclosures attached to the two vacuum vessel midplane ports that are dedicated to remote handling. Figure 2 shows a plan view of an ABM. Air locks are provided to allow passage of tools and equipment into the ABM enclosure while under vacuum. Maintenance operations can therefore be accomplished without venting the vacuum vessel, although work may also be done in air or another appropriate atmosphere during long machine shutdown periods. The enclosures are shielded by movable plugs to prevent activation of the booms by plamsa neutrons. The booms are robotically programmed to move from the stored position in the enclosure to the required position in the vacuum vessel where operators can choose the desired mix of manual/robotic control. The ABMs are capable of being removed from the tokamak inside a transport cask, which will allow transfer to the decontamination area and then to a warm cell for hands-on maintenance.

The choice of the articulated boom configuration was influenced by two other experimental tokamaks. The Joint European Torus (JET) has built and operated an articulated boom for in-vessel maintenance. This design is expected to provide a wealth of data as the boom sees more use and new control systems are integrated. A boom is also being built for the Tokamak Fusion Test Reactor (TFTR) and will be delivered to Princeton Plasma Physics Laboratory (PPPL)[1] in 1987. The timing of this program will provide valuable input for the CIT boom.

An alternative to the ABM, a track-mounted manipulator, was suggested in a tokamak study in 1976.[2] This approach requires some form of an articulated boom to handle the conduit and cables, and also to install/remove the manipulator from the vessel. In addition, a permanent in-vessel rail support would be subject to damage from plamsa disruptions, and installing a removable track will increase the total downtime for in-vessel operations. For these reasons and the uncertainty of using an unproven design, the choice for CIT was to adopt the approach used by JET and TFTR.

Transport Systems. A system of lifting slings, handling tools, transport casks, and dollies are required to transport in-vessel components to and from the tokamak to points within the CIT site boundaries. The casks will provide shielding for radioactive components as well as containment for contamination. Destinations for these components include the decontamination facility, warm cell, hot cell, and waste storage area. Casks are required for the first wall tiles, divertor modules, articulated boom, inspection/viewing manipulator, and in-vessel tools. The first wall tile and divertor module casks are shielded to protect personnel from these highly radioactive components which are directly exposed to plasma neutrons. The ABM and inspection/viewing manipulator, which are both shielded from the plasma, require casks that are primarily containment vessels for on-site transportation. Radioactive particles and tritium contamination on in-vessel manipulators will therefore be confined to those areas designed for handling these materials. Temporary support racks and brackets to provide laydown or erection of casks are also included in Transport Systems.

Inspection/Viewing/Testing System. Special purpose inspection, viewing, and testing systems are required for in-vessel operations. These include inspection of in-vessel components, viewing of manipulator operations, vacuum leak testing, and nondestructive examination of completed vessel welds. During normal plasma operations, most of the heat load falls on the graphite first wall tiles that must protect the vacuum vessel. A normal plasma pulse lasts about 3.5 s. Approximately one hour of cooldown time is required between pulses. Plasma disruptions may damage first wall components that must be intact for the follow-on plasma shot. To assess wall conditions, an inspection/viewing manipulator is provided. The viewing and inspection equipment consists of a small, high resolution TV camera and lighting system which is mounted on a compact, easily deployed, articulated arm inserted through a vertical port above each large radial maintenance port. This arm will also be useful for providing additional viewing of the ABM during in-vessel maintenance operations.

An audio system is provided as part of the inspection/viewing/testing equipment. The transmission of sounds emitted by remote tools and their interaction with the components being maintained provides important feedback to operators.

A mobile remote leak detection device is an important part of the inspection system. Leak detection and location in tokamaks is a critical issue. Some candidate methods for leak detection include:

- o Pumpout at weld joints and demountable seals for tracer gas introduction,
- o An ex-vessel "sniffer" used in single wall areas where accessible,
- o An in-vessel "sniffer" used in partial vacuum,
- o A photon detection device using glow discharge, and
- o A particle "leak telescope."

The leak telescope is an idea suggested in 1977.[3] The principle involves the straight line path of particles in a vacuum which may be detected by a directional ion gauge or residual gas analyzer (RGA) thus locating the origin of the leak or outgassing. A mockup of the device was briefly tested in 1977 as discussed in the reference. Development work is in progress for use on TFTR.

Cutting/Welding/Machining Systems. Special purpose equipment is required to install mounting studs for first wall tiles to accomplish vacuum leak repair, and to weld and cut for replacing the bellows that attach the various ports to the vacuum vessel. In addition a dedicated orbital welder is used to join the vacuum vessel sectors at initial assembly.

The arrangement of the graphite first wall tile is shown in Fig. 3. Most tiles are round, 80 mm in diameter, and 10 mm thick. They have a central, internally threaded foot which is attached to the vessel wall by screwing them onto studs which have been welded to the wall. Two types of tiles (inside and outside) are used in an overlapping pattern to completely cover the wall, as shown in the figure. The tiles are adjustable in height by virtue of the tile stud and its thread locking characteristics. A remote stud welding machine is provided to mount studs as necessary within the vacuum vessel. This machine is mounted on the ABM, when required.

Remote equipment is also required for various welding and cutting operations. Once a leak is detected, a manual (manipulator held) welder is needed to make the repair. Orbital cutting and welding machines are required in the event that vacuum vessel port bellows must be replaced. The ports are designed such that the bellows can be replaced from inside the vessel. Orbital cutting machines, one each for small and large ports, are transported by the ABM to the proper location.

The orbital welder that initially welds the tokamak vessel is also a part of this system. The core of the CIT device is assembled into half-modules which consist of TF coils, internal plasma control coils, and a vacuum vessel/first wall assembly. The two torus half-modules are brought together and aligned with fixtures at the open ends in preparation for welding. A guide track is installed in the inner bore of the vacuum vessel near the weld joint. The orbital welder is mounted on this track and makes the required number of passes, controlled from the outside of the vessel. This operation is repeated at the other joint on the opposite side of the torus. Welding fixtures and guide rails can be manually disassembled and removed since personnel access is possible at this time.

Miscellaneous Tools. This equipment group includes small manual and power tools, such as wenches, sockets, drivers, drill motors, and other end effectors which are required for the in-vessel manipulators. Two major equipment items included in this category are the Tile Installation/Removal Machine (TIRM), and the Divertor Module Installation/Removal Machine. Cleanup equipment is also included in this category. A concept for the TIRM is shown in Fig. 4. This machine is mounted on the ABM. It is conceived as a turret-type mechanism which can bring different tools into operation in sequence. For initial tile installation, careful alignment is required to assure that tile internal threads mate properly with tile studs on the vacuum vessel wall. The tile stud alignment tool accomplishes this mission. Additionally, tile and stud threads are designed to preclude cross-threading. For damaged tile replacement, special alignment tools (one each for inside and outside tiles) are used to bring the machine into proper position for operations. A tile grappler is used for the actual installation and removal operation. A conceptually similar machine is planned for installing and removing divertor modules.

EX-VESSEL OPERATIONS

The ex-vessel maintenance operations consist of repairing and replacing auxiliary reactor components, such as diagnostic, heating, and fueling systems, and performing inspections utilizing both personnel and remotely operated equipment in the test cell. An overhead, bilateral manipulator system mounted to a telescoping boom is the primary means of accomplishing dexterous operations after the igloo shield modules have been disassembled. This manipulator system has a 10-kg lift capacity and incorporates remotely controlled lighting and viewing, and an audio sensor. Tools used by the manipulator are designed to be compatible with the end-effectors. The system to be used for test cell operations incorporates force-reflection. A similar manipulator system may be required for hot cell operations, although through-the-wall mechanical manipulators and shield windows may be adequate. Figure 5 is an elevation view of the CIT which shows personnel access behind the close-proximity shield and the boom-mounted overhead manipulator.

Inspections prior to personnel entry or during remote maintenance operations will be accomplished by any one of numerous commerically available surveillance robots. They are either cable or radio controlled and incorporate local viewing and lighting systems, radiation detection monitors, and may have manipulator arms for light-duty tasks. It is presently planned to have a mobile robot if the floor areas around the machine remain uncluttered. In that case, a device like that shown in Fig. 6 could be used for ex-vessel inspections.[4] If the test cell floor area cannot be designed with clear access for robot operations, then the overhead crane will be used to emplace a fixed-position inspection robot.

A number of equipment categories were established to accomplish the ex-vessel maintenance tasks. To attain the required device maintainability, remote maintenance equipment and procedures, including facility related features are being developed in parallel with the development of the machine configuration. For critical remote operations, development programs will make extensive use of a mockup facility to assure the functional adequacy and reliability of the concepts and equipment.

Manipulator Systems. Manipulator systems will be required in the test cell and hot cell to accomplish dexterous operations. The test cell will use a force-reflecting servomanipulator with essentially the same mechanical capabilities as man. It will be operated primarily in a teleoperated mode to disconnect equipment interfaces and to assist the main crane for lifting components.

Transport Systems. Lifting slings, shackles, lifting beams and frames, transport dollies, and general purpose temporary support equipment will be required in the test cell, hot cell, and decontamination/transfer area to move equipment from the tokamak to the hot cell or warm cell. The transporter for the test cell manipulator is a bridge-mounted, telescoping boom with preprogrammed positioning capability.

Remote Cutting/Welding/Machining Equipment. Tokamak system cooling lines, electrical bus bars, vacuum system seal welds, etc., will require remote cutting, welding, and machining operations because of high radiation levels in the test cell. Also, repair operations in the hot cell must all be remote. Wherever possible, the redesign of commercially available equipment is the primary approach; these will then be demonstrated and tested in the mockup facility.

Miscellaneous Tools. Small hand and power tools, such as wrenches, sockets, drill motors, etc., will be required in the test cell, hot cell, and warm cell. Additionally, larger tools, lathes, milling machines, etc., may be required in the hot cell and warm cell. Because of contamination and activation, it will not be convenient to transfer tools from area to area, thus a separate set of tools are dedicated for each area.

Decontamination Equipment. To minimize the radiation exposure and risk to personnel working in the warm cell and to prevent the spread of contamination, decontamination procedures and equipment are provided. The major equipment item will be the decontamination spray system located in a decon cell or possibly within the hot cell. Minor equipment will be laundry sinks, dishwashers, drying/storage racks, etc., in controlled areas adjacent to the warm and hot cells. All equipment leaving the test cell is decontaminated and routed to either the hot cell for remote operations or the warm cell for hands-on operations.

Rad-Waste Treatment/Disposal. Monitoring and control of radioactive material generated by maintenance activities in the test cell, hot cell, warm cell, and decontamination area must be maintained and coordinated with the general site rad-waste treatment and disposal practices. A solid rad-waste handling installation is located in the hot cell consisting of a robot arm, compacting equipment, and cask handling equipment.

Typical Ex-Vessel Operation. Replacement of Faraday shields and loop antennae for an rf module illustrates a typical maintenance operation. Prior to disassembling the shield modules, electrical and coolant interfaces are decoupled using personnel access. The appropriate shield modules are removed using the overhead crane, and then structural and vacuum interfaces will be decoupled using the overhead manipulator. The rf module is extracted onto a temporary support platform for access by the manipulator. The modular Faraday shields and antennae may be replaced in situ using end-effector tools. Figure 7 is an elevation of CIT prior to removing shield modules and extracting the rf module.

Figure 8 shows the extracted rf module being repaired in the test cell. This scenario is based on a scheduled repair cycle that is not so frequent as to adversely affect tokamak availability. Very frequent repairs may require spare rf modules and hot cell operations.

MAINTENANCE-RELATED FACILITIES

Most of the maintenance activities for the repair or replacement of reactor auxiliary equipment will occur in the test cell. These include the repair of rf modules, the replacement of modular diagnostic components, and various inspections. Components that must be moved to the hot cell for repair or disposal are lowered through the test cell floor hatch onto a transfer cart. The cart passes through the decontamination cell and then into the hatchway area below the hot cell. The decontaminated component is then lifted into the hot cell for remote operations. Components that are moved back from the hot cell to the test cell are decontaminated again. The warm cell is located below the hot cell and serves as an area for controlled hands-on maintenance for components that are mildly activated or contaminated.

The Fabrication, Assembly, and Mockup Building, which is adjacent to the test cell, contains a full-size replica of one-quarter of the reactor and the necessary remote handling equipment for accomplishing maintenance operations. Initially, the mockup will be used to develop special maintenance equipment and procedures and will provide the basis for verifying the maintainability of the CIT configuration. Later on, the mockup will be used for trial fitups of replacement components and for operator training. The mockup facility is expected to be used throughout the CIT lifetime, including support for tokamak decommissioning. This facility provides a simulated CIT environment for remote equipment testing. Because remote tooling and equipment used in the vacuum vessel or located in the test cell will become contaminated and/or activated, a separate set of tools and equipment is required for the mockup area.

CONCLUSION

The conceptual design work investigating the maintainability of the CIT configuration indicates that this reactor design can be maintained in a cost-effective manner. The impact of compactness on maintenance and disassembly for this design is being alleviated by requiring modular auxiliary equipment with simple, accessible interfaces. The auxiliary equipment is being designed to be compatible with remote handling equipment which is based on present state-of-the-art equipment. Research and development (R&D) activities were started in FY 1987 to support the advanced conceptual design for FY 1987. It is anticipated that CIT will become a line item project in the 1988 budget.

REFERENCES

1. TFTR Maintenance Manipulator and Antechamber Final Design Review; Princeton Plasma Physics Laboratory, July 1, 1986.

2. P. H. SAGER and E. R. HACER, "Design Considerations for Access to Tokamak Fusion Reactors," Nuclear Engineering and Design, 39, 153, (1976).

3. E. S. ENSBERG, J. C. WESELY, and T. H. JENSEN, "Leak Telescope," Rev. Sci. Instr., 48, No. 3, 357 (1977).

4. J. R. WHITE et al., "Surveillance Robot for Nuclear Power Plants," Proceedings of the 33rd Conference on Remote Systems Technology, ANS Winter Meeting, San Francisco, November 1985.

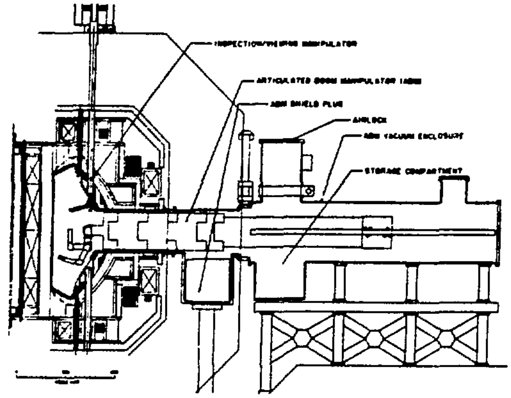

Fig. 1. CIT elevation with ABM system.

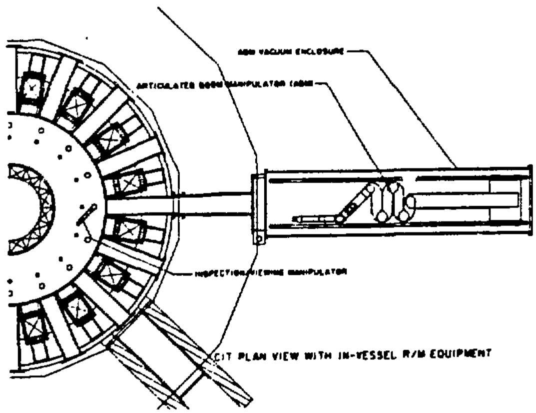

Fig. 2. Plan view of ABM installed.

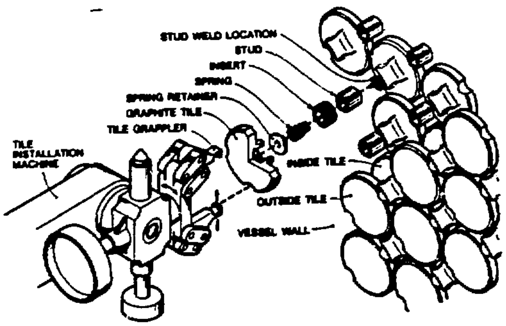

Fig. 3. Graphite first wall tiles and tile installation machine.

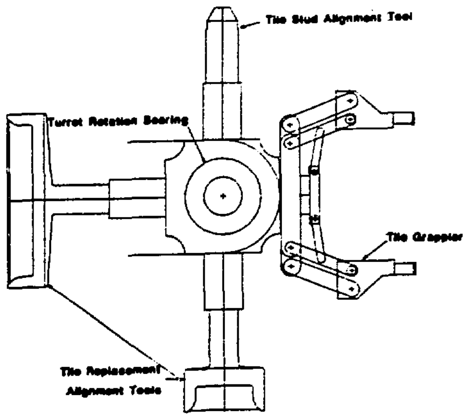

Fig. 4. End view of the graphite tile handling machine.

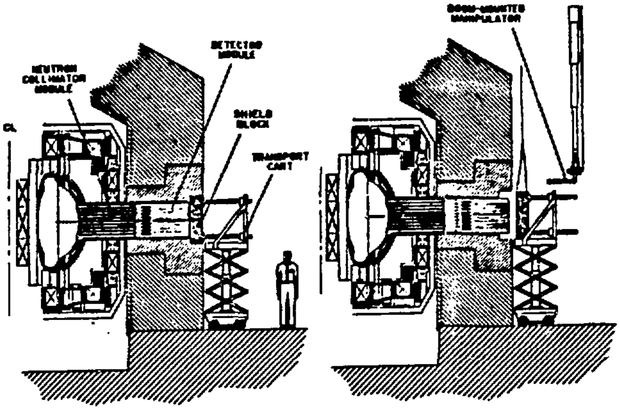

Fig. 5. Personnel access is permitted behind the igloo shield.

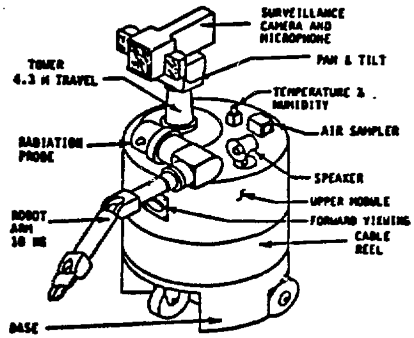

Fig. 6. Teleoperated inspection robot.

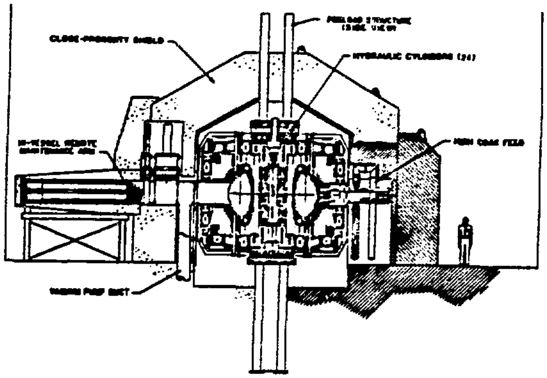

Fig. 7. CIT elevation with igloo shield.

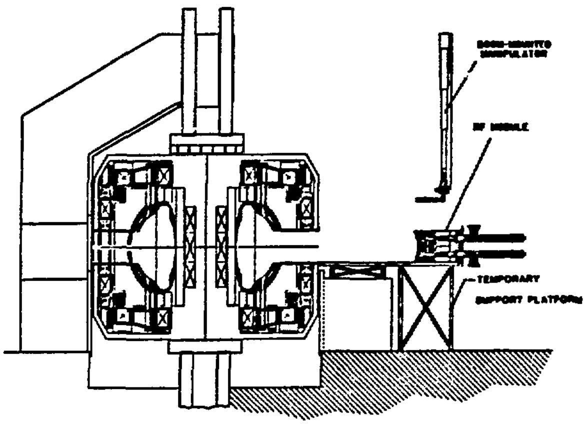

Fig. 8. RF module replacement.

DISCLAIMER