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EX-VESSEL REMOTE MAINTENANCE DESIGN FOR THE COMPACT IGNITION TOKAMAK*

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ABSTRACT

The use of deuterium-tritium (D-T) fuel for operation of the Compact Ignition Tokamak (CIT) imposes a requirement for remote handling technology to carry out maintenance operations on auxiliary machine components. These operations consist of removing and repairing components such as diagnostics and radio frequency (rf) heating modules using remotely operated maintenance equipment. The major equipment that is being developed to accomplish maintenance external to the plasma chamber includes the bridge-mounted manipulator system for test cell operations, decontamination (decon) equipment, hot cell equipment, and solid rad-waste handling equipment. Wherever possible, the project will use commercially available equipment. Several areas of the maintenance system design have been addressed in fiscal year (FY) 1987. These included conceptual designs of manipulator systems, the start of a remote equipment research and development (R&D) program, and definition of the hot cell, decon, and equipment repair facility requirements. The manipulator work included investigating transporters and viewing/lighting subsystems. In each case, existing commercial units are being assessed initially, along with viable alternative approaches. R&D work also included demonstrations of remote handling operations on full-size, partial mock-ups of the CIT machine at the Oak Ridge National Laboratory (ORNL) Remote Operations and Maintenance Development Facility.

INTRODUCTION

The CIT will be the next experimental machine in the U.S. Fusion Program and will be located at Princeton Plasma Physics Laboratory. Its use of D-T fuel requires the implementation of remote handling technology for maintenance and disassembly operations. The module will be surrounded by a close-in nuclear shield designed to permit personnel access into the test cell 24 h after shutdown. With the shield in place, certain maintenance activities in the cell may be done hands-on. Maintenance on the tokamak will be accomplished remotely with a boom-mounted manipulator after disassembling shield modules. Maintenance within the plasma chamber will be accomplished with two articulated boom manipulators operating in a vacuum environment. These areas are not discussed in this paper.

The machine will initially operate in a nonactivated hydrogen phase for approximately two years. This will permit verification of the integrity of the total system and allow hands-on repair of any equipment that fails during shakedown or early operation. In addition, the operation of installed maintenance equipment in the test cell will be demonstrated. Once D-T operations commence, device maintenance will require remote handling techniques. The design activities for FY 1987 have focused on establishing equipment interfaces with the facility design, developing manipulator system requirements, and using mock-up demonstrations to support the tokamak configuration design. These activities are described in the following sections.

FACILITY FEATURES

The maintenance philosophy for the test cell is influenced by the close proximity neutron/gamma shield surrounding the machine, which allows personnel access into the test cell. Hence, maintenance operations can be performed hands-on in the test cell with the shield intact but must be remotely performed when the shield is disassembled for machine access. The shield has a modular construction so that removal of a shield module exposes a segment of the machine for maintenance work. Figure 1 is an isometric view of the tokamak with the shield structure partially removed. A bridge-mounted master-slave manipulator system and the overhead crane are used to maintain or replace equipment modules that interface with the machine. Figure 2 is a cutaway view of the tokamak, the bridge-mounted manipulator, and the polar bridge crane contained in the test cell. A second, floor-based mobile

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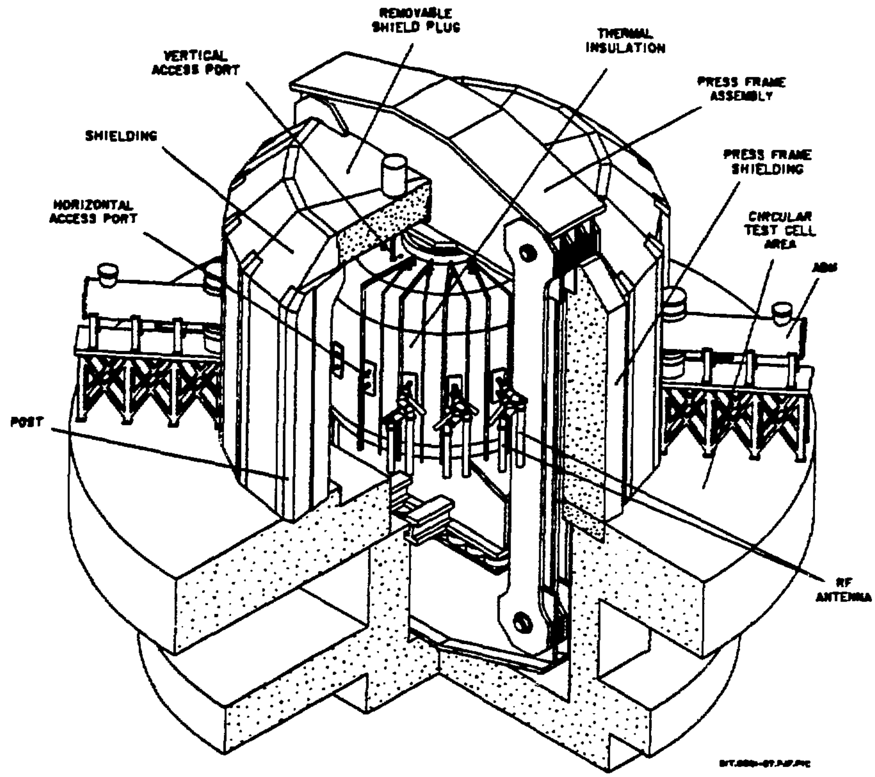

Fig. 1. Compact Ignition Tokamak with the nuclear shield partially removed.

manipulator (not shown) is used for operations in the area underneath the machine.

The shielded test cell is adjacent to an airlock transfer area, leading into the decon cell. After decon, highly activated components are remotely loaded into a shielded cask for transport to the hot cell. Non-activated components are transferred to the warm cell in an unshielded containment structure. The hot cell and warm cell are located in an existing shielded building, which will be modified to meet the CIT needs. The hot cell will also contain the equipment for solid rad-waste handling.

MAINTENANCE CONCEPT DEVELOPMENT

The CIT maintenance concept relies primarily on remote means to repair and replace failed equipment on the tokamak machine. Highly irradiated and contaminated auxiliary components of the fusion device, such as diagnostics, rf heating, and fueling systems scheduled for repair or replacement, will be removed from the test cell through shielded doors on a cart transfer system. The general sequence of operations for component maintenance is shown in Fig. 3. The main path for failed components is remote removal and transport to a shielded facility for decon followed by transfer to the hot cell for repair. If repairs cannot be performed, the component will be scrapped. The radioactive components will be remotely processed by special tools to reduce the volume of scrap before it is placed in sealed containers, which are then stored awaiting off-site shipment.

The major thrust of the work for FY-1987 has been to define maintenance requirements to a degree sufficient to identify major impacts on the facility configuration. These studies included evaluation of remote handling and manipulator transporter system arrangements, access to machine components requiring remote maintenance, and requirements for transport, decontamination, and repair or disposal of failed components. The progress of these studies is described below.

Assessment of Manipulator Systems

Remote handling and manipulator transport systems have a major impact on cell configuration and equipment layout. This study investigated the best way to provide manipulator coverage of the tokamak and associated cell equipment. Alternatives included overhead

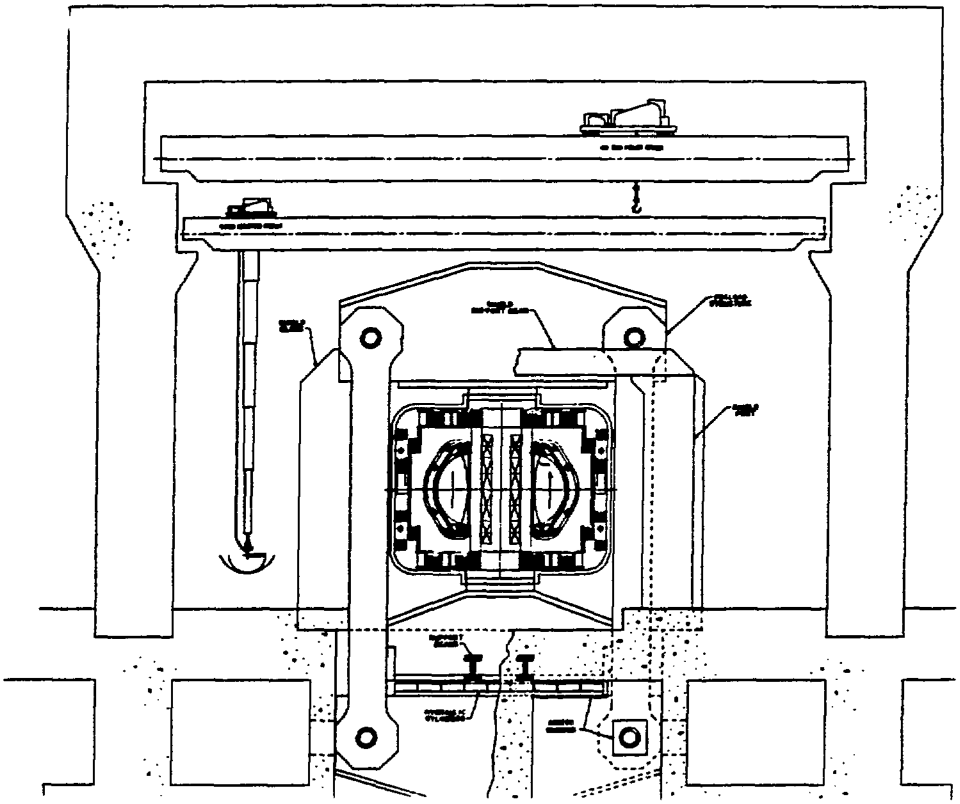

Fig. 2. A bridge-mounted manipulator system and the overhead crane are the primary equipment for test cell maintenance operations.

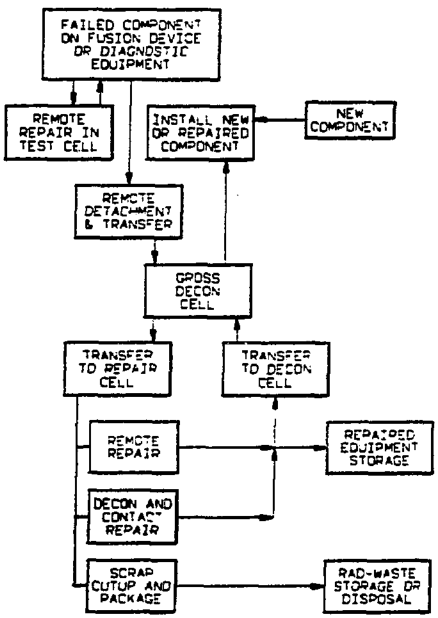

Fig. 3. Equipment maintenance sequence.

systems with either a telescoping boom or a rigid mast and floor-based systems including fixed-mount and mobile manipulators.

The prime candidates that evolved from these studies were the bridge-mounted manipulator with telescoping mast, shown in Fig. 4, and a floor-mounted system with an articulated boom, shown in Fig. 5. These systems are compared in Table 1.

The overhead system has been selected for the baseline configuration. This resulted from a comparison of the two systems and also modification of the arrangement of the igloo shield to provide unrestricted manipulator access. The overhead system provides full test cell coverage without interference from floor-mounted machine components.

Impact of the Igloo Shield on Maintenance in the Test Cell

The repair of any of the ex-vessel auxiliary machine components involves gaining access to the vertical ports on top of or beneath the machine and to the 18 midplane ports on the side

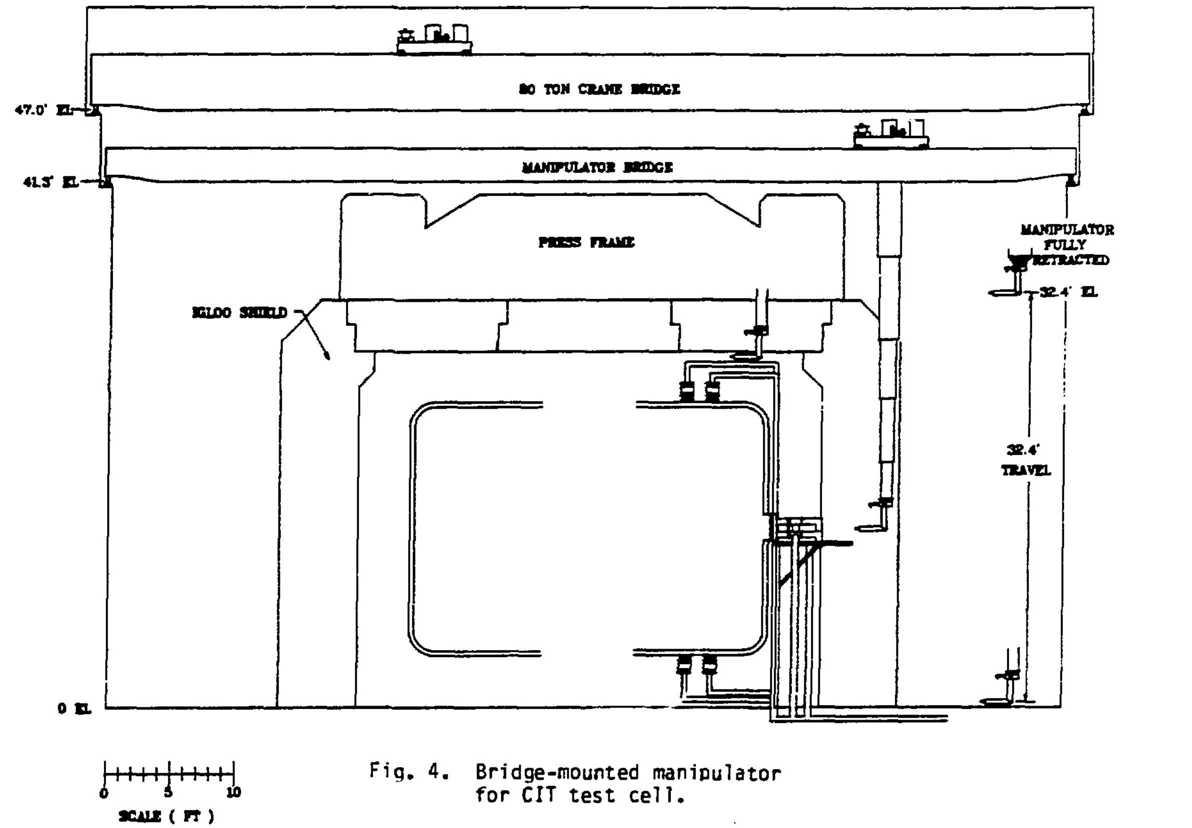

Fig. 4. Bridge-mounted manipulator for CIT test cell.

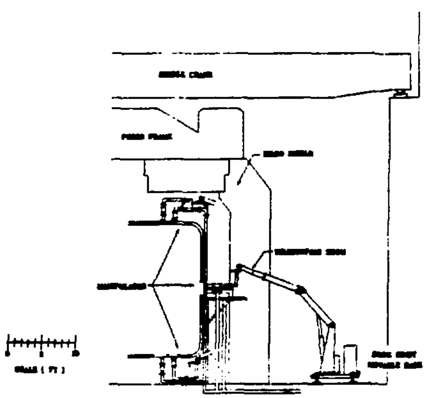

Fig. 5. Elevation view of CIT cell with typical floor-mounted manipulator positions.

of the machine. Any of these tasks requires insertion of the manipulator slave with its TV viewing cameras and auxiliary hoist into the opening made by removing a shield module, as shown in Figs. 6 and 7. In this study, it was shown that the shield walls limited lateral movement of the manipulator to essentially a head-on radial approach to each port. This created remote handling problems for the component designer and imposed some abnormal requirements for the slave-arm configuration and motions. Severe restraints were also imposed on the viewing systems and the means for providing auxiliary hoisting assistance.

As a result of this study, the shield designers revised the igloo design to maximize manipulator access. The bridge-mounted manipulator now has free access to all the ports except those underneath the machine. The overhead transport system can position the manipulator slave arms and viewing equipment in and around each diagnostic port and rf heating port to perform the intricate tasks of disconnecting and replacing vacuum, electrical, and cooling interfaces.

Computer Modeling of Manipulator Tasks

Three-dimensional, CATIA-developed kinematic models of manipulators and solid models of the upper diagnostic and midplane port areas of

Table 1. Comparison of Bridge-Mounted and Floor-Mounted Manipulator Systems

	Polar Bridge-Mounted Manipulator with Telescoping Mast	Floor-Mounted Manipulator with Articulated Boom
Positioning and Coverage	- Covers entire work area of test cell - Limited horizontal reach into confined spaces - Vertical extensions limited to 30-35 ft. - Radial approach constraint	- Requires several locations to cover test cell area - Good for both horizontal and vertical extension - Questionable access to upper diagnostics - Requires two different arm configurations
Compatibility with Other Systems	- Competes with bridge crane for overhead space - Creates 20-25% blind area for hook coverage of igloo in round cell configuration - Interferes with crane load moves	- Competes for floor space with other floor-mounted equipment - Crane can provide 100% support - No interference with crane load movements
Obstacle Avoidance	- Bridge provides overhead clearance - Telescoping boom avoids need for aisle-way clearance	- Some interference with boom traverse - Requires horizontal access clearance for floor-level work
Impact on Cell Design	- Increases cell height by 5-6 ft. - Favors rectangular over round cell configuration to minimize blind spots for hook coverage in center of test cell area	- May force cell configuration with more floor space depending on number of stations required
Operations	- Operates independently throughout cell - Can operate through top plug opening - Can traverse inside of shield	- Requires crane support to relocate - Must always remove side shield segments and sometimes top plug - Must operate between shield supports
Failure Recovery	- Must be disassembled in place and components removed, except bridge	- Entire unit can be transferred out of cell
Relative Cost	- Bridge system more costly, but only one required - Other manipulator devices needed for total coverage	- Lower cost per system, but may require more than one - Other manipulator devices may be needed for total coverage

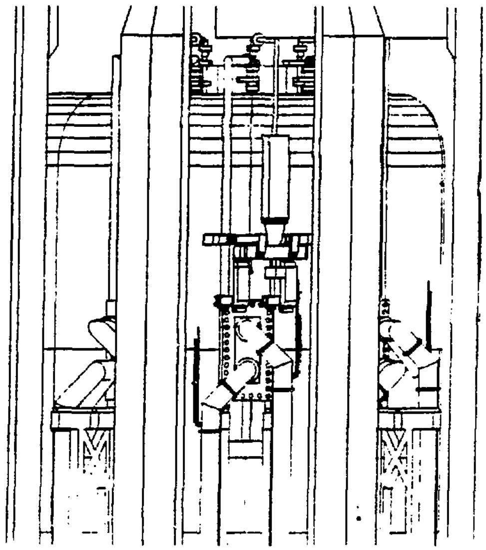

Fig. 6. Elevation view of midplane and upper ports and overhead manipulator.

the CIT machine are proving to be a powerful tool in our efforts to evaluate access and reach requirements. Figures 6-8 are examples of the CATIA system models. The preliminary studies conducted so far have identified the initial manipulator requirements listed in Table 2. In particular, these efforts have revealed accessibility conditions, such as those shown in Fig. 8 which may require special arm/joint configurations for avoiding obstacles. An example of the special arm/joint configurations that are being evaluated is shown in Fig. 9.

Table 2. Initial Manipulator Requirements

o Two-arm (separable)	- Guiding, balancing - Tool handling - Efficiency
o Real-time M/S response	- Efficiency - Manipulator protection
o Force-reflection M/S	- Efficiency - Difficult tasks - Unknowns - Manipulator protection
o Maximum envelope: 4-in. x 4-in. cross-section	- Small clearances - Compact equipment arrangement
o Redundant kinematics	- Multiple stances - Multiple obstacle avoidance - Compact/complex equipment arrangement

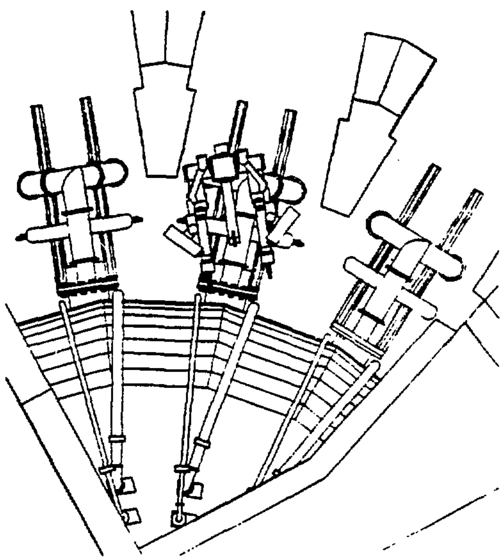

Fig. 7. Plan view of upper ports and manipulator system.

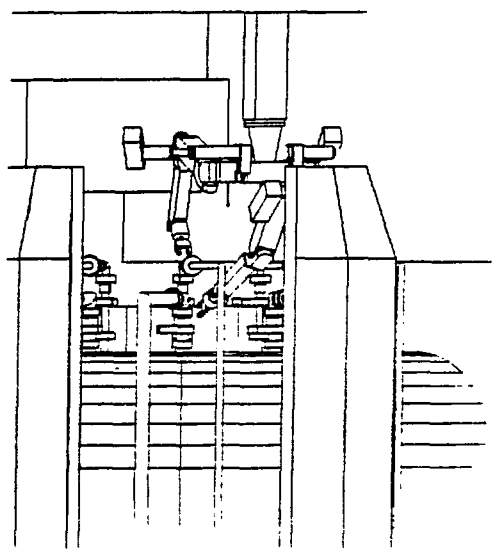

Fig. 8. Elevation view of upper ports and manipulator system.

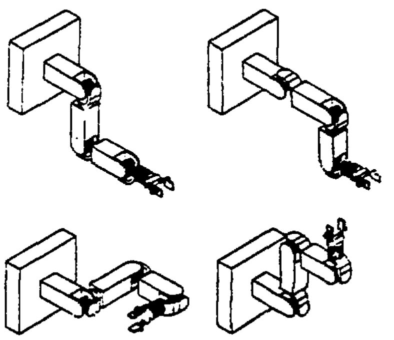

Fig. 9. Slave arm with 7 degrees of freedom in various positions of reach.

Remote Maintenance Demonstration

Studies of CIT ex-vessel maintenance tasks have been under way to determine capabilities and equipment requirements for the ex-vessel maintenance system. At present, mock-up demonstrations for upper diagnostic hardware and midplane port devices are being designed or are complete. From this work, several specific maintenance tasks and equipment have been recognized as necessary for the ex-vessel maintenance system. These demonstrations are conducted on full-scale, partial mock-ups of the CIT machine at ORNL's Remote Operations and Maintenance Development Facility using a Central Research Laboratory Model M-2 manipulator.

One demonstration is intended to simulate various tasks required to maintain diagnostic hardware and associated vacuum piping located on the upper surface of the CIT. The mock-up demonstration will investigate vision requirements (camera locations) and manipulator access to this equipment. Design and component procurement are under way to develop a means of remotely assembling high-vacuum piping systems. One vacuum pipe flange that was considered is manufactured by Varian Associates under the trade name Conflat. Its inherent features may hinder efforts to remotize its assembly. Its delicate copper seal, without modification, is easily damaged by manipulators. The flange clamping force is supplied by bolts (16 for a 4-in.-OD tube) mounted in a circle outside the copper seal. This makes each remotized joint expensive (captive bolts are generally expensive) as well as time-consuming to assemble or remove. The first mock-up demonstration used this type of flange.

The vacuum pipe flange now being considered for CIT use is manufactured by Helicoflex Company and is specifically designed for remote handling. It is the type specified for use on the Joint European Torus (JET) in the European Fusion Program. Its metal seal is relatively easy for manipulators to handle, and the seal also aids in flange alignment and support. One driving bolt provides the flange clamping force. Hardware required to assemble a vacuum system using this type of flange coupling will be evaluated. Methods and procedures for remotely assembling these vacuum joints will be tested and refined during FY 1988.

A second demonstration is being conducted to help in understanding the viewing needs for maintaining the upper diagnostics. Because of the compact and complex arrangement of the diagnostics and their associated vacuum piping, and the physical constraints of the igloo shield, its support structure, and the press frame, there is not much space for TV cameras. Ideally, the operator would prefer a belly-mount view as well as upper right and left views. It is not apparent that all of these views can be provided, since the location of cameras could interfere with machine components. The M-2 upper cameras are mounted on R-O positioners and can be moved to determine appropriate locations and their resulting views.

A third demonstration project is intended to simulate the removal and installation of the rf module, which is mounted in several midplane ports. The ex-vessel maintenance system will be required to remotely detach and remove the rf module from the CIT device for refurbishment in the hot cell. Common tasks to be performed remotely include:

- removal and installation of the igloo shield sections,
- aligning and supporting the rf coaxial pipes during removal and installation,
- making and breaking connections at the rf coaxial pipes and midplane port (flange bolts, electrical connectors, and coolant connectors),
- pushing and pulling the rf module into and out of the midplane port.

Remote Maintenance Design Guide

A manual that provides basic guidelines for design of equipment to be remotely maintained is being developed for issue to equipment designers responsible for the diagnostic, fueling, and rf heating systems, to name a few. The guidelines will be based on proven techniques used at other facilities for design of similar equipment. Designs specific to CIT will be incorporated from the remote maintenance demonstration mock-ups of the CIT machine components conducted at ORNL.

Maintenance Facilities

The functional requirements and special design features of the maintenance facilities needed for decon, remote and contact repair, scrapped equipment and rad-waste processing, and equipment and rad-waste storage have also been studied to determine their impact on facility design. Detailed operational sequences were generated, resulting in the following generalized requirements.

- o Local contamination control is needed, particularly for replacement of equipment interfacing with the vacuum vessel, to minimize the spread of activated graphite dust and other particulates from the vessel interior surfaces.
- o Controlled intercell transfers are needed throughout the test cell, repair cells, and tritium handling areas.
- o All equipment leaving the test cell must undergo decon before repair, storage, or scrapping. As a further precaution, all equipment introduced into the test cell from the maintenance facilities is also decontaminated. Decon fluid storage and processing equipment is needed. An alternative proposal for a nonchemical system that recycles the cleaning agent and minimizes waste is under consideration.
- o Damaged first-wall graphite tiles, diverter plates, and other components from within the vessel will be compacted, packaged, and stored in shielded casks.

ACTIVITIES FOR FY 1988

The work planned for FY 1988 will focus on R&D activities to support the development of a manipulator system prototype; the manipulator transporter; inspection and viewing equipment; and various fasteners, flanges, and connectors for remote handling. Some work will be done on cutting and welding equipment. In addition, work will be started for designing a full-scale quadrant mock-up of the machine to be located at the Princeton site. The design-related work will be more limited and will concentrate on the preliminary design of decon and waste handling equipment, the hot cell equipment, and the remote maintenance control room.

Upgrading the existing mock-ups at ORNL to reflect the final machine configuration will be a priority activity. The mock-up of the upper vacuum pipes was based on an early version of the machine size and the igloo structure. Changes to the igloo were, in fact, a result of the first mock-up demonstrations. The rf mock-up will be modified to study access and reach for various diagnostic modules. A new mock-up of the vacuum pipes under the machine is planned for the second half of 1988.

CONCLUSIONS

The CIT is providing the impetus to apply existing remote handling technology to fusion device maintenance and to develop new approaches where needed. The activities for this past year have focused on developing maintenance requirements and conceptual designs of maintenance equipment. The early use of partial mock-ups has been invaluable in studying problems of access and reach and has had an impact on the development of the machine configuration. The work for next year will emphasize manipulator system development, preliminary design of facilities-related equipment, and the continued use of full-size mock-ups.

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