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ABSTRACT

The use of deuterium-tritium fuel in the Compact Ignition Tokamak will require applying remote handling technology for ex-vessel maintenance and replacement of machine components. Highly activated and contaminated components of the fusion devices auxiliary systems, such as diagnostics and RF heating, must be replaced using remotely operated maintenance equipment in the test cell. In-vessel remote maintenance included replacement of diverter and first wall hardware, faraday shields, and for an in-vessel inspection system. Provision for remote replacement of a vacuum vessel sector, toroidal field coil or poloidal field ring coil was not included in the project baseline.

As a result of recent coil failures experienced at a number of facilities, the CIT project decided to reconsider the question of remote recovery from a coil failure and, in January of 1990, initiated a coil replacement study. This study focused on the technical requirements and impact on fusion machine design associated with remote recovery from any coil failure.

INTRODUCTION

The Compact Ignition Tokamak (CIT) Project located at the Princeton Plasma Physics Laboratory (PPPL), will be the next major experimental machine in the U.S. Fusion Program. Its use of deuterium-tritium (D-T) fuel will result in high radiation levels and the need for a high degree of remote maintenance (RM) capability. Highly activated and contaminated components from the fusion device's auxiliary systems, such as diagnostics and RF heating, must be replaced using remotely operated maintenance equipment in the test cell and maintenance facilities.

Recent coil failures experienced by TFTR, JET, JT-60, and TORE SUPRA have caused CIT to reconsider its past position regarding coil failures. Prior to these recent failures, toroidal field (TF) coil failures were considered unlikely and therefore CIT did not incorporate provisions to replace them. Poloidal field (PF) coils were considered to have a low probability of failure, but nevertheless such failures had to be considered.

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In January, 1990 the project initiated a coil replacement study to assess the impact of making remote recovery from a TF coil failure a project requirement. The effort was led by ORNL, with participation by members throughout the project team, as well as reviewers from industry and the fusion community. The requirement to provide for repair or replacement of one or more machine coil components has had a significant impact on the maintenance system capabilities. This paper discusses how the CIT maintenance conceptual development has developed to meet the new challenges that are required to obtain a degree of maintainability never before attempted on a fusion machine. The results of this study are documented in detail in Ref. 3.

BASELINE CONCEPTUAL DESIGN

The CIT fusion device is located in the center cell of the test cell facility. The machine will operate initially in a non-activating hydrogen phase for approximately 1-2 years. This will permit hands on repair of equipment that fails during shakedown runs, and will also allow demonstration of remote operations.

The basic remote handling systems concept for CIT has been described previously in Ref. 1. In-vessel maintenance activities will be performed by appropriate end-effectors supported on an articulated boom that is introduced through one of the horizontal ports. This system is required to have a high degree of dexterity and sensitivity to accomplish the exacting tasks associated with maintaining first wall components and other in-vessel elements.

The ex-vessel remote handling system has the same requirements as the in-vessel system for performing many dexterous tasks as well as the ability to handle large, heavy loads and position them with precision. Virtually all machine components that interface with the vertical and horizontal ports of the vacuum vessel will be designed for remote handling and replacement. These components will be repaired or disposed of in the hot repair cell. Figure 1 shows the arrangement of the various cells in the shielded facility. The development of the CIT ex-vessel maintenance concept was described in Ref. 2. An overhead bridge-mounted manipulator system is the primary means for remote operations on the upper vertical ports and the horizontal ports, and on the floor area of the test cell. A floor-based mobile robot would perform remote operations in the area under the machine, including the lower vertical ports. In general, these two systems accomplish the ex-vessel remote maintenance operations.

In the baseline conceptual design, the maintenance philosophy considered that TF coil failures were considered unlikely, and no plans were included to replace them. PF coil failures were considered to have a low probability, and therefore recovery was not considered. The central solenoid, however, is the most highly stressed component and is the critical element of the PF system, so replacement of the central solenoid was intended for remote

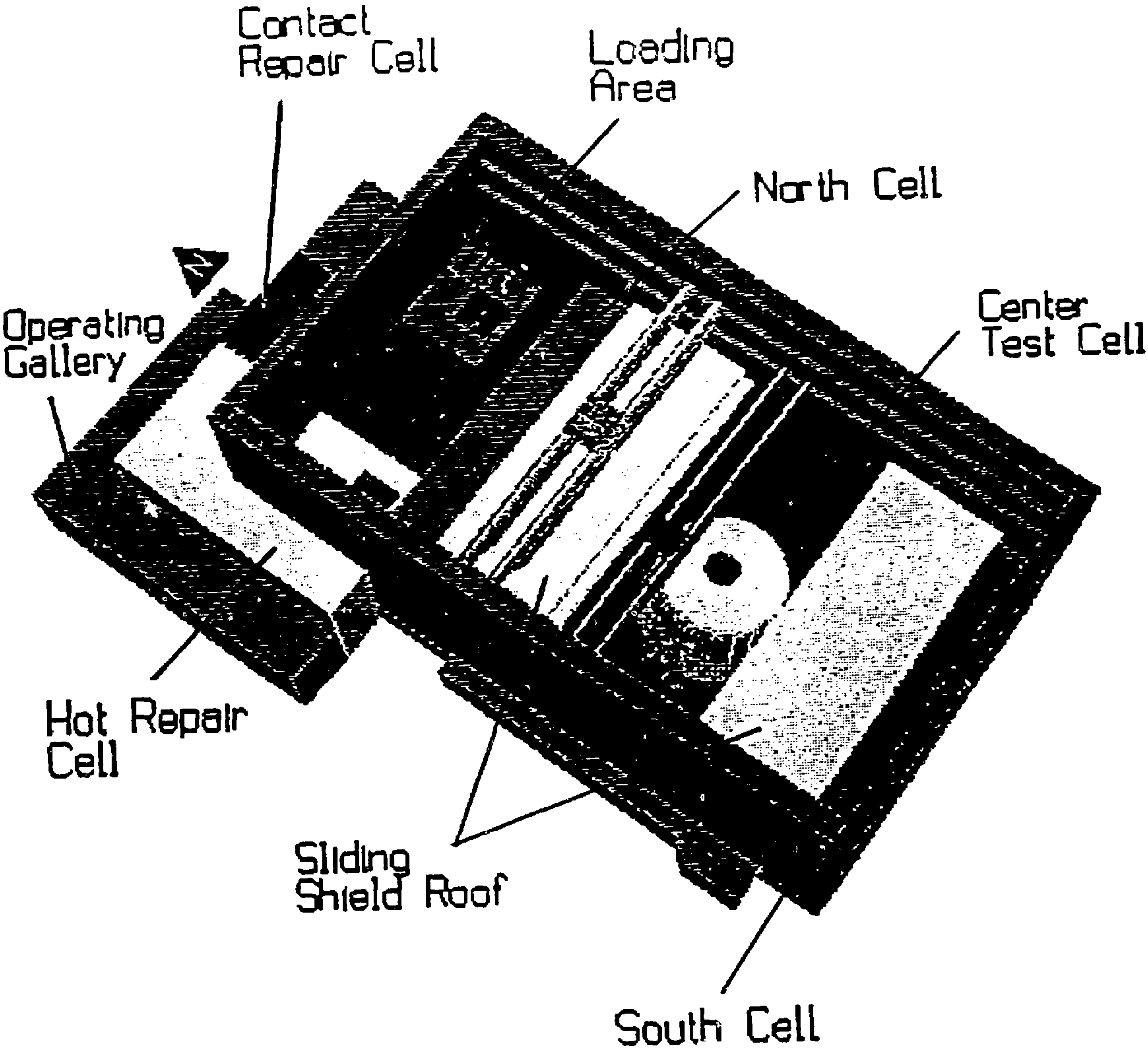

Figure 1
CIT Facility

replacement. The general plan to address ring coil failures was to develop operation scenarios involving coil configurations or alternate operating modes which would allow CIT to achieve its major mission goals without coil replacement. As the machine will operate initially in a nonactivating hydrogen phase for approximately 1-2 years, this will permit verification of the integrity of the whole system and allow hands-on repair of any equipment that fails during shakedown or early operation.

The baseline design featured a monolithic, fully welded, TF coil/structure assembly. This does not lend itself to disassembly hands-on or remote. The structural continuity of the monolithic design is a good feature; however, coil replacement would be doubtful, especially remotely, and it did present some manufacturing and assembly problems. Therefore CIT has adopted a modular TF coil design in response to these concerns.

MODULAR DESIGN APPROACH

A modular design, rather than a monolithic design, is required to make coil replacement practical. The proposed modular design utilizes six, 3-coil modules with each containing 1/6 of the vacuum vessel (Fig. 2). The vessel sectors will be joined by bolting and with a seal welded vacuum barrier, while the modules themselves will be joined by welding. This modular arrangement has distinct manufacturing advantages. More of the fabrication work can be done at the factory with better control quality, which reduces field assembly tasks. Both of these should facilitate project planning and control.

The initial goal was to satisfy the requirement that all TF coil failures be manually repairable prior to activating the device. Subsequently, the task was to determine the design, cost and schedule impacts associated with meeting the requirement that all TF coil failures be repairable remotely after the device has been activated.

To recover from a TF coil failure, the module containing the failed coil would have to be removed and replaced with a spare. No changes are needed for replacement of the central solenoid assembly since this was already planned for. It was concluded for the ring coils, however, that redundancy was a better trade-off than replacement. To make these ring coils replaceable would require several joints per coil greatly reducing the reliability as well as increasing their cost. Rather, the coils were modified to make each into two "pancakes". Leads will be brought out of each to permit the pancakes to be operated independently at a sufficient current level to compensate for a failed pancake.

COIL REPLACEMENT SEQUENCE

A detailed replacement sequence was developed for the worst case situation, which is a TF coil failure. The replacement sequence consisted of twenty major steps, as defined in Table 1, with each

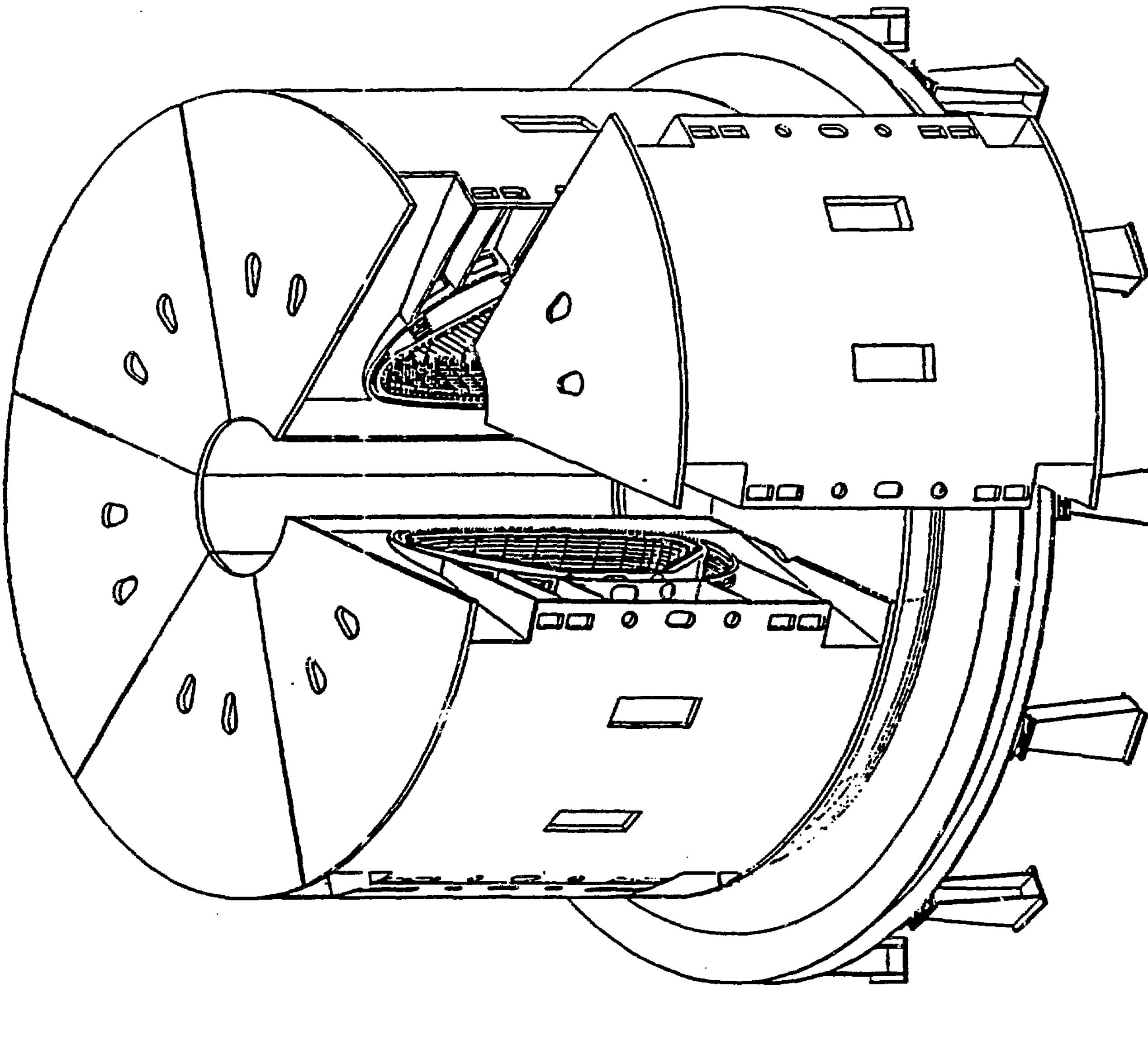

Figure 2
Modular CIT Design

TABLE 1

SUMMARY OF REMOTE REPLACEMENT TASK

ACTIVITY	SERIAL SHIFTS		TOOLING($K)	CREW SIZE TECHS.	CREW SIZE SUPT.+ENG.
1) Preparations	66		40	10	3
2) Remove diags.	54			10	3
3) Prep. center cell	24			10	3
4) Remove cryostat	64		140	10	3
5) Remove upper components	22		220	6	3
6) Remove solenoid	44			5	3
7) Remove cryostat panels	30			6	3
8) Relocate PF's	128		210	11	3
9) Section VV	60	parallel tasks	590	4	1
10) Remove failed module	76		1630	7	3
11) Position new module	101		1700	9	3
12) Connect VV sector	96	parallel tasks	1640	4	1
13) Install new module	93		1840	9	3
14) Replace PF's	134			11	3
15) Replace cryo panels	33			8	3
16) Replace solenoid	52			5	3
17) Replace upper components	29			6	3
18) Replace cryo dome	113			10	3
19) Replace diags.	84			10	3
20) Prepare for operations	38			10	3

Total 1351 = 113 weeks $8010K Total Tooling Cost
- 13 parallel tasks
100 weeks duration

step containing as many as 15 activities. This sequence provides a consistent and thorough basis for identifying tools and fixtures, itemizing costs, ensuring that no aspect of the replacement has been overlooked, and establishing clear communication of what exactly the replacement operation entails.

This sequence was in almost constant revision throughout the study as errors were discovered, omissions detected,or new aspects were defined. This sequence was used for both hands-on and remote replacement cost and schedule estimates. A comparison of the duration between the hands-on and remote replacement in Table 2 shows that remote coil replacement is estimated to take ~2 years or ~3 times longer than hands-on recovery.

This sequence was also used as a "script" for a graphic simulation. A three-dimensional computer modeling with Interactive Graphics Robot Instruction Program (IGRIP) was used extensively to investigate the component handling requirements. IGRIP can model workspaces and kinematics within a remote facility to simulate cells, manipulators, cranes, transporters, etc..

This graphic model (Fig. 3) was a valuable aid in visualizing the replacement sequence. It proved to be an excellent design tool as well. It was used to evaluate the reference design, and assess the effectiveness of RM design concepts. A videotape of the replacement sequence was prepared and distributed to reviewers.

MACHINE MODIFICATIONS

During the study several modifications to the design were identified that would facilitate both hands-on and remote replacement tasks. These are presented in the various categories by the major elements.

Cryostat and Cryostat Penetrations

For replacement of a failed coil it is advantageous to modularize the cryostat. Otherwise the entire cryostat, along with every service line would have to be removed to replace a single hexant. Cryostat sections were designed with remote features for assembly/disassembly. At present, more than 200 penetrations for power buses, coolant and vent lines, electrical and instrumentation leads, as well as the vacuum vessel ports were identified in the study. Each penetration is provided with a flanged bellows seal system designed for remote replacement.

PF Ring Coils

The upper four ring coils would be remotely replaced in case of failure. They would also have to be removed for a TF module replacement. As stated above, the lower PF ring coils will not be remotely replaced, but will have a redundant dual pancake design. These coils would be lowered to provide access for cutting, replacement, and rewelding of the TF coil module.

TABLE 2

COMPARISON OF HANDS-ON AND REMOTE REPLACEMENT REFLECTS RELATIVE OPERATIONAL DIFFICULTIES:

	Hands-on	Remote
Serial shifts (weeks)	495 (41.25)	1351 (113)
Duration (weeks)*	35.5	100*

* Based on 2 8-hr. shifts/day, 12 shifts/week
** 13 weeks parallel in-vessel/ex-vessel tasks

Crew size (ave.)	7.5	8.5
Man Days (Tech)	3174	9384
Eng. & Mgmt. (man days)	820	3312

Typical RH crew consists of:

Manipulator operations (2 ea)	4 ***
Crane operators	2
Ex-cell technicians	2-3
Supervisor	1
RH engineers	2

*** Maximum crew size during parallel in-vessel/ex-vessel operations includes 8 manipulator operators

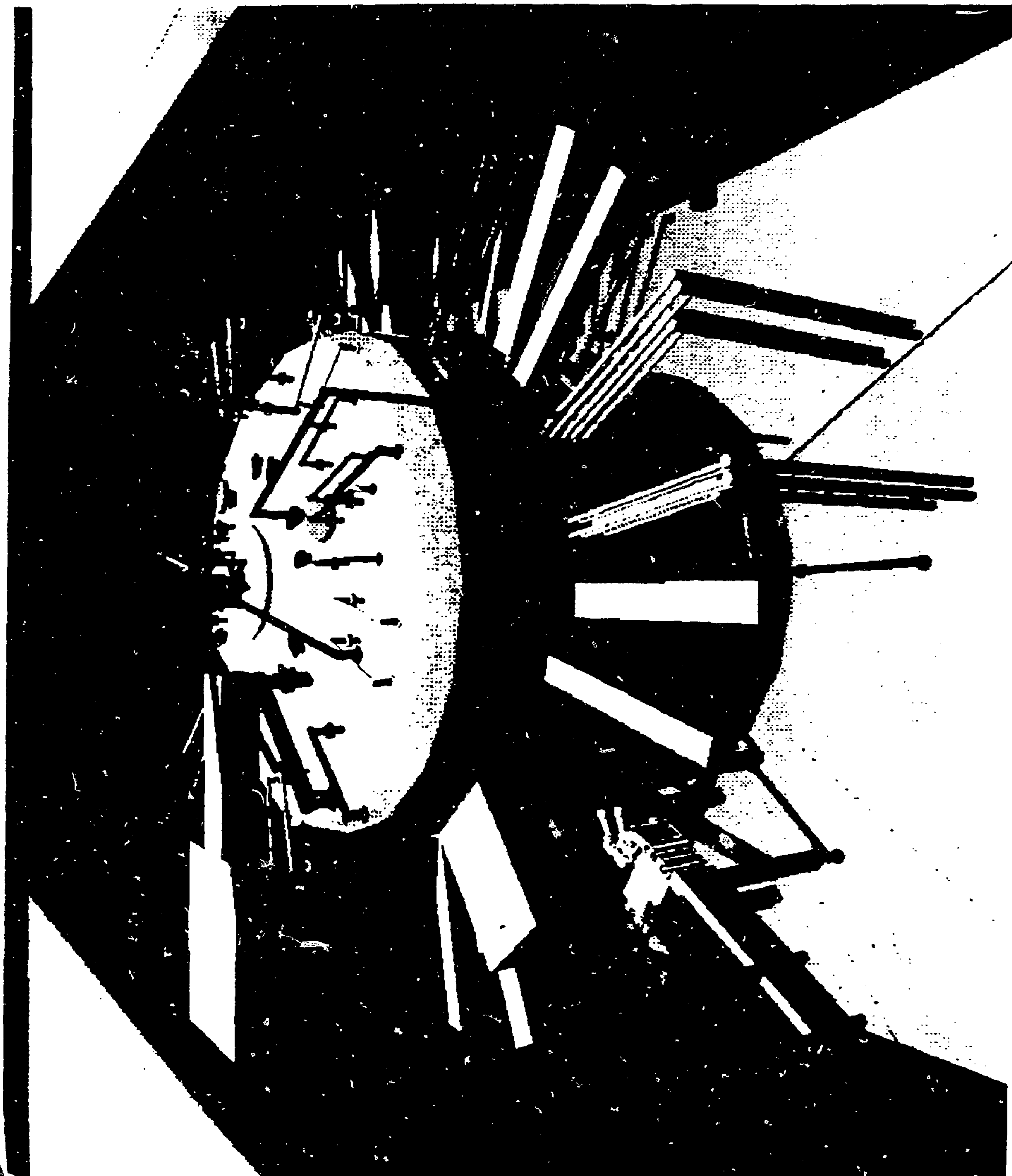

Figure 3
Graphic Model of CIT

TF Coil Module

PCI Energy Services, Inc. provided the concept for initial construction and subsequent remote cutting and welding of the TF coil modules. PCI provided input and guidance as to the feasibility of machine welding techniques, space geometry requirements, and weld joint design for the 3-inch thick steel coil case plates. PCI recommended that all welds, both initial construction and remote replacement, be made using machine welding, i.e. weld head, tractor, and track from outside the hexant. Permanent track mounting brackets will be attached to the outside of the hexants at each joint location. Hands-on and remote welding can use the same welding heads, tractors, tracks and control system. Remote milling was deemed to be the best method for separation of the module joints because debris/chip control is most easily accomplished and the finished cut provides an adequate weld preparation.

Vacuum Vessel

A vacuum vessel joint design, capable of withstanding disruption loads and providing a high integrity vacuum barrier is a key feature of this remote coil replacement concept. The initial concept that was selected incorporates bolted flanges and lip seal welds. The vacuum seal is located to allow access for cutting/welding tools, and the flange design accommodates remote handling bolt tensioning and unbolting tools.

Remote Coil Bus Connectors

Remote removal/replacement of TF/PF coil assemblies requires provision of jumper assemblies with high-current pluggable connectors with integral cryogenic cooling. A remotely handled cryogenic connector design is part of present R&D plans to be developed. The jumper to be developed must provide sufficient compliance to make up, yet stiff enough to be self supporting under the weight of copper conductors.

Facility

The study determined that the center cell size must increase to allow for storage and staging areas, and equipment laydown space. Hot storage will be required for activated components that are removed from the center cell. Also, the decontamination facilities must be enlarged. The present concept of the sliding shielded roof hatch over the test cell is being reconsidered to ensure it's still feasible for the enlarged test cell. Equipment transfer routes and maintenance facility space and handling requirements are being re-evaluated in light of the additional components that are required for coil replacement. The role of the high bay area is being reassessed with respect to continued personnel access during the prolonged shutdown as would be envisioned for a TF coil replacement.

Special RH Tooling

With the exception of the portable milling equipment for separating the module to be removed, much of the tooling needed for replacement is required for the initial assembly operations. The major cost impacts for remote operations are in the development and procurement of remotized versions of these tools.

This effort would include:

- Module joint welding/cutting tools
- Space frame gage for mapping module joint interface
- Adjustable shims, leveling and radial positioning jacks for alignment of replacement module
- Vacuum vessel flange alignment tools
- Vacuum vessel flange bolt tensioners
- Vacuum vessel seal welding/cutting tools
- PF ring coil lifting and positioning fixture
- TF/PF jumper handling and alignment fixtures

The estimated cost of this remote tooling is ~$8 M (Table 1).

During remote recovery, an additional manipulator system is required to minimize the duration of the replacement effort. It is uncertain whether this would be a floor based unit or a second overhead unit. In either case the second system must allow operations independent of the first overhead manipulator system. In addition, this system is needed to provide high-capacity manipulation for under machine operations such as the installation of the module positioning jacks.

MOCK-UPS

The expanded requirements for remote maintenance in CIT to accommodate remote coil replacement demands an increase in the degree and scale of mock-ups. Project planning must give consideration to the need to identify and prioritize critical design features, and then to complete small scale mock-ups as soon as possible to verify or reject these features. These mock-ups would continue to evolve for the refinement of component designs and development of tooling. Final validation testing would take place at some point during final assembly of the machine when certain key operations would then be performed using remote tooling under simulated remote operational conditions.

CONCLUSIONS

This study has substantiated that is indeed feasible for CIT to be designed for remote recovery of any coil failure. For the TF coils and the central solenoid this would be accomplished by replacement. For the ring coils this is achieved by redundancy rather than replacement. Modularity lends itself to remote maintenance requirements. The worst case recovery would take ~2 years. It is imperative, however, that for this to be accomplished in the most effective manner, the necessary RM features must be designed in from the start along with all other functional features.

ACKNOWLEDGEMENTS

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