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REMOTE HANDLING REQUIREMENTS AND CONSIDERATIONS FOR D-T FUSION REACTORS*

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ABSTRACT

This paper presents an overview of the maintenance considerations for next-generation fusion reactors. It draws upon the work done at the Fusion Engineering Design Center over the past several years in the conceptual development of tokamaks and tandem mirrors. It specifically addresses the maintenance philosophy adopted for these devices, the configuration development using a modular design approach, scheduled and unscheduled maintenance operations, assembly and disassembly scenarios for component replacements, maintenance equipment requirements, and the operating availability of these devices. In addition, recent work on the development of a totally remote tokamak configuration is presented.

INTRODUCTION AND SUMMARY

The first generation of deuterium-tritium (D-T)-fueled reactors began preliminary operations within the past two years. These devices, although engaged primarily in plasma physics research, mark the beginning of the need for remote handling techniques and equipment to ensure timely maintenance and operations due to modest neutron-induced activation. Next-generation devices are expected to be considerably larger and to have higher activation levels requiring that their designs be intimately tied to the considerations for remote disassembly and maintenance operations. Since the earlier concept studies of the Engineering Power Reactor [1] at Oak Ridge National Laboratory (ORNL) and The Next Step [2] at ORNL, Argonne National Laboratory, and GA Technologies, Inc., configuration designs based on the maintainability of large, activated tokamaks have evolved. This is due, in part, to fusion reactor maintainability studies [3,4], which provided the first serious investigations of the impact that maintenance has on the configuration, the equipment requirements, and device downtime.

A modular approach to the design of these devices complements the requirements for remote handling by allowing independent component replacement. Modules that have reasonable access and that are designed to accommodate remote equipment are mandatory for next-generation devices. Modules such as torus sectors may be as large as 1/12 the plasma chamber, may weigh up to 400 tonnes, and may be 7 m high; or they may be relatively small diagnostic components weighing tens of kilograms. In general, all peripheral device components (such as the heating systems, fuel injectors, test modules, diagnostics, etc.) are located in "window" areas on the plasma chamber and between toroidal field (TF) coils to permit access to them. The plasma chamber itself is sectored so that each sector may be removed by passing between fixed TF coils. The primary vacuum seals for the chamber are also accessible in this window area.

The maintenance philosophy most widely adopted is based on allowing personnel access into the reactor cell 24 h after device shutdown. This requires additional device shielding (beyond the needs of protecting device components such as the superconducting coils) to limit surface dose rates to 2.5 mrem/h, and it requires that the shield remain in place when personnel are present. Remotely operated equipment is required for operations that remove device components or, in general, that expose the reactor cell to the highly activated and tritiated interior of the plasma chamber. The 2.5-mrem/h dose rate is the most common shield design requirement and assumes that a worker may spend up to 400 h annually at a shield surface and still meet the as low as reasonably achievable (ALARA) guideline of worker dose limit. This is 1/5 of the maximum permissible exposure [5]. Based on conceptual maintenance studies, 400 h appears reasonable for devices with an operating availability of 25-50%.

The mainline designs for next-generation devices in the U.S. Fusion Program are tokamaks and tandem mirrors. Both of these concept developments have

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included considerations for scheduled and unscheduled maintenance operations, assembly and disassembly scenarios for component replacements, and operating availability. Design studies for the Fusion Engineering Device (FED) [6], the International Tokamak Reactor (INTOR) [7], and an upgrade to the Mirror Fusion Test Facility (MFTF-α+T) [8] have been based on the considerations discussed above and indicate that designs can be developed that are reasonably maintainable.

These design studies were also used to define the requirements for maintenance equipment systems comprised of various manipulators, transporters, contamination containment structures, cranes, and inspection systems. A number of design concepts were developed to assess equipment costs and feasibility using present technology. It has been concluded that present and near-term future technology is sufficient for equipment development and will meet the needs for reactor maintenance, provided that the reactor designs accommodate the requirements and limitations of the equipment.

The recent INTOR activities include an investigation of a configuration based upon totally remote operations and maintenance. This is a departure from traditional tokamak designs and is being done in order to develop a comparison of the costs and engineering implications of a design that allows personnel access versus a totally remote design approach. Much of the work for this task was completed in May 1984 and established some early conclusions. One preliminary conclusion, based on the work thus far, is that reducing the shield thickness at the plasma chamber (due to the elimination of the biological requirement for the all-remote design) may adversely affect cost and feasibility of operations because of a significant increase in the reactor building wall thickness, significantly higher activation in the reactor cell, and higher nuclear heating in the superconducting coils.

MAINTENANCE PHILOSOPHY

The maintenance philosophy that is the basis for all next-generation reactor designs is one which permits limited personnel access to the device. This is accomplished by providing sufficient shielding around the plasma chamber to attenuate gamma radiation induced in the structures by 14-MeV neutrons. Generally a combination of stainless steel and water is sufficient if the thickness is between 120 and 160 cm. This will reduce the dose rate at the shield boundary to 2.5 mrem/h, 24 h after device shutdown. Approximately 1 day is required after shutdown to allow the radionuclides of manganese to decay, after which it is the long-lived radionuclides of cobalt which contribute to the surface dose rate.

Originally, the 2.5-mrem/h dose rate was established as an acceptable level for personnel access by dividing the maximum permissible annual dose to workers (5 rems) by a standard working year (approximately 2000 h). This approach does not account for the ALARA requirement, and further consideration of a work year indicates that 1400 h is the maximum time available for worker operations next to the device. In an attempt to satisfy ALARA, the 1/5-design objective has been adopted (i.e., 1 rem per year), which limits workers to 400 h at a shield boundary that has an activation of 2.5 mrem/h. Maintenance studies indicate that this is reasonable for devices with an availability of 25-50%.

CONFIGURATION DEVELOPMENT

Tokamaks and tandem mirrors have considerable geometric differences. Tokamaks are toroidal devices with essentially all of the coils external to and surrounding the plasma chamber. The peripheral components are arranged radially around the device and interface with the torus in the open area between the TF coils. The central region of the device where the TF coils rest is virtually inaccessible. Figure 1 shows a typical tokamak device. Tandem mirrors are linear devices, with virtually all of the coils located within the plasma chamber. The peripheral components are located radially along the length of the device, and external access is generally more available on these linear machines. Figure 2 is representative of a next-generation tandem mirror.

Both of these designs have common maintenance problems in that the structures within the shield boundary are highly activated (10^6 rads/h at the surface that views the plasma), modular components are large, (many will weigh several hundred tonnes), and virtually all components requiring replacement will be contaminated with tritium. Therefore, for

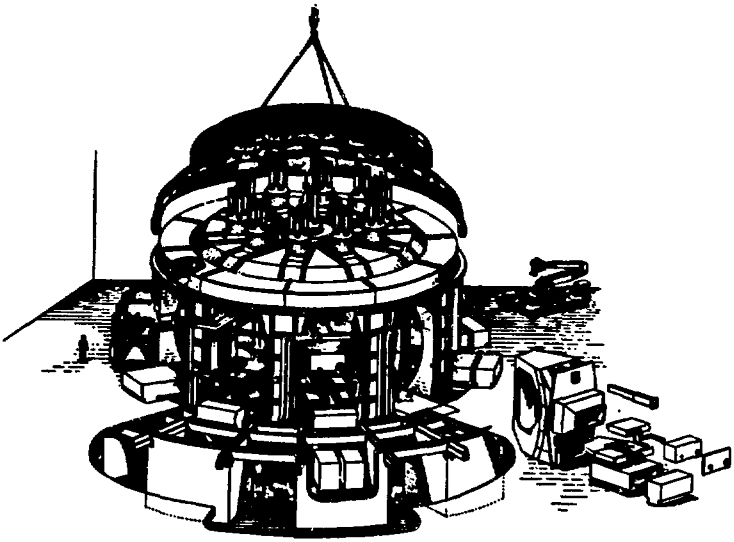

FIGURE 1: FED REFERENCE CONFIGURATION

ORNL-DWG 83-4006 FED

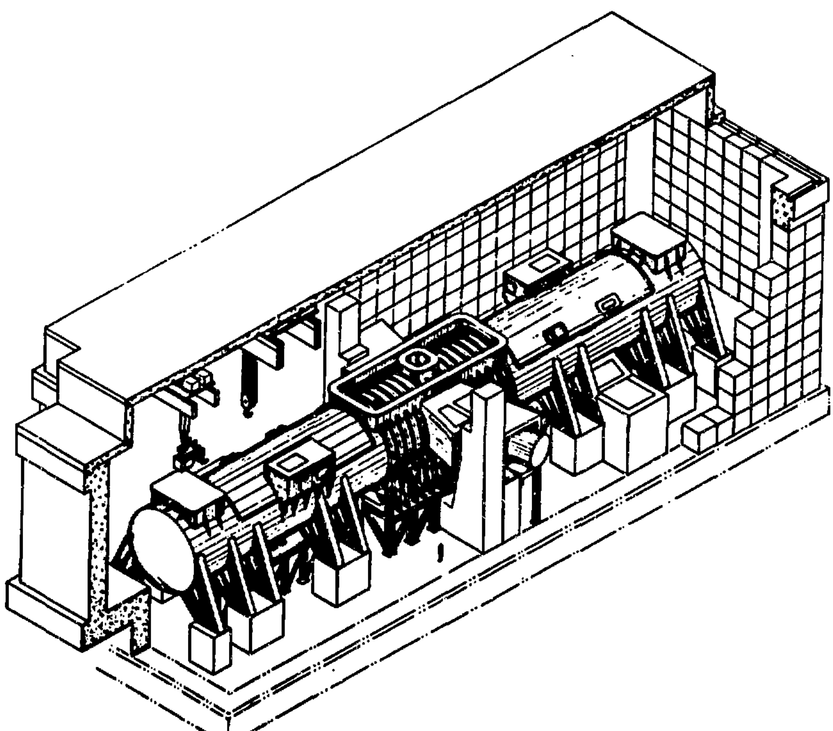

FIGURE 2: MFTF-α+T REFERENCE CONFIGURATION

both designs, large crane systems are required along with heavy-capacity transporters; decontamination facilities are needed; and large hot cells are part of the facility design.

Tokamak configuration development since the Engineering Test Reactor (ETR) [9] studies at ORNL has included certain features to enhance maintenance and disassembly, and these have generally been the basis for all subsequent designs. These include (1) establishing the number and size of the TF coils to permit the removal of one torus sector for each coil using straight-line radial motion; (2) designing peripheral components such as limiters and divertors, test modules, rf and neutral-beam heating, fueling, and diagnostics as modules with flanged interfaces to the plasma chamber to permit independent removal of these systems; (3) locating the poloidal field (PF) coils above and below these component interfaces so that modules, including torus sectors, can be independently removed without removing PF coils; and (4) locating all superconducting TF and PF coils within a common cryostat.

MODULAR DESIGN

Modular designs were developed for all subsystem components to permit independent replacements. For example, removal of the pumped limiter or a test module may be accomplished without removal of the torus sector, and any module is removable without disturbing other component modules. This is shown in Fig. 1. The main benefit of this approach is the enhancement of total device availability, since downtime is a function of the number of components which require removal and reinstallation. The largest tokamak module is the torus sector shown in Fig. 1, weighing 375 tonnes and measuring 7 x 5 x 4 m. (The upper and lower outboard PF coils are larger due to their circular geometry.) The smallest module in the same figure is the test module, weighing 10–20 tonnes and measuring 1 x 1 x 1-1/2 m.

Access to all modules is through the open areas between the TF coils. Vacuum flange connections, coolant lines, electrical connections, and instrumentation must be designed for operations which utilize remote handling equipment such as manipulator systems (even though these operations may be done with personnel), and right-of-way access must be provided for both contact and remote methods of disassembly.

The development of a configuration design also considers the initial assembly of the device in its modular component arrangement. Clearly, if the device can be assembled in a modular hierarchy, subsequent disassembly of components is simplified. Figure 3 shows an assembly/disassembly of the U.S. INTOR reference design.

SCHEDULED/UNSCHEDULED OPERATIONS

Maintenance operations can be classified as being scheduled (i.e., they are expected and planned for), or unscheduled (i.e., they are unexpected but planned for). An example of a scheduled operation is the annual replacement of limiter modules, whereas an unscheduled operation is the removal of a torus sector. There is another class of operations which considers the replacement of permanent structures, such as a TF coil. The TF coil is a high-reliability, lifetime component which will not be considered here.

The components which are considered to require scheduled maintenance or removal are the limiters (or divertors), rf heating, fueling, test modules, and pumps and certain coils on tandem mirrors. All other components may be considered to require unscheduled operations. The development of a maintenance operating plan must consider both categories in order to assess the likelihood of achieving the desired device availability. Such an assessment was done for the MFTF-α+T and is shown in Fig. 4. This device has phased operations during its lifetime, with each phase having a different availability objective. This is shown at the top of the figure. Adjacent to each component is an estimate of its useful life and the calendar time when a replacement is expected. All of the major components are listed, along with the required changeouts for various blanket tests. The extreme right-hand column shows the number of components (spares) needed during the device lifetime.

ASSEMBLY/DISASSEMBLY

Removal of a torus sector is a major operation which considers the requirements for device shutdown and bakeout for detritiation, disassembly operations utilizing personnel and remotely operated equipment, reinstallation of components, and plasma chamber reconditioning prior to startup. Details of this

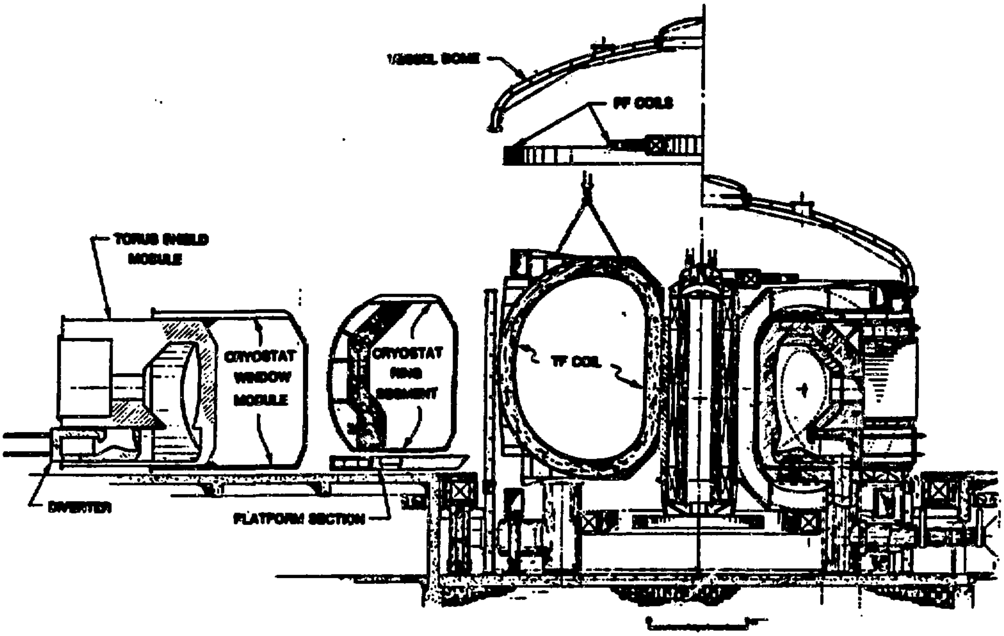

FIGURE 3: TF COIL REPLACEMENT APPROACH SHOWING WHICH COMPONENTS MUST BE REMOVED TO GAIN ACCESS TO THE COIL

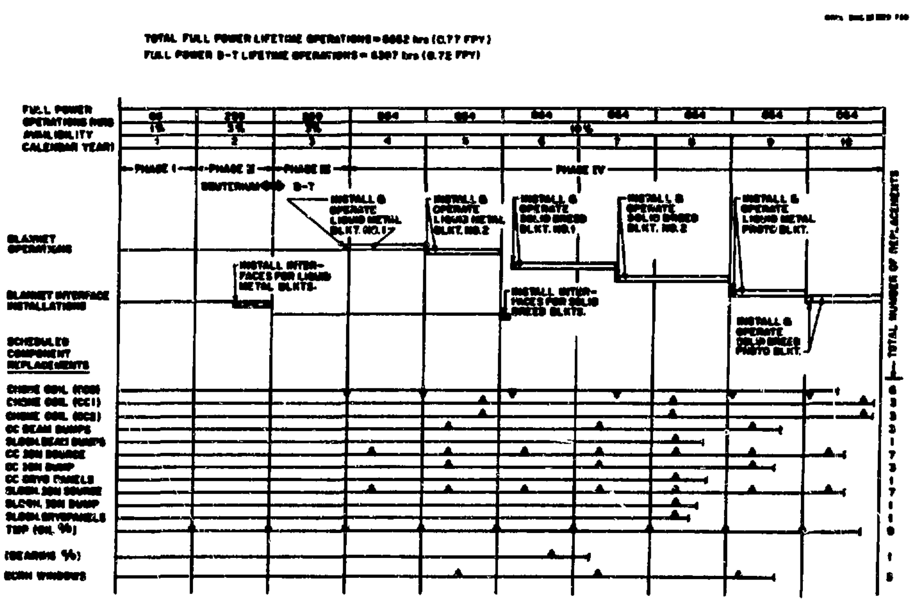

FIGURE 4: THE LIFETIME PLAN FOR SCHEDULED OPERATIONS OVERLAYS COMPONENT REPLACEMENTS WITH THE SIX TEST MODULE CHANGEOUTS OF PHASE IV

operation were analyzed for the FED design [10] as part of an assessment to establish maintenance equipment requirements. Tables 1 and 2 show the detailed breakdown of steps and procedures and the identification of equipment. A similar analysis was recently done for the INTOR reference design and is shown in Table 3, along with estimates of the time required for each operation and the total downtime necessary to complete this maintenance scenario.

Similar analyses have been developed for the major components of the FED design [6] and for the limiter replacement of one of the designs for the Tokamak Fusion Core Experiment (TFCX). Table 4 shows the scenario for replacing a single pair of the 16-module sets; the analysis also includes complete replacement of all limiters annually, concluding that these operations are most cost effective if they are done in multiples of two. Hence, two sets of maintenance equipment are required.

Maintenance operations on the superconducting magnets impose a special impact on device downtime. Warming the coils to room temperature and subsequently cooling them back to liquid helium temperature is estimated to require approximately 5 additional weeks of device downtime. Since these systems are contained in cryostats which are independent from the plasma chamber, operations described above on the torus sectors are not impacted by this additional time, since the coils are kept at cryogenic temperatures.

Personnel operations are permitted during maintenance operations, provided the device shielding remains intact. These include removal of coolant and electrical connections, inspection, and setting up remotely operated equipment. Because of the potential for tritium contamination in the reactor cell, personnel are assumed to wear protective suits.

MAINTENANCE EQUIPMENT

Remote maintenance equipment concepts have been developed for some of the major component replacements. These include manipulator systems, transporters, welders and cutters, and lifting fixtures. The FED report [10] includes some of this equipment design, based on the requirements for sector removal and in-vessel manipulator operations. Figure 5 shows several of these design concepts.

Earlier work on equipment concepts was started at the FEDC in 1980 at a two-part workshop [11] which assembled experts in remote handling from laboratories and industry. The conclusion at that time was that existing technology and equipment could be modified for fusion reactor maintenance. More recent assessments of remote handling technology and robotics support the earlier conclusion. Equipment development for specific reactor maintenance tasks and the demonstration of this equipment is needed. Development work along these lines is under way at the Princeton Tokamak Fusion Test Reactor (TFTR) and the Joint European Torus (JET).

AVAILABILITY

Availability for fusion devices can be simply defined as operating time divided by total calendar time. A device which has a 50% availability objective must be operated approximately 4000 h per year, leaving approximately 4000 h for maintenance operations, test module changeouts, and diagnostic replacements. Determining the downtime required to accomplish these is, however, based upon subjective analyses using device configuration designs which are conceptual in nature. Hence, the absolute correctness of downtime presents some uncertainty. Estimates of mean time to repair (MTTR) are indeed estimates. In addition, since there is very little historical data to support estimates of component lifetimes, reliability analyses to determine mean time between failures (MTBF) also presents uncertainty.

One way to get around this problem is to do sensitivity studies based on a total device availability objective. In this manner, systems, subsystems, and components can be assigned reliability requirements which are used as design requirements. This was the approach used for the Engineering Test Facility (ETF) [9] and FED [6] reactor designs. More recently, development work on the reactor modelling programs at the FEDC includes codes which will analyze component reliabilities and total device availability.

ALL-REMOTE CONFIGURATION STUDIES

The INTOR studies sponsored by the International Atomic Energy Agency (IAEA) for 1983 include investigation of an all-remote approach to a

TABLE 1

SECTOR REMOVAL PROCEDURES AND EQUIPMENT

1 General Device Shutdown ⇨

- De-energize coils } 3 h
- Drain & store torus coolant water }
- Bakeout torus using hi-temp N_2 gas — 18.5/24 h
- Lower torus temperature — 18.5 h
- Prepare maintenance equipment

64 h

2 Disassemble Sector Interfaces ⇨

- Remove struct. bolts (44-2 1/2 cm)
- Cut vac. flange (22 m)
- Uncouple coolant lines

Lines	Connect's	Diam (cm)
2	4	30
1	2	20
6	12	8
1	2	10
4	8	15

- Uncouple waveguide

1	2	3

- Uncouple coax (combination electrical & coolant)

1	2	20

- Remove lines in window area
- Cut vac. flange of duct elbow
- Remove elbow to storage
- Install floor cover plate over open duct
- Cut vac. flange of duct
- Roll back duct; remove to storage

3 Sector Removal

- Install sector handling device* and lock into position
- Engage extraction mechanism to sector
- Pull sector onto handling device
- Extract handling device and sector
- Attach contaminant collector to sector
- Lift sector and transport to hot cell air lock

Equipment - Stage 1

- General device shutdown does not require the use of maintenance equipment; the procedures listed are automated and executed from the control room
- Preparation of maintenance equipment consists of removing equipment from storage and placing it in reactor cell during the 18.5-h cooldown phase

Equipment - Stage 2

- General purpose mobile manipulator
- Debolting tool (2-1/2 cm bolts)
- Track-mounted cutter
- Nut runner for "Grayloc" type couplings
- Lifting slings for pipe sections
- O/H crane(s)

Equipment - Stage 3

- General purpose manipulator
- O/H crane(s)
- Sector handling device

*Sector handling device has provisions for containing contaminated debris.

TABLE 2

SECTOR REPLACEMENT PROCEDURES AND EQUIPMENT

4 Sector Replacement ⇨

- Visually inspect floor area and open bay for particulate matter
- Decontaminate open bay and floor area
- Transport repaired sector to handling device
- Engage extraction mechanism to sector
- *Roll handling device and sector into window area
- Lock handling device into position
- Push sector into its final position in torus
- Inspect vacuum flanges and bolt holes for alignment
- Remove sector handling device
- Install structural bolts (44-2 1/2 cm)
- **Weld vacuum seal (22 m)
- Inspect floor area; decontaminate as required

5 Assemble Sector Interfaces ⇨

- Install shielded duct; weld vacuum flange (8 m)
- Remove floor cover plate
- Install duct elbow; weld flanges (8 m, 8 m)
- Leak check all welded flanges (22 m, 8 m, 8 m, 8 m)
- †Position lines, connect couplings

Lines	Connections	Diam (cm)
2	4	30
1	2	20
6	12	8
1	2	10
4	8	15

- Same for waveguide

1	2	3

- Same for ICRH coax assembly

1	2	20

- Leak check each coupling by pressurizing systems with tracer gas
- Check work area around sector for contaminated debris; cleanup as required

6 General Device Startup

- Final inspection by maintenance personnel
- Remove maintenance equipment to storage
- Circulate coolant in sector
- Activate torus pump system
- Recondition plasma chamber using bakeout, discharge cleaning, etc.
- Energize coils
- Begin reactor operations

Equipment - Stage 4

- CCTV (general purpose mobile manip.)
- Decon vacuuming device
- Radiation monitoring device
- General purpose mobile manipulator
- O/H crane crane
- Sector handling device
- Bolting tool
- Track-mounted welder

Equipment - Stage 5

- O/H crane
- Portable remote viewing
- Track-mounted welder
- ††Leak detection equipment
- General purpose mobile manipulator
- Decontamination equipment

Equipment - Stage 6

- O/H crane

*Sector alignment onto handling device is provided by guidelines; final alignment is provided by guide tracks which support the handling device.
**Vacuum seal flange on sector is prepared in hot cell.
†Lines are preassembled into holding fixture.
††Pump down torus to base pressure; use tracer gas analyzer at sector pump system for vacuum test; use tracer gas analyzer at coolant couplings.

TABLE 3

SECTOR REPLACEMENT WITH PERSONNEL ACCESS

	Steps	Mode of operation	Personnel	Duration (hrs)
1a.	General device shutdown	A		1
b.	De-energize coils; drain sector of coolant	A		5
c.	Torus bakeout cycle	A		60
2a.	Radiation survey of entire device	C	4	8
b.	Install work platforms and scaffolds	C	4	4
c.	Set up two remote cutters	C	2	1
d.	Cut vacuum seal around sector	C	4	2
e.	Remove structural attachments	C	2	2
f.	Remove connections to ICRH module	C	2	4
g.	Disconnect and remove coolant lines for bulk shield, F/W, blanket, diverter	C	3	12
h.	Remove work platforms	C	4	4
i.	Install sector handling device	C	4	2
j.	Extract module and move to hot cell	R		4
3a.	Position sector onto handling device	R		2
b.	Install sector into torus; remove handling device	R		4
c.	Radiation survey; decontaminate as required	R		8
d.	Install work platforms	C	4	4
e.	Install and connect coolant lines for bulk shield, F/W, blanket, diverter	C	3	16
f.	Leak test sector coolant connections	C	2	2
g.	Install connections to ICRH module	C	2	6
3h.	Test electrical and coolant connections to ICRH module	C	2	2
i.	Install structural attachments to sector	C	2	2
j.	Set up two remote welders	C	2	1
k.	Weld vacuum seal around torus	C	4	3
l.	Leak check torus vacuum seal	C	4	4
m.	Remove work platforms	C	4	4
4a.	Recondition plasma chamber for startup	A		168
	Total Time After Shutdown			335 h (14.0 days)
	Total man-hours in cell		264	
	Total man-rem exposure (264 x 2.5)		.7 man-rems	

TABLE 4

LIMITER BLADE REPLACEMENT

(One station, Modules A and B)

	Steps	Mode of operation*	Duration (hrs)
1a.	General device shutdown	A	
b.	Limiters drained of coolant	A	
c.	Maintenance equip. prepared	-	
d.	Bakeout at elevated temp.	A	24
2a.	Disconnect coolant lines	C	8
b.	Disconnect flange attachments	C	4
c.	Position & connect extractor device to module	C/A	4
d.	Extract Module A	R	2
e.	Lift & move Module A to hot cell transfer tunnel	R	2 (4) (in parallel with 2f.)
f.	Position & connect extractor device to Module B	R	4
g.	Extract Module B	R	4
h.	Lift & move Module B to hot cell transfer tunnel	R/A	2 (4)
3a.	Position replacement Module B onto extractor device	A/R	4
b.	Install Module B	R	4
c.	Inspect Module B alignment	R	2
d.	Position replacement Module A onto extractor device	A/R	2 (4) (in parallel with 3c.)
e.	Install Module A	R	2
f.	Radiation survey for personnel access; decon as required	R	8
g.	Inspect bolt alignment of flanges & seal interface	C	2
h.	Install flange attachments	C	4
i.	Vacuum test flange seal	C	4
j.	Install coolant pipes & connections	C	8
k.	Pressure test coolant connections	C	4
4a.	Recondition plasma chamber for startup	A	168
	Total Time After Shutdown To Replace 1 Limiter Set		262 hrs (10.9 days)

*A = automated operation
C = contact operation
R = remote operation

configuration development. The purpose of this work is to compare the engineering impact, the cost, and the feasibility of a design which permits personnel access and one which prohibits personnel access. Preliminary conclusions were reported by the four INTOR delegations (E.C., Japan, U.S., and U.S.S.R.) in May 1983 and are summarized below.

CONCLUSIONS

Maintenance considerations for next-generation D-T reactors have a major impact on the development of these designs. Studies of component replacements for both tokamaks and mirrors have shown the significance of maintenance and disassembly considerations on achieving device availability, including the advantages of having limited personnel access. Maintenance equipment concepts have been developed, and there is general agreement that existing remote handling technology is sufficient to solve remote handling problems; however, development and demonstration are still required. Adopting an all-remote design approach for next-generation devices will limit the flexibility of maintenance operations, since these devices are still to be considered experimental machines which will provide the operating data base for prototypical power reactors.

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