COO-4184-8
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Developing Maintainability for Fusion Power Systems

Final Report

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November 1979

Prepared for the U.S. Department of Energy
Under Contract No. EG-77-C-02-4184.A003

DISCLAIMER

ABSTRACT

This report presents the results of the study, "Developing Maintainability in Controlled Thermonuclear Reactors", by McDonnell Douglas Astronautics Company - St. Louis for the United States Department of Energy (DOE) under contract number EG-77-C-02-4184.A003. The reporting period is the final phase of the study from 1 November 1978 through 31 October 1979.

The overall purpose of the study is to identify design features of fusion power reactors which contribute to the achievement of high levels of maintainability. Previous phases evaluated several commercial tokamak reactor design concepts. This final phase compares the maintainability of a tandem mirror reactor (TMR) commercial conceptual design with the most maintainable tokamak concept selected from earlier work. A series of maintainability design guidelines and desireable TMR design features are defined. The effects of scheduled and unscheduled maintenance for most of the reactor subsystems are defined.

The comparison of the TMR and tokamak reactor maintenance costs and availabilities show that both reactors have similar costs for scheduled maintenance at 19.4 and 20.8 million dollars annually and similar scheduled downtime availability impacts, achieving approximate availabilities of 79% at optimized maintenance intervals and cost of electricity. The TMR cost of electricity is estimated to be significantly greater than that of the tokamak, primarily because of higher capital costs. A reduction of 26% in capital cost is required to allow the same downtime and other maintainability constraints to be imposed on the TMR and on the tokamak reactor and to achieve the same cost of electricity. Investigation of the size trends of a TMR currently under study indicate that this cost reduction is feasible.

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1.0 INTRODUCTION

Maintenance of a commercial fusion power reactor is a major cost element in determining its economic feasibility. To evaluate the potential economic impact of maintenance on these reactors the maintainability of conceptual commercial designs has been investigated in a continuing study since 1977. This report presents the results of the final phase of this study.

During the initial study phases the influence on the cost of electricity of first wall/blanket maintenance and other reactor subsystems for a representative group of four tokamak reactor conceptual designs has been evaluated. Both scheduled and forced outages have been studied. Desirable design features and design guidelines have been selected. As a result, a more maintainable concept of a tokamak reactor has been defined.

This final study phase follows with a definition of the maintainability of a commercial Tandem Mirror Reactor (TMR) conceptual design and a comparison with the Improved Maintenance System (IMS) tokamak concept developed in the initial part of the study. To conduct an evaluation between two such dissimilar concepts requires that the maintainability of all reactor subsystems be included and that both the scheduled and forced outage influence of the required maintenance for these subsystems be defined. In addition, the maintenance plan for scheduled outages must include the effects of combined maintenance actions instead of evaluating principally the effect of only one subsystem which is selected because it appears to be of primary influence on maintenance. In the study of tokamak reactor concepts the first wall/blanket is such a subsystem but for the TMR several subsystems can be of relatively equal importance in establishing maintenance requirements. The relative influence of individual subsystems on forced outages must also be evaluated to identify the design characteristics which reduce this source of unavailability.

The objectives selected for this final study phase were: (1) to develop maintenance plans for a tandem mirror fusion power system which include definitions of outage durations and frequency, and (2) to compare tandem mirror reactor maintenance characteristics with a selected tokamak reactor reference concept.

Only one TMR conceptual commercial design is available for this evaluation. The investigation of the requirements to apply tandem mirror physics to a commercial fusion reactor has been given only limited attention in comparison to the multiple studies defining a commercial version of the tokamak fusion reactor concept. For this reason the comparison made in this study is between this first TMR commercial reactor concept and the tokamak commercial reactor concept that is considered the most maintainable. However, another TMR commercial conceptual design is currently under study. The trends evident in preliminary results of this newer TMR design are also evaluated insofar as possible in this maintainability analysis. In making comparisons all reactor concepts have been normalized to have the same net electrical power output.

These fusion power system design approaches are evaluated by developing individual maintenance scenarios for a selected group of subsystem components and then combining them into a scheduled outage scenario by determining a critical path for a representative outage. No one component is preselected as the driving maintenance requirement although the fraction of the first wall/blanket exchanged is used as the life limiting criterion for determining maintenance intervals as has been the case in earlier studies. The scheduled outages for different replacement fractions of selected life limited components are optimized for minimum cost of electricity (COE) and COE goals are selected. These goals each determine an allowable availability which is used to establish a total downtime allowable for forced outages. Through this procedure the relative subsystem forced outage allowances can be defined to indicate which subsystems have the greater influence on forced outages. As a result of this evaluation, desirable features and some design guidelines for TMR concepts are selected. The subsystems included in this evaluation process involve all reactor components as defined by the standard cost accounts listed in Reference 1. These principally include the first wall/blanket, magnets, neutral beam injectors, vacuum pumping, direct converter and all cooling and steam generation systems.

Some of the specific topics of possible use for reference in this report are given in Table 1-1.

TABLE 1–1
LOCATION OF REFERENCE MATERIAL

TOPIC	LOCATION	
	SECTION	PAGE
REFERENCE REACTOR NORMALIZED PARAMETERS	3.1	3-2
INDIVIDUAL COMPONENT SCENARIOS		
BASELINE TANDEM MIRROR REACTOR	4.2.1	4-19 THRU 4-37
IMS TOKAMAK REACTOR	4.3.1	4-70 THRU 4-88
ADVANCED TANDEM MIRROR REACTOR	4.2.6	4-66 THRU 4-69
TANDEM MIRROR REACTOR MAINTENANCE EQUIPMENT	4.2.2	4-37 THRU 4-46
MAINTENANCE EQUIPMENT DEFINITIONS		
BASELINE TANDEM MIRROR REACTOR	4.2.4	4-53
IMS TOKAMAK REACTOR	4.3.4	4-100
TANDEM MIRROR REACTOR EQUIPMENT SKETCHES	4.2.1	4-19 THRU 4-37
REACTOR COMPONENT LISTS		
MAINTENANCE MODES	4.1	4-3 THRU 4-10
RELATIVE FORCED OUTAGE DOWNTIMES		
BASELINE TANDEM MIRROR REACTOR	4.2.5	4-60 THRU 4-65
IMS TOKAMAK REACTOR	4.3.5	4-106 THRU 4-108

2.0 SUMMARY

Maintainability of a Tandem Mirror Reactor (TMR) conceptual commercial design compares favorably with that of a tokamak reactor with approximately the same electrical output. Annual scheduled maintenance costs for the TMR are estimated at approximately $19.4 million while those for the tokamak are estimated at approximately $20.8 million. These costs include operating costs, maintenance capital return on investment and the cost impact of scheduled maintenance downtime.

The TMR design concept used as a baseline for this comparison with tokamak designs has been defined by the Lawrence Livermore Laboratory in 1977 (Reference 2). A side elevation of this design with the maintainability features that are incorporated for the purposes of this study is shown in Figure 2-1. The net electrical capacity is 989 MW. The tokamak reactor concept used for comparison has been adapted from the Culham Laboratory Mark IIB conceptual design (Figure 2-2). This reactor concept incorporates features found desirable for maintenance during

TMR BASELINE CONFIGURATION

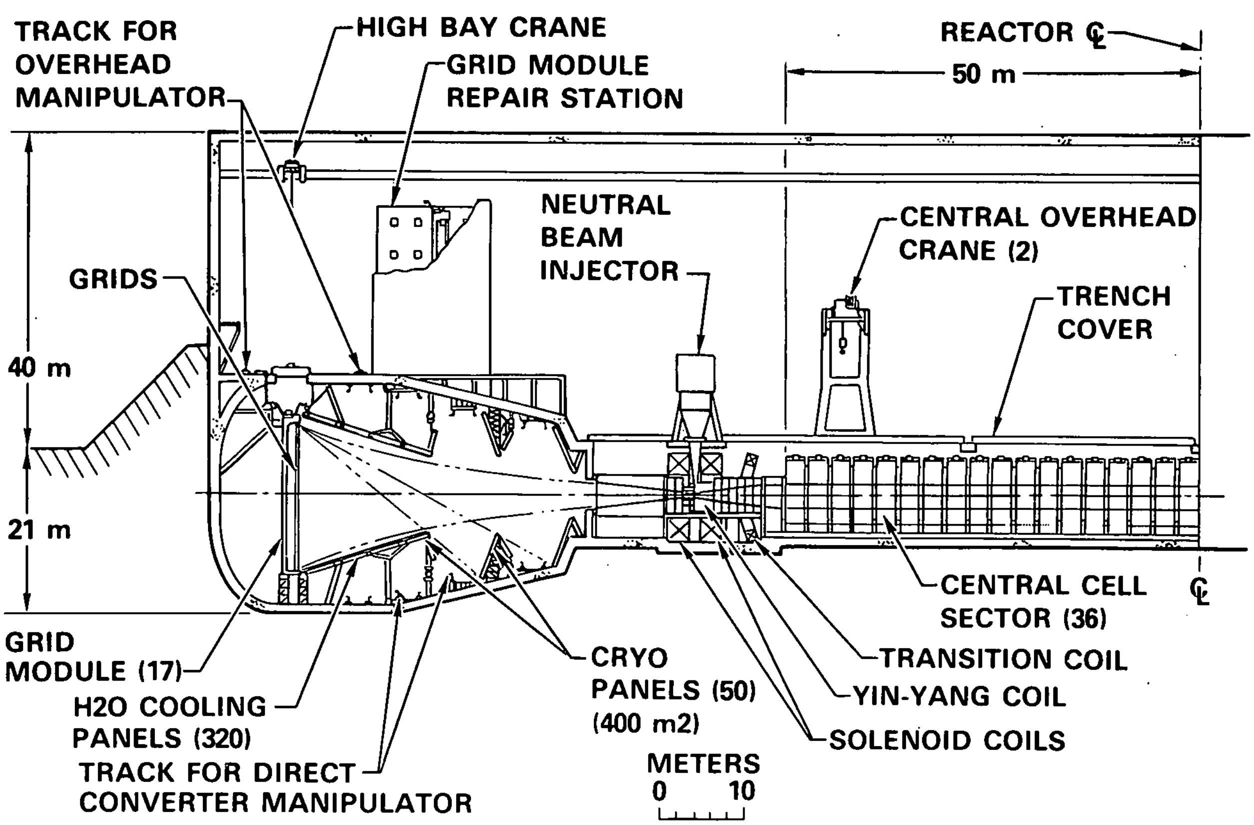

FIGURE 2–1

TOKAMAK BASELINE CONFIGURATION

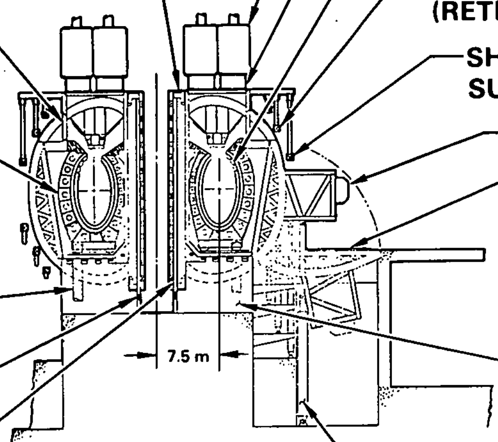

FIGURE 2–2

maintainability studies of several tokamak commercial reactor conceptual designs (Reference 3). The net electrical capacity of this reactor is 962 MW. The reactors have been normalized to similar neutron first wall loadings, approximately 2 MW/m^2, and to similar first wall life characteristics.

Some elaboration of the TMR baseline design has been defined to establish a base for the development of maintenance procedures. This has been accomplished without distortion of the original design concept insofar as possible. One major design feature is the installation of the central cell and end plugs in a trench. The trench covers are used as the primary vacuum wall and high impedance joints in the region of the blanket and first wall shielding become a secondary vacuum wall (Figure 2-3). All magnets are enclosed in this primary vacuum chamber. An end plug wall and shield is defined to protect the end plug magnets. This shielding is installed as a series of 12 modules, including two modules within the Yin-Yang magnets (Figure 2-4). The direct converter collector vanes are installed in modules with each module supporting 40 vanes. These modules, complete with collector vanes, are removable by use of a crane through sealed doors in the

CENTRAL CELL VACUUM ZONES

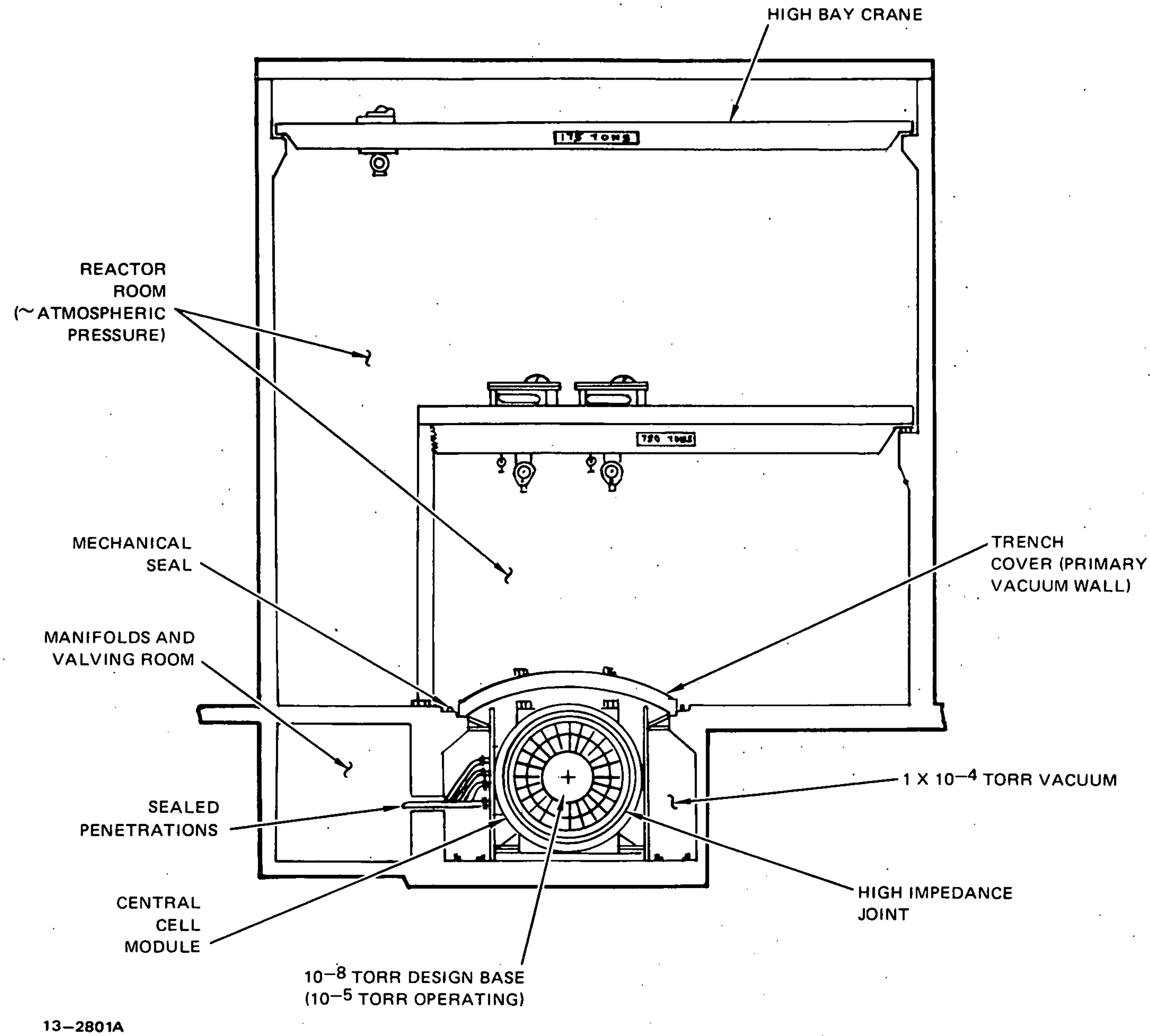

FIGURE 2–3

roof of the direct converter chamber (Figure 2-5). The direct converters are radiation cooled and, therefore, active cooling of the direct converter chamber walls is required. Water cooled panels are used for this purpose and the chamber is enlarged to provide access behind the panels for maintenance. These panels also shadow cryopump panels located in the direct converter chamber from the radiant heat. The cryopumps are accessed for maintenance in the same manner as

END PLUG ARRANGEMENT

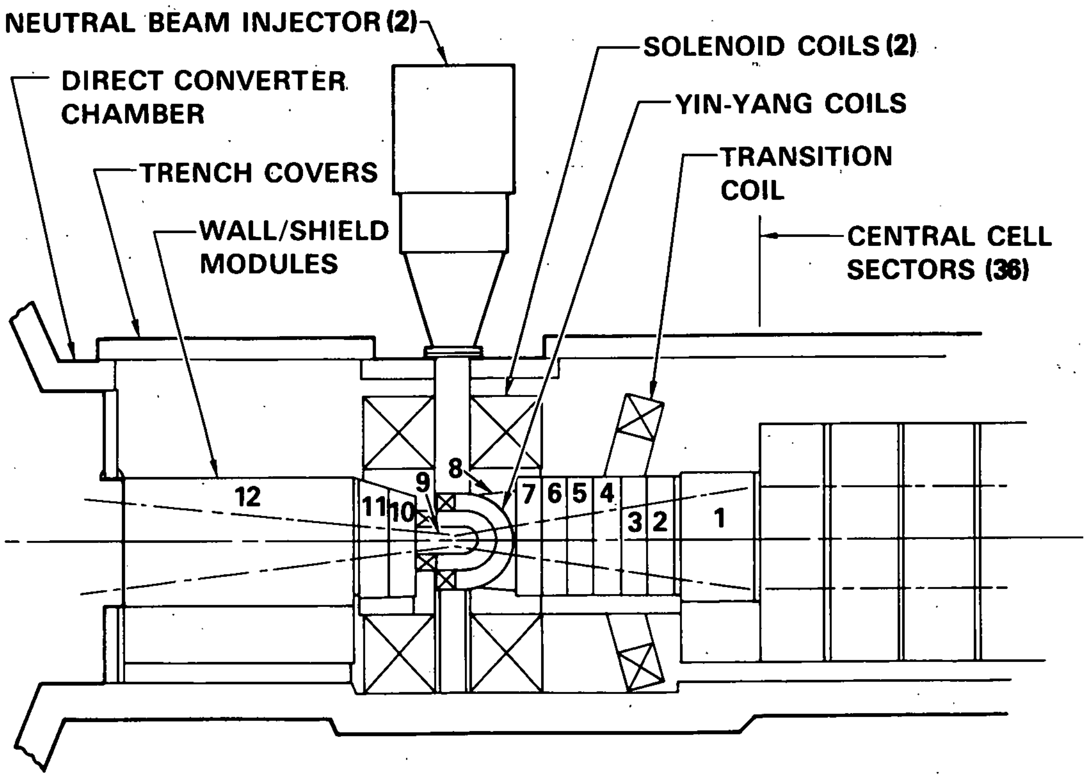

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FIGURE 2–4

DIRECT CONVERTER GRID REPLACEMENT

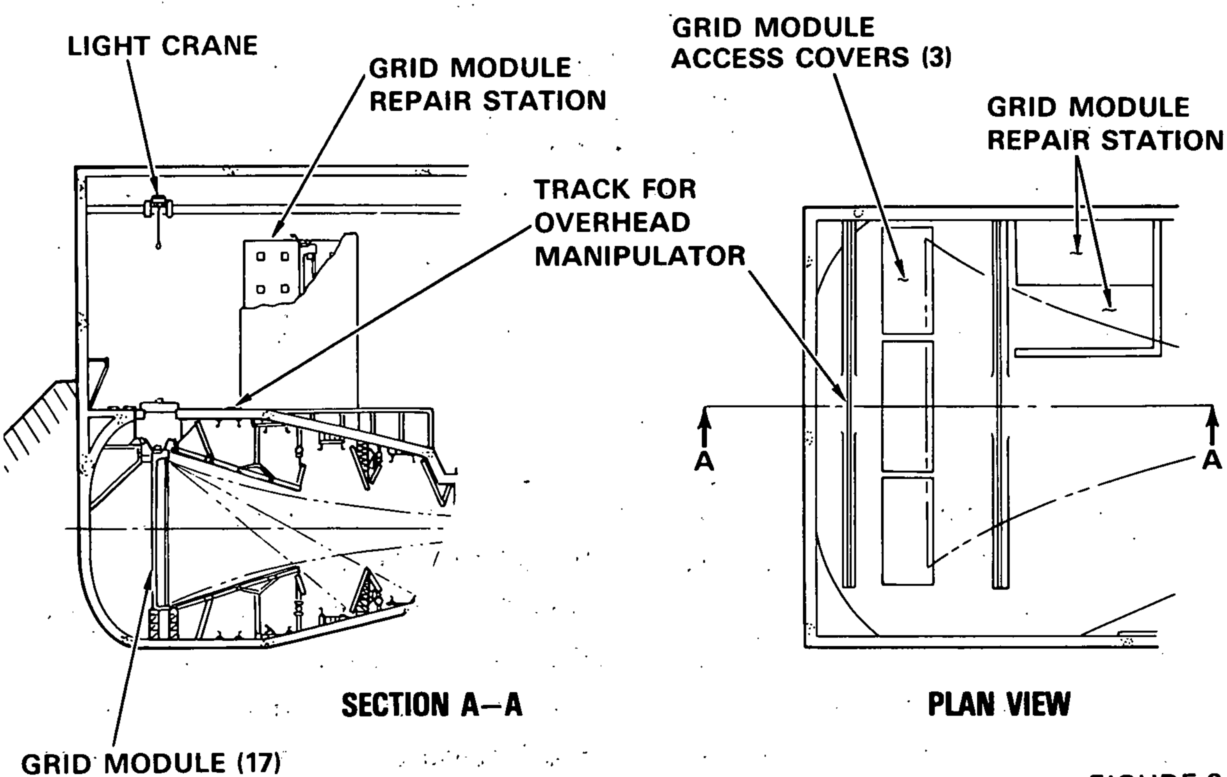

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FIGURE 2–5

the water cooled panels (Figure 2-6). Access to the direct converter chamber for panel maintenance is through a door in the wall which separates the direct converter from the end plug (Figure 2-7). The end plug neutral beam injectors (NBI's) are modularized to provide for ion source and stripping cell removal and the NBI cryo-pumps are attached to the side panels through which the modules are removed. (Figure 2-8). Numerous additional minor design details have been incorporated to assist in developing maintenance procedures.

The TMR maintenance plan includes the combined maintenance actions required by almost all of the TMR reactor subsystems. Because of current trends toward decreased radiation dosage limits, fully remote maintenance operations are defined. The scheduled maintenance action downtimes for significant components have been estimated. The longest duration maintenance operation is replacement of the cryo-pump panels in the direct converter chamber. The time per panel is only 2.1 days after initial access but the large number of panels makes this the critical path maintenance action that determines the total maintenance downtime. The replacement

DIRECT CONVERTER CHAMBER GENERAL ARRANGEMENT

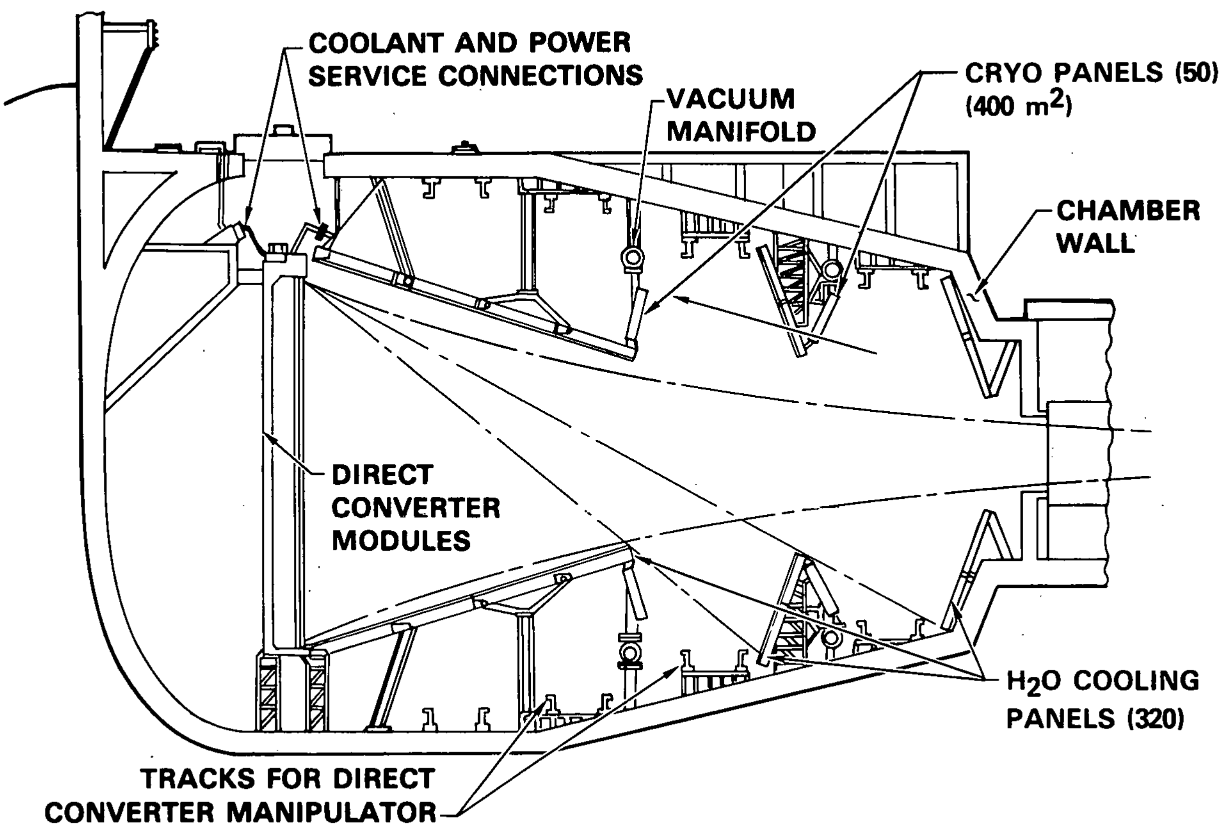


FIGURE 2–6

DIRECT CONVERTER CHAMBER ACCESS

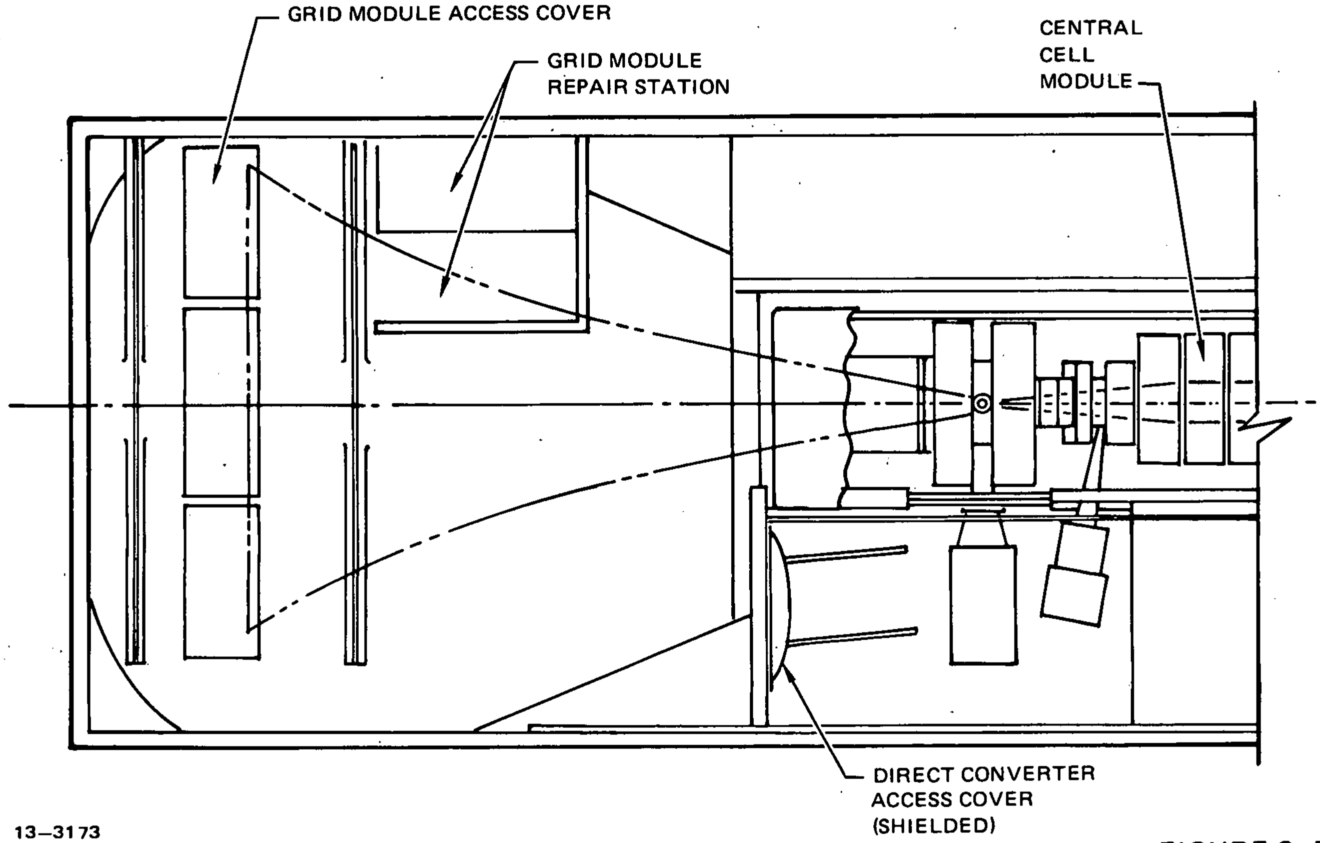


FIGURE 2–7

NEUTRAL BEAM INJECTORS–GENERAL ARRANGEMENT

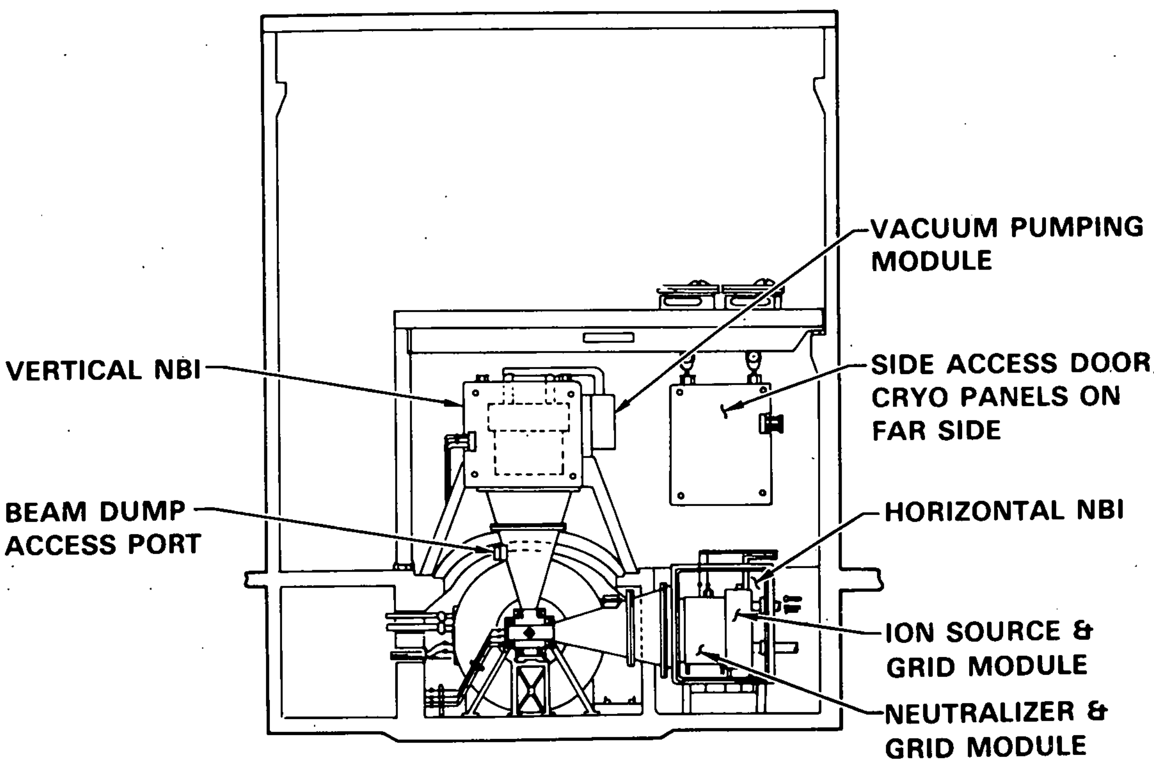


FIGURE 2–8

time of a central cell sector in the TMR is short compared to that for the first wall/blanket sector of a tokamak reactor, i.e., 6.2 days for the first TMR central cell sector compared to 16.8 days for the first tokamak sector. However, the 36 sectors in the TMR increases the required total downtime relative to that required for the 16 sectors used in the baseline tokamak reactor. The largest difference in maintenance time between the TMR and tokamak designs studied is for replacement of the magnets. Only 18 days is required for replacement of the Yin-Yang coil set compared to 347 days for a tokamak toroidal field coil. While these are unlikely events, the diminished penalty from this most difficult maintenance requirement is significant. In general, the time to replace major components in the TMR is less than that required for similar components in the tokamak reactor (Tables 2-1 and 2-2). Two major exceptions are the direct converter cryopump replacement and the end plug neutral beam ion source replacement.

TABLE 2–1

TMR SELECTED MAINTENANCE ACTION DOWNTIMES

MAINTENANCE ACTION	DOWNTIME PER UNIT, DAYS (1)	
	SCHEDULED	FORCED OUTAGE (2)
CENTRAL CELL SECTOR REPLACEMENT		
FIRST SECTOR	6.2	8.4
ADDITIONAL SECTORS	3.6	-
NEUTRAL BEAM ION SOURCE REPLACEMENT		
EACH MODULE	7.2	9.4
NEUTRAL BEAM INJECTOR CRYOPUMP REPLACEMENT		
HALF OF EACH NBI CRYOPUMP ASSEMBLY	3.9	6.1
END PLUG WALL REPLACEMENT		
PLUG TO CENTRAL CELL WALL	9.2 (3)	11.4 (4)
ENTIRE PLUG WALL	16.6 (3)	18.8 (4)
DIRECT CONVERTER GRID REPLACEMENT		
FIRST GRID MODULE, CENTER OF DC	4.9 (5)	7.1 (6)
EACH ADDITIONAL MODULE	1.1	1.1
DIRECT CONVERTER CRYOPUMP/COOLING PANEL REPLACEMENT		
FIRST PANEL	6.6/6.2	8.8/8.4
EACH ADDITIONAL PANEL	2.1/1.6	-/-
YIN-YANG COIL SET REPLACEMENT	-	18.0

(1) 24 HOUR, 3 SHIFT DAYS WITH PRODUCTIVITY FACTOR = 0.625 INCLUDED.

(2) FAULT ISOLATION OMITTED, SHUTDOWN AND STARTUP INCLUDED.

(3) WITHOUT TRENCH COVER REMOVAL BETWEEN PLUG AND CENTRAL CELL.

(4) YIN-YANG WALL MODULE(S) ONLY.

(5) INITIAL TIME DIFFERS FOR GRID MODULES UNDER SIDE DOORS.

(6) TO REMOVE MODULE UNDER DOOR SUPPORT - REMOVE MINIMUM OF 2 MODULES AND ADD 2:00 HOURS.

(7) NOT INCLUDED IN SCHEDULED OUTAGE ANALYSIS.

TABLE 2–2

TOKAMAK SELECTED MAINTENANCE ACTION DOWNTIMES

MAINTENANCE ACTION	DOWNTIME PER UNIT, DAYS(1)	
	SCHEDULED	FORCED OUTAGE(2)
FIRST WALL/BLANKET REPLACEMENT		
EACH SECTOR	16.8	18.7
NEUTRAL BEAM ION SOURCE REPLACEMENT		
ONE ION SOURCE ON ONE NBI	1.5	3.4
THREE (ALL) ION SOURCES ON ONE NBI	3.5	5.4
NEUTRAL BEAM INJECTOR ISOLATION VALVE REPLACEMENT		
ONE VALVE ON ONE NBI	1.7	3.6
DIVERTOR CRYOVACUUM PUMP REPLACEMENT		
EACH PUMP	2.0	3.9
DIVERTOR BOMBARDMENT PLATE REPLACEMENT		
FOR EACH SECTOR, ONE PLATE	1.0(3)	3.6
TOROIDAL FIELD MAGNET REPLACEMENT	-	347(4)
SHIELD DOOR SEAL REPLACEMENT	0.9(5)	5.3
COOLANT VALVE REPLACEMENT	1.9(6)	3.8
ELECTRICAL POWER LEAD REPLACEMENT	1.1(6)	1.8
CHARGE EXCHANGE ANALYZER REPLACEMENT	2.2(6)	4.0

(1) 24 HOUR, 3 SHIFT DAYS WITH PRODUCTIVITY FACTOR = 0.625 INCLUDED.

(2) FAULT ISOLATION OMITTED, SHUTDOWN AND STARTUP INCLUDED.

(3) ASSUMES POLOIDAL MAGNET MOVEMENT ACCOMPLISHED FOR ANOTHER MAINTENANCE ACTION.

(4) NOT INCLUDED IN SCHEDULED OUTAGE - ASSUME LOWER PF MAGNETS ARE SEGMENTED.

(5) ASSUMES SHIELD DOOR OPENED FOR ANOTHER MAINTENANCE ACTION.

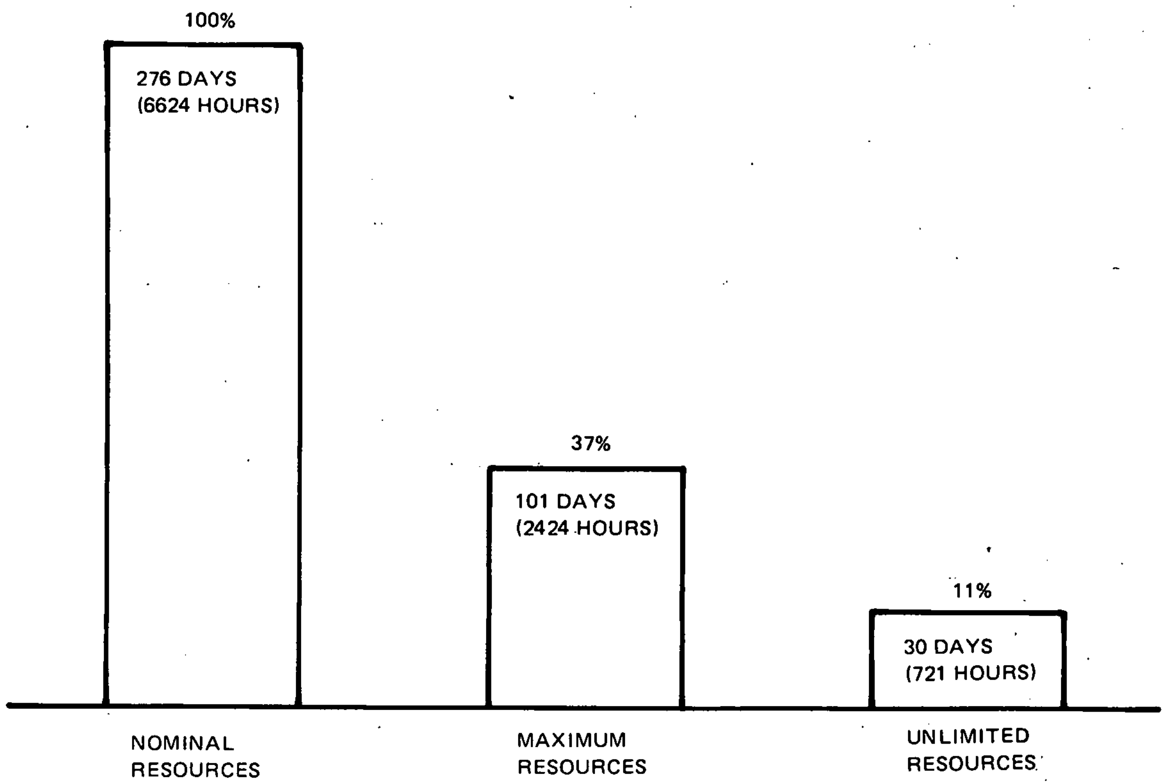
(6) MAINTENANCE ACTIONS ARE USED AS TYPICAL FOR TMR ALSO.

The critical path for scheduled downtime of the TMR is the replacement of the cryopump panels in the direct converter chamber. This requires 38 days to replace 50% of the panels or 18 days to replace 12%. However, replacement of the central cell sectors or the end plug first wall also results in near critical path downtimes. The critical path for the tokamak reactor requires 38 days to replace 50% of the first wall/blanket sectors or 23 days to replace 12.5%. A cost of electricity estimate for these cases indicates that the minimum cost of electricity will occur when replacing between 12% and 25% of the critical path units during a scheduled outage.

These outages assume that all other maintenance can be conducted in conjunction with the critical path operations. This assumption also implies that the maintenance equipment, maintenance personnel and other resources, such as floor space, are all available as required. The impact of the unavailability of resources for a trial set of 231 maintenance activities conducted during a scheduled outage with all maintenance actions conducted remotely has been estimated and is found to be significant. When unlimited resources are available for this set of maintenance actions the scheduled downtime is approximately 30 days. (The use of a scheduling code produced slightly different results than the equivalent critical path estimate of 28 days). When the maximum maintenance equipment considered feasible is made available and is used as a limit, the scheduled downtime increases to 101 days. When only a nominal set of equipment is available (only a few of a kind) the downtime increases to 276 days (Figure 2-9). Only maintenance equipment is limited in

IMPACT OF LIMITED RESOURCES ON SCHEDULED DOWNTIME

SCHEDULED OUTAGE DOWNTIMES



MSCS CODE SCHEDULES

PRIMARY MAINTENANCE ACTIONS: 18 CENTRAL CELL SECTORS
50 CONVERTOR PUMP PANELS

13–3160

FIGURE 2–9

this comparison with no limit imposed on personnel or facilities. This analysis, even though brief and incomplete, serves to indicate the influence that limited maintenance resources can have on any maintenance estimate.

Another influence on the scheduled outage duration is the extension of downtime caused by maintenance equipment failures. The effect of a set of typical failures has been examined for both the TMR and the tokamak maintenance equipment concept. All failure modes considered for the TMR allow for rapid rescue of the equipment and continuation of the work with an estimated maximum delay time of 3 days (Table 2-3). This particular delay is caused by a heavy crane failure under load. The comparable maximum delay time for the tokamak reactor is estimated at 6.5 days. The maintenance access available in the TMR reactor hall allows for improved maintenance of this equipment and should reduce its forced outage rate. This access results from the ability to shield all major reactor components by use of simple shielding covers.

The comparable capability of the TMR and tokamak reactors to accommodate forced outages is examined by calculating the days of forced outages allowed during an operating year when both reactor concepts are constrained to the same availability goal or cost of electricity (COE) goal (Figure 2-10). The scheduled outages

TABLE 2–3

MAINTENANCE EQUIPMENT FAILURE RECOVERY TIME ESTIMATES

EQUIPMENT	SCENARIO	RECOVERY TIME (DAYS)
TANDEM MIRROR EQUIPMENT		
o DIRECT CONVERTER (DC) MANIPULATOR	MANIPULATOR INSIDE DC CHAMBER FAILS WITH PANEL ATTACHED.	1.9
o TRENCH ROBOT	ROBOT FAILS TO RETRACT SHIELD SEGMENT UNDER LOAD.	1.3
o SHIELDING MANIPULATOR	MANIPULATOR FREEZES WHILE MOVING WALL/SHIELD SEGMENT LATERALLY	.8
o NEUTRAL BEAM INJECTOR (NBI) MANIPULATOR	MANIPULATOR STOPS WHILE MOVING ION SOURCES LATERALLY FROM NBI	1.7
o OVERHEAD MANIPULATOR	FAILURE WHILE DISCONNECTING FLUID LINE ON CENTRAL CELL	.7
o HEAVY CENTRAL CELL CRANE	HOIST FAILS WHILE LIFTING CENTRAL CELL SECTOR	3.0
o PERSONNEL MODULE	MODULE MANIPULATOR FAILS TO RELEASE WITH MODULE IN TRENCH	.7
TOKAMAK EQUIPMENT (FROM 1978 STUDY OF CULHAM CONCEPT)		
o REACTOR SECTOR REMOVAL MACHINE	FAILURE OCCURS WITH SECTOR PARTIALLY RETRACTED	6.5
o HELIUM COOLING DUCT WELD HEAD	WELD HEAD FAILS WHILE WELDING DUCT	1.7

EFFECT OF UNSCHEDULED MAINTENANCE ON COE AND AVAILABILITY
(Includes Only FW/Blanket & Cryopump Maintenance)

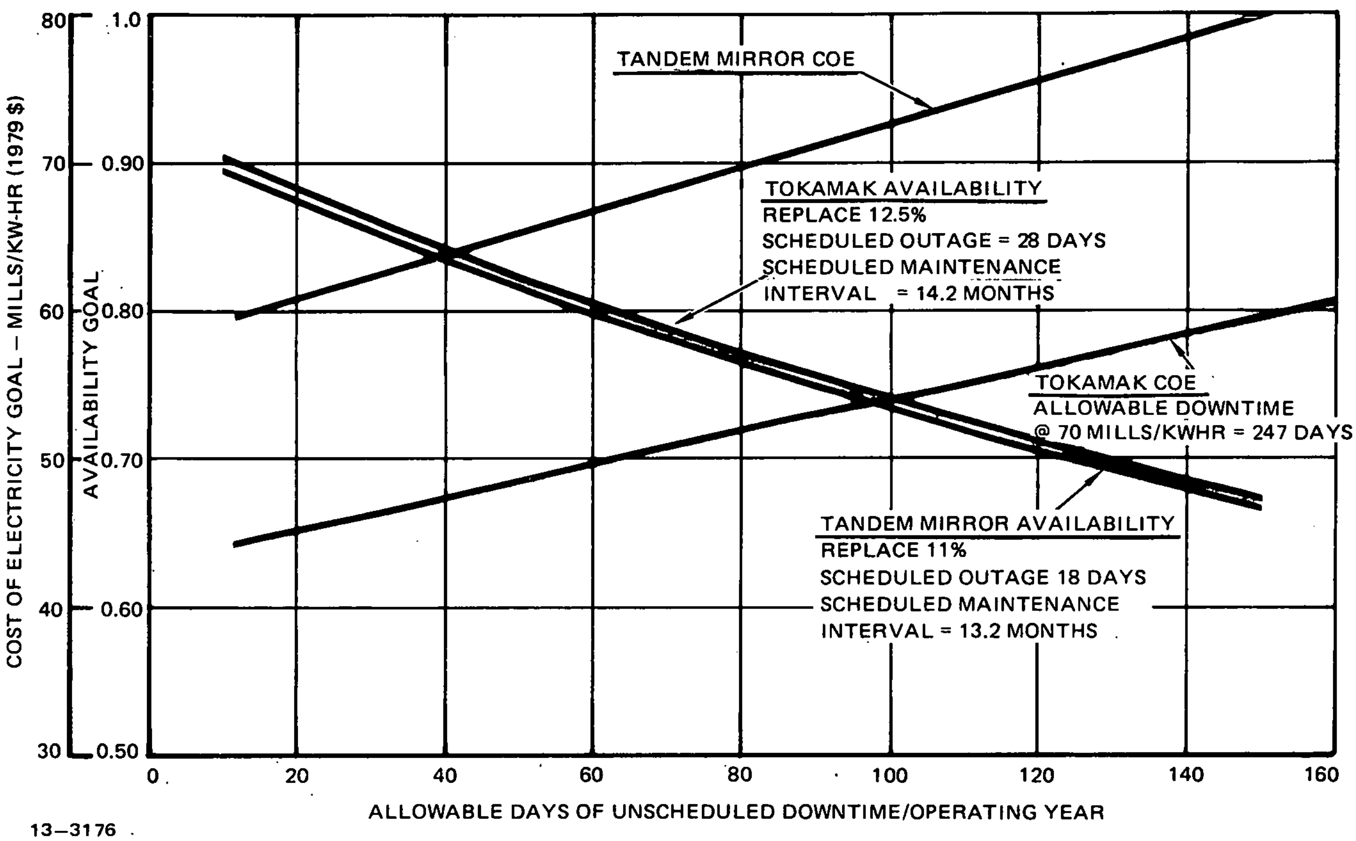


FIGURE 2–10

assumed are those derived through the critical path analysis and through the optimization of replacement fractions for the components that drive the scheduled downtime. The allowable days of unscheduled downtime is almost the same for both reactors when their operation is constrained to a common availability goal. For an availability goal of 80% the allowable days for the TMR and tokamak are approximately 60 and 62, respectively. However, the cost of electricity for the baseline TMR is greater than that for the tokamak because of the higher capital cost of the TMR. Therefore, at a common cost of electricity goal of 60 mills/kw hr the allowable forced outage time for the TMR is 16 days while the allowable time for the tokamak reactor is 156 days. To balance these times it is important to reduce either the capital cost of the TMR or the estimated forced outage downtime requirements or both.

The current estimate of the capital cost of the TMR is approximately 3.02 billion (1979 dollars). If this cost is decreased by 26 percent the allowable forced outage downtime will be equal to that for the tokamak reactor concept. This required reduction in capital cost is insensitive to the cost of electricity goal selected (Figure 2-11).

The forced outage downtime requirements for the TMR replaceable components have been estimated relative to each other. Redundancy is incorporated wherever it is considered feasible. Subsystems accomodating redundant components include primarily the vacuum system, cooling system and the power supplies. Redundancy in the 1.2 MeV neutral beam injectors is assumed to be impractical even though replacement of the ion sources in these neutral beams is estimated to consume the largest percentage of forced outage allowable downtime (approximately 23% of the total). Other components estimated to generate significant forced outage downtime include the direct converter grid modules, vacuum seals, piping connections and valves (Table 2-4). Redundancy is used in critical valves and piping loops and in vacuum seals. Direct converter collector vanes have not been made redundant.

IMPACT OF CAPITAL COST ON TMR ALLOWABLE UNSCHEDULED DOWNTIME

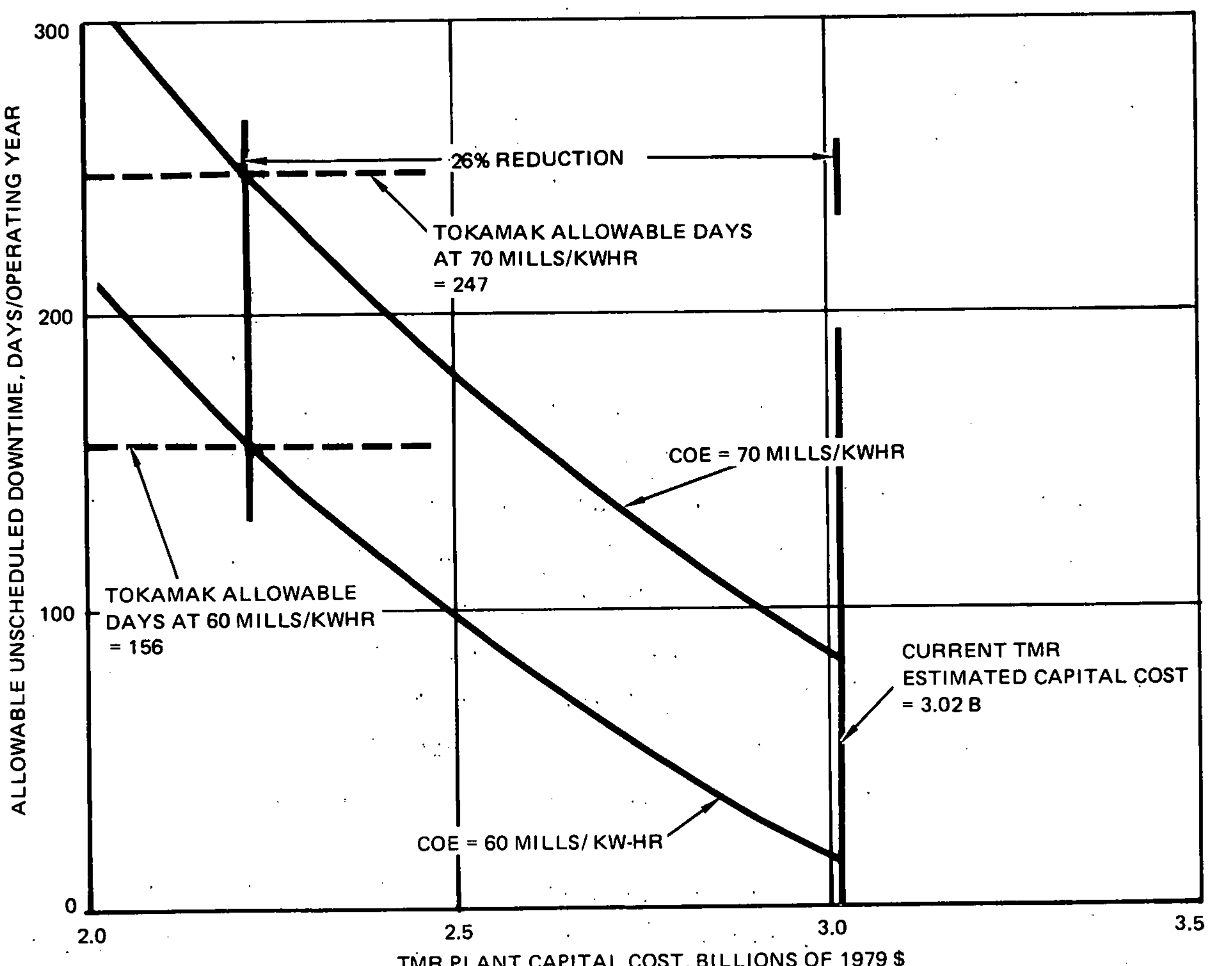


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FIGURE 2–11

TABLE 2–4

TMR SIGNIFICANT FORCED OUTAGE COMPONENTS

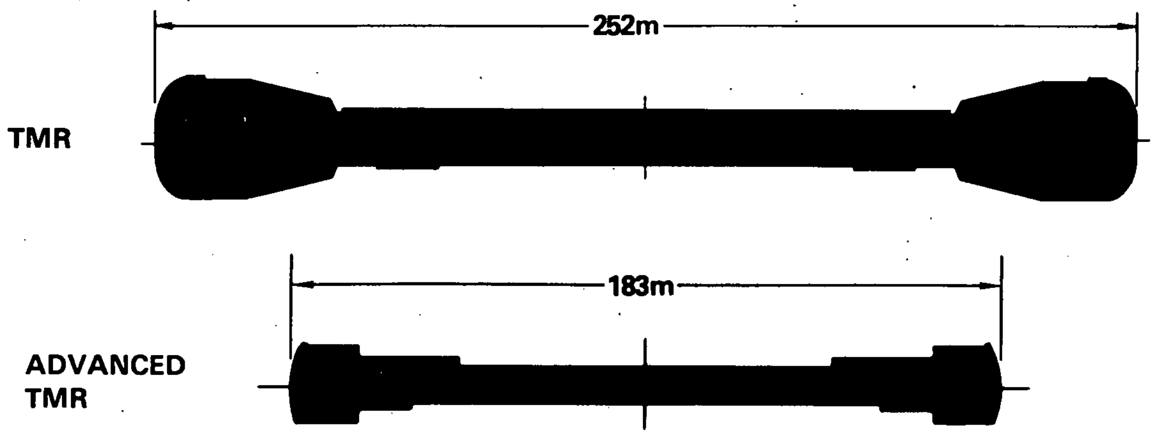
COMPONENT(2)	UNSCHEDULED DOWNTIME(1) (PERCENT OF TOTAL ALLOWABLE)	ALLOWABLE DOWNTIME(3) DAYS/OPERATING YEAR
END PLUG NEUTRAL BEAM ION SOURCES	22.9	19
END PLUG NEUTRAL BEAM STRIPPING CELLS	14.8	12
DIRECT CONVERTER GRID MODULES	11.1	9
END PLUG AND DIRECT CONVERTER VACUUM WALL SEALS	10.0	9
CENTRAL CELL VACUUM WALL SEALS	5.0	4
CENTRAL CELL MAGNET PIPING CONNECTIONS	4.4	4
CENTRAL CELL FIRST WALL/BLANKET	3.5	3
DIRECT CONVERTER THERMAL PANELS	3.3	3
FUEL INJECTION NEUTRAL BEAM ION SOURCES	2.7	2
DIRECT CONVERTER CRYOPUMP CRYOGEN/CONTROL VALVES	2.3	2
CENTRAL CELL PRIMARY COOLING PIPING CONNECTIONS	1.9	2
END PLUG NEUTRAL BEAM CRYOPUMP PIPING CONNECTIONS	1.4	1
END PLUG ION SOURCE VACUUM PUMP	1.4	1
END PLUG NEUTRAL BEAM CRYOPUMP SHUTTERS	1.3	1
DIRECT CONVERTER CRYOPUMP SHUTTERS	1.2	1
FUEL INJECTION NEUTRAL BEAM VACUUM COOLING PIPING CONNECTIONS	1.1	1
END PLUG MAGNET COOLANT SYSTEM CONNECTIONS	1.0	1
OTHER COMPONENTS (< 1 PERCENT EACH)	10.1	9
	100.0%	84

(1) VARIATIONS IN PRELIMINARY ESTIMATES CAN ALTER RESULTS SIGNIFICANTLY.
(2) ONLY COMPONENTS THAT CANNOT BE MAINTAINED DURING REACTOR OPERATION ARE CONSIDERED.
(3) FOR 70 MILLS/KW HR COE GOAL, TOTAL FORCED OUTAGE DOWNTIME ALLOWABLE = 84 DAYS

In those critical cases where redundancy is impractical, designs of high reliability must be developed or possibly the system design reworked to provide for redundancy.

Because of the limited data available to estimate the forced outage rates of components and the resultant uncertainty of the foregoing relative downtime impacts, emphasis is placed on the potential for reducing capital costs of the TMR to achieve allowable forced outage downtimes that are more comparable with the tokamak reactor concept. Examination of an advanced TMR conceptual design currently under study by the Lawrence Livermore Laboratory indicates that a 970 MWe reactor will be approximately 183 meters long and occupy a reactor hall with a volume of 350,000 m^3 (Figure 2-12). This represents a 27% reduction in the length of the baseline TMR reactor and a reduction of 34% in the required building volume. Advanced TMR design concepts indicate a trend toward smaller and less costly reactors. The maintainability of the advanced TMR also indicates significant improvements. For example, the scheduled downtime requirement for replacing 50% of the cryopump panels in the direct converter chambers is reduced by 45%. Approximately

ADVANCED TMR SIGNIFICANTLY IMPROVES MAINTAINABILITY



	TMR	ADVANCED TMR
CENTRAL CELL MODULE REPLACEMENT TIME (50%) –	593 HRS	500 HRS
DC CRYOPANEL REPLACEMENT TIME (50%) –	781 HRS	430 HRS

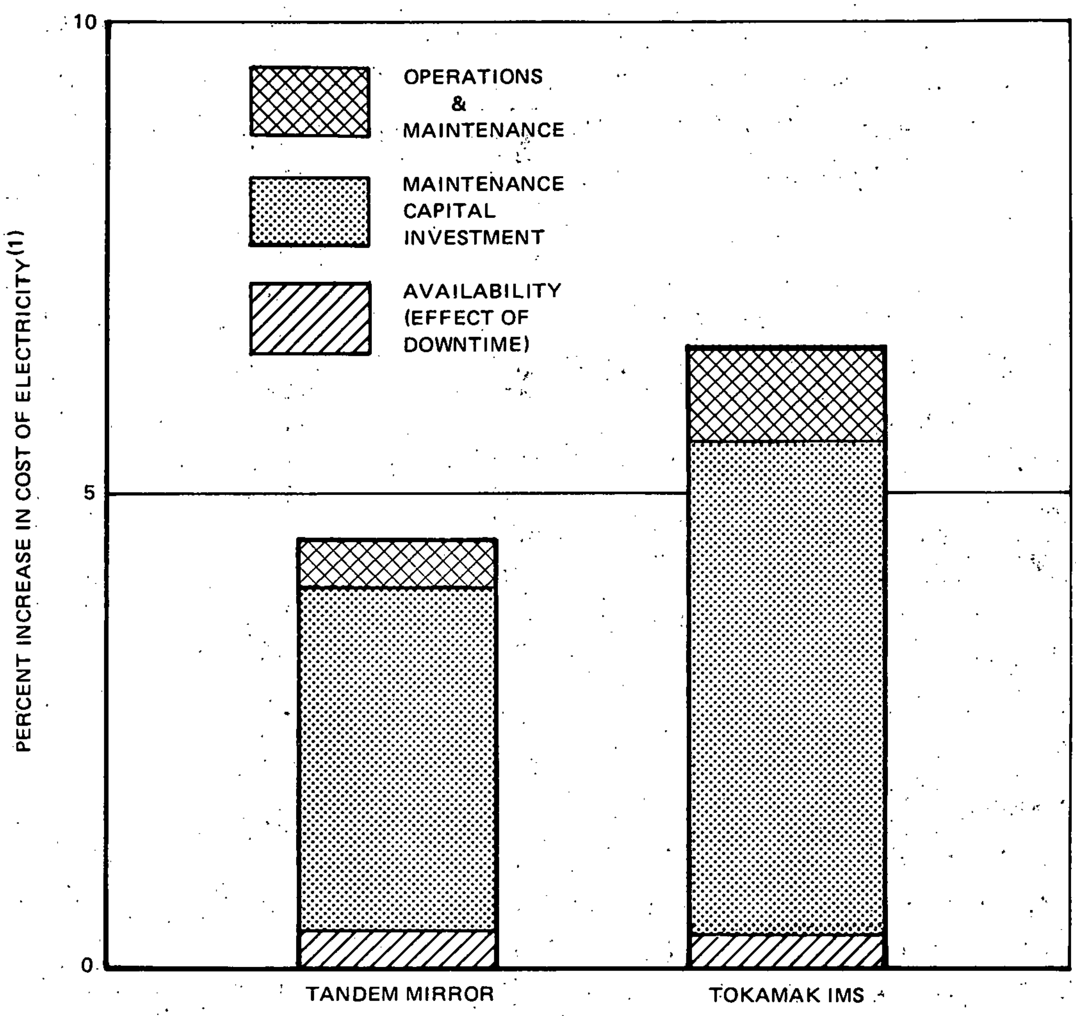
13–2808A

FIGURE 2–12

58% of this reduction is attained because less downtime is required per panel with the improved access available in this design and 42% of the reduction is realized because fewer panels are required. (Better access allows handling larger panels.) Also, the time required to replace a central cell sector is reduced through redesign of the joint between sectors. However, the increase in the number of sectors to 44 from the required 36 for the baseline TMR tends to negate this advantage. In summary, the trend toward a lower capital cost, which should also result in a lower maintenance cost and easing of forced outage requirements, is expected to improve the comparison with the tokamak reactors. This trend should continue as the TMR commercial design concepts become more mature.

A comparison of the percentage increased in cost of electricity (COE) resulting from scheduled maintenance costs shows that the scheduled maintenance for the TMR baseline reactor increases COE by 4.7 percent while the tokamak reactor design requires an increase of 6.6% (Figure 2-13). Since the TMR capital cost is larger than the tokamak capital cost, the optimized COE is also larger (67.2 mills/kw hr to 50.1 mills/kw hr for the tokamak reactor). However, since the maintenance costs are approximately equal, a lower percentage increase for the TMR results. The significant factor is that the annual maintenance cost for the TMR is low even though

TMR MAINTENANCE IMPACT COMPARES FAVORABLY WITH TOKAMAK



(1) RESULTING FROM SCHEDULED MAINTENANCE
(2) REACTORS HAVE THE SAME NET POWER OUTPUT

13–3159

FIGURE 2–13

it is a larger machine and involves a wider variety of subsystems than the tokamak reactor. This maintenance cost equality is achieved largely because of improved access and the resultant simplicity of the maintenance procedures. In addition, the baseline TMR maintenance procedures require maintenance capital costs which are estimated to be less than those required for the tokamak reactor, i.e., $98 million compared to $111 million, and these procedures result in almost the same availability for both reactors (.794 for the TMR and .795 for the tokamak reactor). For TMR, scheduled maintenance plans produce minimum impact on cost of electricity when replacing only 4 central cell sectors and 6 cryopump panels in each direct converter.

For the tokamak reactor the minimum impact on cost of electricity occurs when replacing 2 first wall/blanket sectors. The theoretically optimum maintenance intervals for these replacement quantities are 13.2 months and 14.2 months for the TMR and the tokamak reactor, respectively. Optimization at these low replacement fractions differs from earlier study results primarily because the first wall life is increased to be consistent with current analytical estimates.

Some desirable features of the baseline TMR conceptual design are listed below:

- The TMR provides excellent access for maintenance with a minimum of operations requiring highly advanced state-of-the-art maintenance equipment.
- Internal access is unnecessary for maintenance except in the direct converters and this requirement is being eliminated in the advanced TMR under study.
- Intertwining magnet configurations are eliminated.
- Maintenance actions requiring disassembly of major reactor structures or sections to gain access to failed components are eliminated.
- Many units can be maintained at the same time. Interference is minimal.
- A double vacuum zone simplifies central cell sector and end plug shield module installation.
- All maintenance equipment can be maintained external to the reactor.
- Redundant neutral beam injector components in the end plugs are desired in order to reduce the expected forced outages caused by this subsystem.

Several conclusions regarding the relative maintainability of the baseline TMR and the IMS tokamak design concepts can be defined:

- The scheduled outage critical path for the TMR is less than that required for the tokamak, 18 and 23 days respectively, and both times are less than or equal to that estimated for the balance of plant (28 days).
- The annual cost of scheduled maintenance for both reactor concepts is estimated to be the same at approximately $21 million.
- To attain equivalent allowable forced outage total downtimes for the TMR and the tokamak at the same cost of electricity, the capital cost of the TMR should be reduced approximately 26 percent.

3.0 SYSTEM DESIGN CHARACTERISTICS

A realistic maintainability evaluation of a Tandem Mirror Reactor (TMR) commercial conceptual design, when compared with the maintainability of a tokamak reactor commercial conceptual design, requires that both designs be of the same relative level of detail and completeness. The tokamak reactor used in this comparison is the Improved Maintenance System (IMS) reactor described in Reference 3. This IMS reactor is based upon the Culham Laboratory conceptual design with changes incorporated to improve maintainability. Much work has been done on tokamak reactors, thus the maintainability of the IMS reactor concept is well developed. On the other hand, the TMR reactor available for comparison is that defined by the Lawrence Livermore Laboratory and described in Reference 2.

Reference 2 contains the first comprehensive study of a commercial tandem mirror reactor and, therefore, the concept and design require additional development to approach that of the tokamak reactors. To help rectify this some changes and clarifications have been made to the LLL TMR to establish the baseline TMR used in this study. While the performance, physics, and basic configuration of the TMR remain unchanged, the attempt is made to incorporate improved maintenance concepts in the baseline TMR. Even with additional design elaboration the baseline TMR is less refined than the IMS tokamak.

3.1 SYSTEM PERFORMANCE COMPARISON - Both the baseline TMR and the tokamak IMS reactor are rated at approximately 1000 MW net electrical power as shown in Table 3-1. Although the recirculating power percentage is much higher in the TMR, both reactors have a peak thermal power of about 3000 MW. This is because of the high efficiency of the direct converter employed with the thermal systems in the TMR, as shown in Figure 3-1, compared to the use of thermal systems only in the tokamak reactor. Both designs have a plasma wall loading of approximately 2 MW/m^2, which results in the same first wall life. A first wall fluence limit of 16 $MW\text{-}Yrs/m^2$ is used throughout this maintainability evaluation.

Since the studies which generated the conceptual designs both sized the reactor for approximately 1000 MWe, additional normalization of the designs is unnecessary. From Table 3-1 it is noted that both reactors use helium as the principal coolant and the first wall area is approximately equal at 980 m^2 and 991 m^2 for the TMR and tokamak reactor, respectively. The number of wall/blanket sectors is 36 for the TMR but only 16 for the tokamak. This difference in the number of sectors is important in deriving the relative maintainability characteristics of the two reactors.

TABLE 3–1
TMR/TOKAMAK REACTOR CHARACTERISTICS

	TANDEM MIRROR	TOKAMAK (IMS)
NET POWER, MW_e	989	962
PEAK THERMAL POWER, MW_{th}	3060 (INCL. D.C. POWER)	3000
Q, (NET POWER/RECIRCULATING POWER)	1.3	5.4
PLASMA RADIUS/ELONGATION, m	1.2/1.0	1.92/2
PLASMA BETA	0.7 (CENTRAL CELL)	0.103
NEUTRAL BEAM ENERGY/POWER, MeV/MW	1.2/588	0.12/60
PLASMA CHAMBER WALL LOADING, MW/m^2	2.05	2.12
PLASMA CHAMBER WALL AREA, m^2	980	991
BURN TIME, SEC.	CONTINUOUS	3600
DUTY CYCLE	1.0	0.97
NUMBER OF WALL/BLANKET SECTORS	36	16
WALL/BLANKET COOLANT	HELIUM	HELIUM
MAGNETIC FIELD ON AXIS, T	2.4 CENTRAL CELL 2.0 YIN-YANG 4.5 PLUG MAGNET	3.9
PLANT EFFICIENCY	34%	33%
RECIRCULATING POWER FRACTION	43%	16%

The plasma performance is remarkably similar for two such different concepts. The TMR central cell plasma is characteristically circular in cross section while the tokamak is approximately elliptical with an elongation of 2:1. The neutral beam power is much higher for the TMR end plugs than for the tokamak heating, resulting in much higher recirculated power requirements. The values of Q given in Table 3-1 are engineering Q's and reflect the greater recirculated power required in the TMR.

3.2 TMR MECHANICAL DESIGN - The Lawrence Livermore Laboratory Report has described the TMR in some detail (Reference 2). The following is a description of the baseline TMR design and some of the approaches used in elaborating on the design for maintainability purposes.

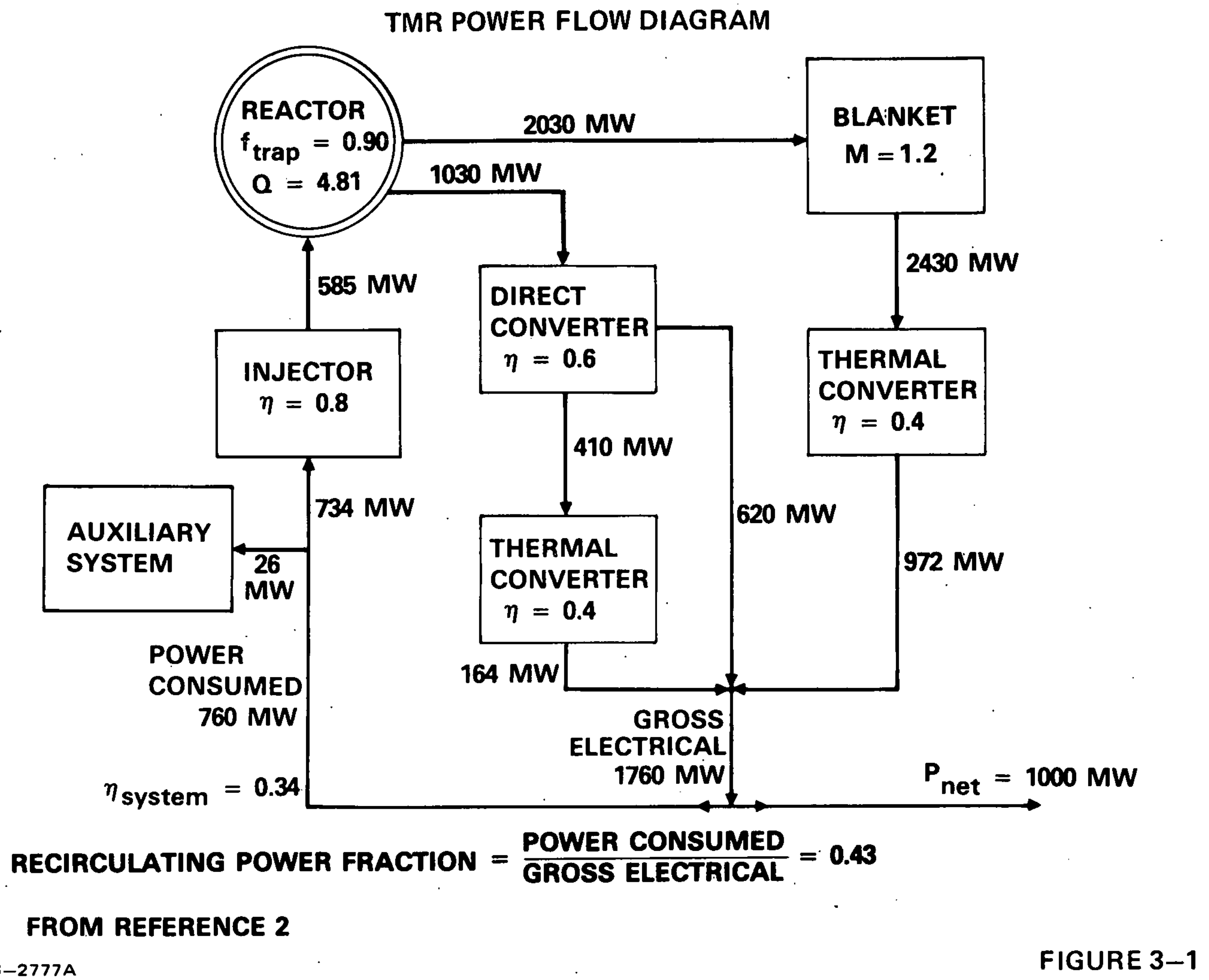


FIGURE 3–1

3.2.1 Design Guidelines and Assumptions - Design guidelines have been set up with the intent of following those used for the IMS tokamak reactor wherever feasible, thus keeping the designs as similar as possible. Some of the maintainability features of the IMS tokamak are shown in Figure 3-2.

Modularity is stressed throughout the baseline TMR design. The maintenance approach is to remove and replace components instead of repairing them in place. Therefore, the reactor is subdivided into modular sections which are as small as possible, yet with the restriction that they be accessible with minimum disturbance of other components. Because of this, some of the modules are quite large. For example, each TMR central cell sector is approximately 2.8 m long x 9 m wide x 10 m high and weighs 620 tonnes. If, for example, the reactor first wall needs to be repaired, the entire central cell sector is removed and replaced with a spare unit. Reactor operations then continue while the removed central cell sector is taken to the hot cell and the first wall is repaired.

IMS TOKAMAK MAINTAINABILITY DESIGN FEATURES

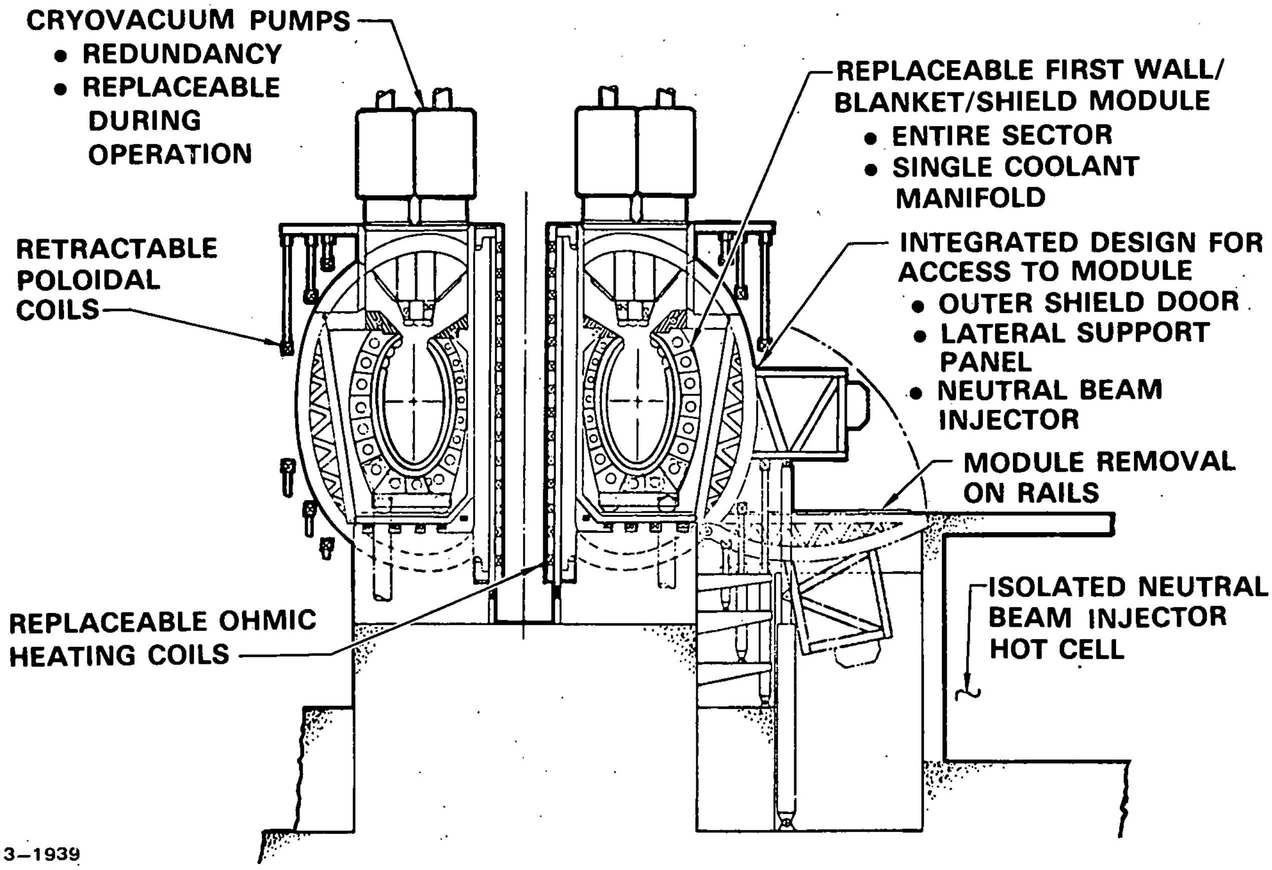


FIGURE 3–2

To minimize large, bulky, and specialized handling equipment, the majority of modules are designed for installation or removal by overhead crane. Each will have standardized lifting lugs, either light or heavy duty, as an integral part of the module structure. No spreader bars, slings or special handling fixtures are required; the hook on an overhead crane will latch directly to any one of many modules. Also integral to the design are guide rails, tapered guide pins and other devices to ensure proper alignment and clearances when positioning modules. All modules will have secondary lift points to allow transfer from one crane to another in the event of a crane failure.

Because of the possible need to conduct maintenance in a radioactive environment all modules are designed for remotely disconnecting and removing them. Where multiple structural attachments are needed preference is given to simple cam type latches that are mechanically linked together to one or two release points. Individual bolts are avoided because of disconnect time and handling problems. Unlatching the module entails simply attaching a remote operated impact wrench to the release "nut" on the module and spinning it until the cams are retracted. This "nut" also is standardized, allowing one remote manipulator head to interface with any module. Fluid and electrical disconnects have the same "nut" allowing them to be disconnected quickly. Mechanical connections in TMR fluid lines are chosen over a welded system for the same reason they are chosen on the IMS tokamak; quicker connecting and disconnecting.

In the event that any of the latch mechanisms seize or fail, a contingency disconnect mode is designed into the modules. This involves removing bolts to disassemble the latch mechanism, a tedious job to perform remotely, but used only as a back-up.

Some additional maintainability design guidelines that are followed in defining details of the baseline TMR include:

- o Maintenance equipment to be accessible during its operation.
- o Use a minimum number of connections for component replacement, particularly fluid connections.
- o A multiple zoned vacuum wall arrangement is preferred.
- o Design for simplified and rapid access to replacable components and for minimum replacement time.
- o Very long life components are considered for unscheduled maintenance only.
- o Design for large module sizes to reduce scheduled maintenance downtime for replacing multiple identical modules.
- o Minimize interference to access by fluid lines, power lines and instrumentation.
- o Design for concurrent maintenance operations.

The foregoing guidelines are all extracted from the tokamak maintainability studies discussed in Reference 3.

3.2.2 <u>TMR General Arrangement</u> - In contrast to the torus shape of the tokamak reactor, the Tandem Mirror Reactor (TMR) is essentially a thin cylinder. Figure 3-3 shows the baseline TMR and its reactor building. The reactor is divided into three regions; the central cell, end plugs on both ends of the central cell, and direct converters at either end of the reactor.

The 100 m long central cell is cylindrical in shape and is the primary power producing region. It is composed of 36 central cell sectors, one of which is shown in Figure 3-4. These sectors are housed in a vacuum trench.

Two end plugs also located in the vacuum trench at both ends of the central cell. Because this region is not supplied with both deuterium and tritium ions,

TMR GENERAL ARRANGEMENT

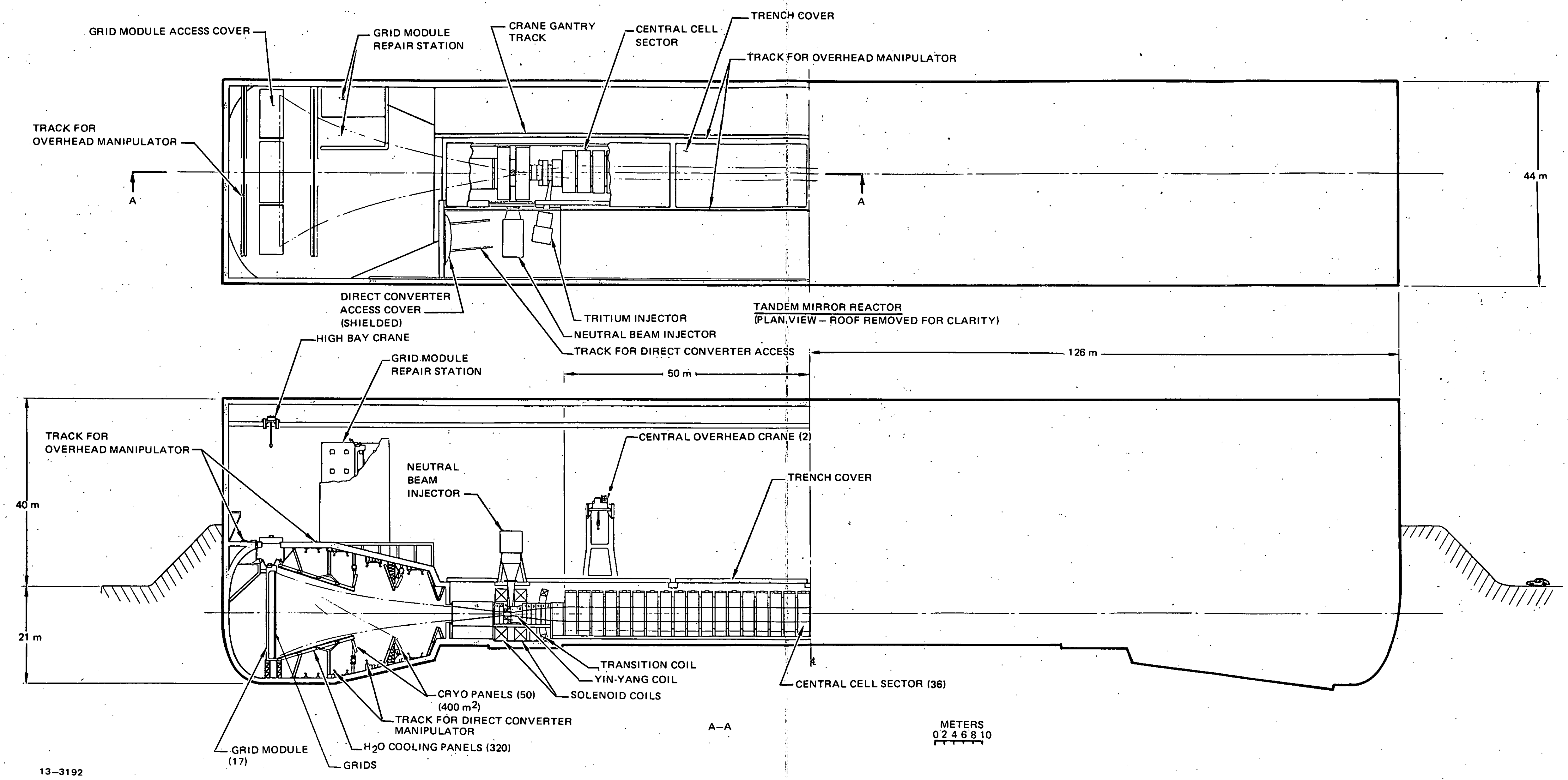


FIGURE 3–3

CENTRAL CELL SECTOR

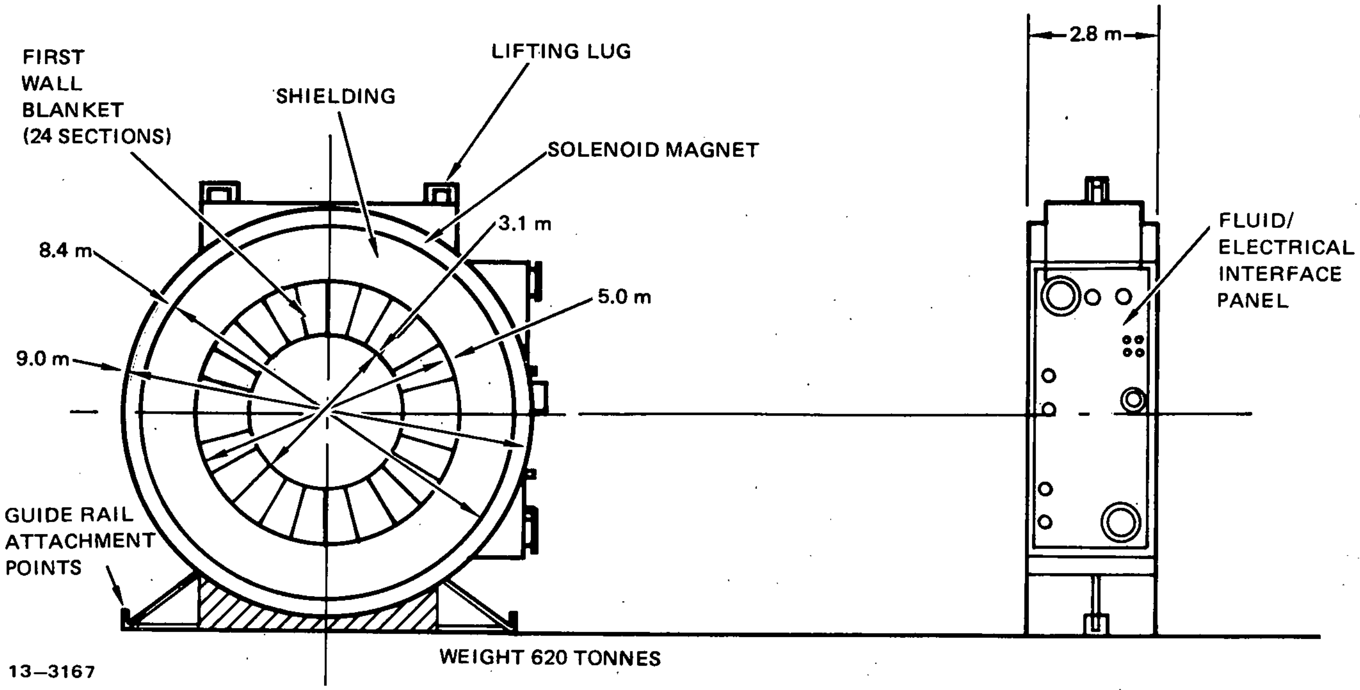


FIGURE 3–4

but with deuterium alone, little fusion takes place. It is not a significant energy producing area and thus is provided with shielding only.

Even with the constricting magnetic fields in the end plugs, a significant amount of particles escape through the ends. To capture these and extract their energy, large direct converters are mounted at both ends of the reactor. These direct converters consist of grids which supply approximately one-third of the power output of the reactor and which are housed in large elliptically shaped concrete and steel structures.

Access to the central cell modules and end plug magnets in the trench is through four steel lined concrete trench covers, each being approximately 30 meters long. Since they weigh about 1000 tonnes each, two overhead cranes are used to remove a cover and stack it on top of another cover for storage. Cross members are used between adjacent covers to avoid the difficult corner seal problem occurring if the covers were to butt up against each other. Unfortunately, this requires that modules under the cross members be moved axially prior to being lifted out. Since neutral beam injectors are mounted directly over the center of each end plug access is restricted to that area from above. However, smaller trench covers are used over the area between the neutral beam injectors and the direct converter chamber. In addition to the two overhead neutral beam injectors (NBI) there are two NBI's mounted at the side of the end plugs. Also, two neutral beam injectors to fuel the reactor with tritium are mounted alongside the reactor at the ends of the central cell.

The direct converter vacuum wall is a large (46 m long x 42 m wide x 28 m high) elliptical concrete and steel structure and does not have any large removable sections for access. There are three small access covers directly over the direct converter grids, allowing these grid modules to be lifted out. In addition there is a vacuum door in the end of the trench region which allows maintenance equipment to enter the direct converter chamber along a track.

The reactor building is a large concrete and steel structure 252 m long, 42 m wide and averages 50 m high. The 10,600 m^2 of reactor room floor space is twice as much as needed for the baseline tokamak. However, because the tokamak reactor room is nearly twice as tall, the internal volumes are nearly the same (530,000 m^3 for TMR vs 510,000 m^3 for IMS Tokamak).

A remote maintenance capability has been designed into the reactor and reactor building. Tracks for remote maintenance equipment span the trench and the direct converter grid module covers. All release and latch mechanisms are designed to interface with the remote maintenance equipment, as do all lift points. Movement of equipment inside the reactor room is principally by crane; the room is laid out for this with no columns, posts, or other obstructions in the way. Access to and from the room is through two large transfer locks, with tractor pulled dollies moving equipment from the reactor room to the hot cell or maintenance equipment area.

3.2.3 TMR Central Cell Region - As mentioned before, the 100 m long central cell is made up of 36 sector modules, any of which can be removed for maintenance. Each sector is 9 m in diameter, 2.8 m long and weighs 620 tonnes as shown in Figure 3-4. Between the central cell sectors are shielding rings made in three segments which are removed by remote maintenance equipment to allow a central cell sector to be lifted out. Each shielding segment weighs approximately 50 tonnes. In addition to preventing neutron streaming, the shielding segments also serve as a structural support between adjacent central cell sectors, carrying the magnetically induced axial loads.

Normal repair of the central cell sector requires the sector to be removed, replaced with a spare, and sent to the hot cell. It is there that the helium cooled first wall/blanket, the superconducting magnet, the shielding, or the manifolding can be repaired.

The actual removing and replacing of a sector is aided by vertical guide rails attached to both trench walls which keep one sector from bumping into another as it is lifted out. Tapered guide pins on the trench floor do the final precise aligning of the sector and also carry axial loads at the base of the sector.

All fluid and electrical connections are located at one side of the sector. These connections include:

1) Primary blanket coolant (GHe) inlet and outlet lines
2) Tritium purge vacuum line
3) Magnet coolant (LHe) inlet and outlet lines
4) Magnet dewar coolant (LN2) inlet and outlet lines
5) Magnet dewar vacuum line
6) Magnet input and output power leads
7) Instrumentation bundle

All connections designed for maintenance use mechanical disconnect devices. No welded connections are used, although the mechanical connections are installed in a location where they can be remotely cut out and rewelded. This feature must be incorporated into the design because remotely operated mechanical disconnects require some provision to replace the disconnects themselves.

The joint between the central cell sectors is assumed to require only a high impedance joint without a vacuum seal. The trench cover is the primary vacuum wall and the volume between the trench cover and the sectors is maintained at a low pressure. Therefore, all that is needed between sectors is a high impedance seal.

3.2.4 <u>TMR End Plug Region</u> - An end plug is located at each end of the central cell. These plugs are classical mirror machines sustained by the injection of high energy neutral beams. The ambipolar potential of each plug provides the electrostatic stopping force for limiting the escape of ions from the ends of the central cell.

A cross-section of the end plug region is shown in Figure 3-5. Each plug consists of a pair of Yin-Yang coils located inside two large solenoid coils, and a transition coil between the Yin-Yang coils and the central cell.

The Yin-Yang coils are modest in size and consist of two cryogenic aluminum magnets, each weighing approximately 100 tonnes. Surrounding the Yin-Yang coils are two extremely large solenoids, weighing approximately 1700 tonnes each. These niobium-tin superconducting magnets have a central vacuum magnetic field strength of 16.5 tesla to which the 1 tesla field generated by the Yin-Yang coils is added. It is partly because of the massiveness of the structure required to support these

END PLUG ARRANGEMENT

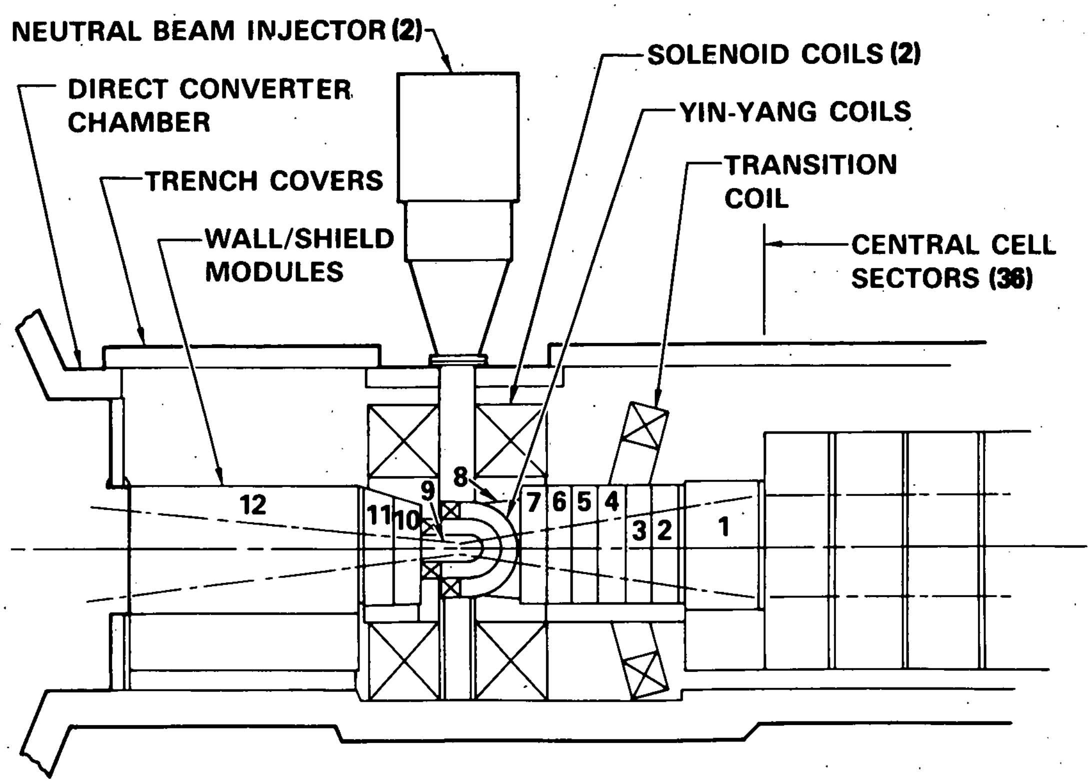


FIGURE 3–5

solenoids that the vertical neutral beam injector is suspended over the end plug instead of locating it in a cavity underneath. Improved access is also a factor in the location of the vertical NBI above the end plug.

The baseline TMR has both Yin-Yang coil pairs orientated such that the long axis of the exit fans are parallel to the floor. Subsequent designs have shown that the Yin-Yang coils should be oriented at 90 degrees to each other with one exit fan horizontal and the other vertical. A vertical exit fan increases building height and the length of the direct converter collector vanes. This has an adverse effect on plant cost and maintenance timelines.

The shielding around the plasma in the end plug region needs to be actively cooled. This shielding is divided into 12 modules of various sizes and weights. The largest is module number 12 (reference Figure 3-5) which is 8 m long and weighs approximately 600 tonnes, while the Yin-Yang shielding modules, as shown in Figure 3-6, weigh only 75 tonnes each. Each module has concentric ridges which, when the modules are sandwiched together, reduces radiation streaming from the joints. This requires that a segmented shield piece be removed, such as between modules number 1 and number 2, and the stack is then moved apart along the horizontal reactor axis before a module can be lifted out. Flexible lines in the plumbing allow this slight movement without disconnecting them. Many of the shielding modules are trapped inside magnets and their removal requires that the key segment be removed first. If, for example, module number 8 needed to be removed from the Yin-Yang coils, the removable shield segments between 1 and 2 are first removed. Then modules 2, 3 and 4 are moved sideways to clear module number 5, following which 7 and 8 can be consecutively slid over and lifted out from the spot vacated by module 5.

YIN-YANG SHIELDING CONCEPT

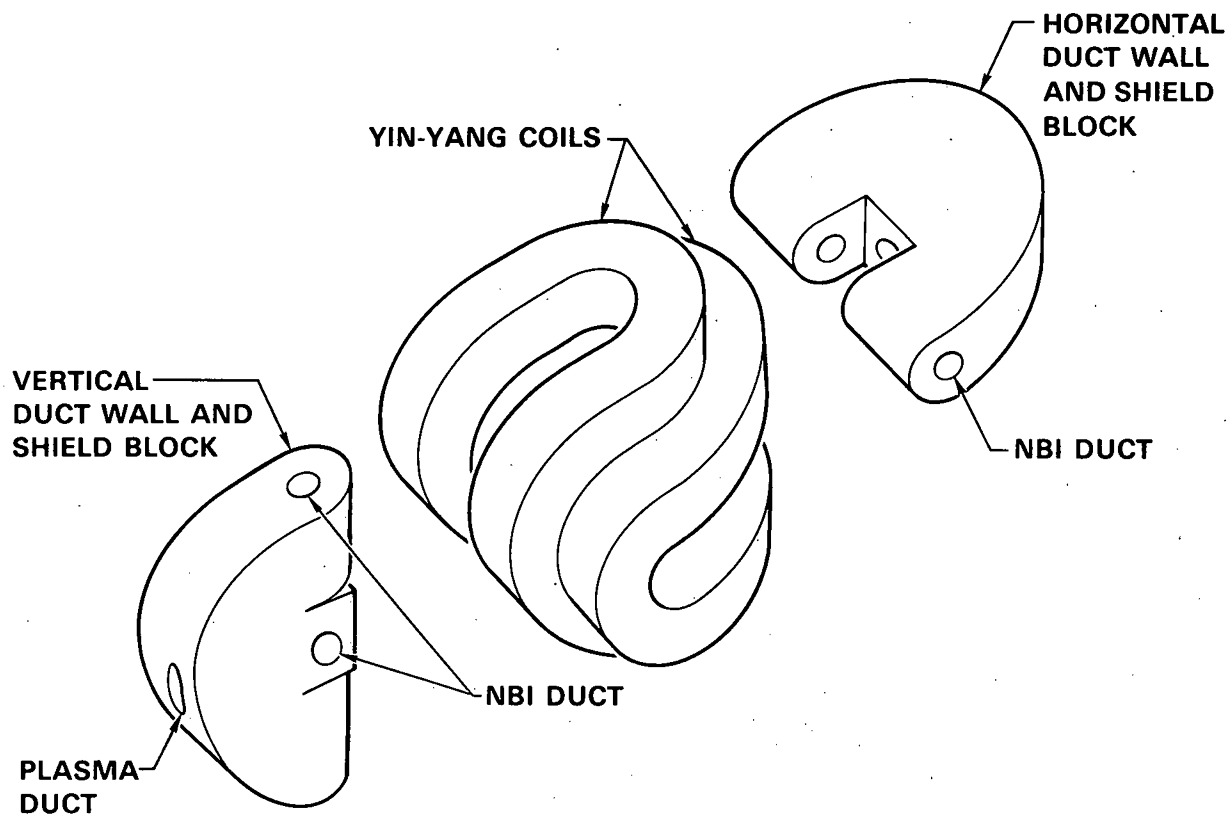


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FIGURE 3–6

Removal of the Yin-Yang coils poses the same type of problem; they must be moved out from inside the large solenoid magnets before they can be lifted away. Not only is this movement difficult, but all the connections to the Yin-Yang coils are in an area that has minimum clearance and are difficult to access. The design and maintenance plans assume this can be accomplished. The location of the connections to the Yin-Yang coils inside of the solenoid coils are assumed to be accessible to the overhead manipulator through the bore of the solenoid coils after the shield modules have been removed.

The approximately 1700 tonne solenoid magnets are beyond the capacity of the overhead cranes. Initial installation and removal, should it ever be needed, is by high pressure air bearings or some type of wheeled transport. Movement is sideways, through an opening in the trench wall, and into an adjacent room. An alternate concept, which needs to be investigated, would involve dividing each solenoid into two or three washer-shaped segments. The weight of these segments would be within the capacity of the cranes and they could be lifted out.

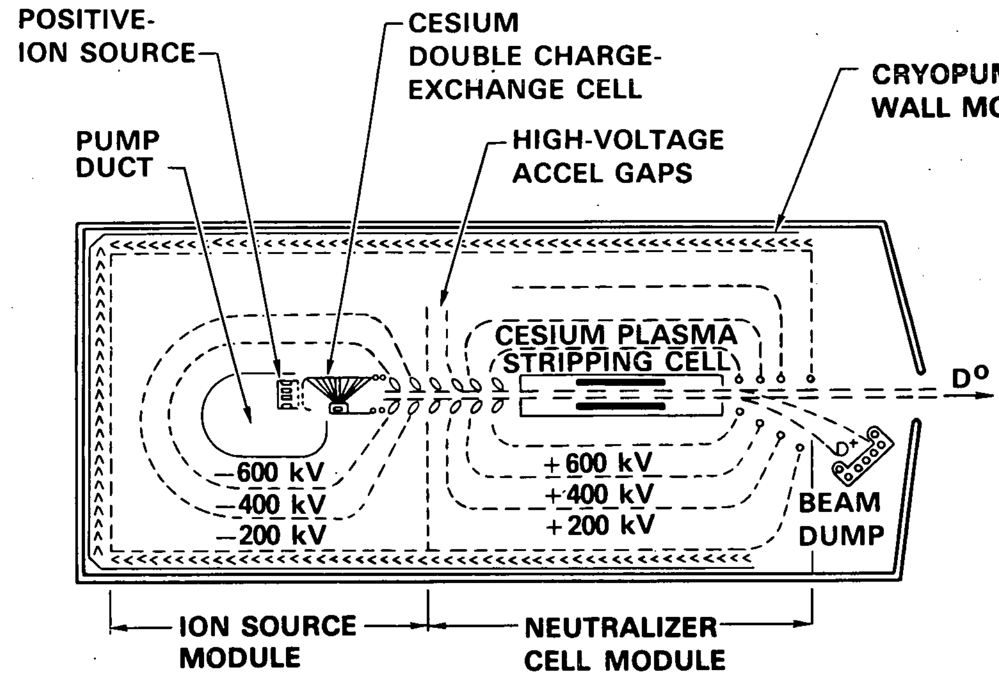
3.2.5 TMR Neutral Beam Injector - Except for changes made to improve maintainability, the neutral beam injectors (NBI's) used on the baseline TMR are the same as the one described in the TMR report (Reference 2). These 1.2 MeV D^0 injectors energize the particles one order of magnitude more than the 120 KeV NBI's used for the tokamak reactor and are more complicated in design. Basically, positive ions are generated and pass through a cesium double charge exchange cell where they become negative ions. These negative ions are accelerated by high voltage grids and then are neutralized in a cesium plasma stripping cell. Any remaining ions are deflected to a beam dump while the 1.2 MeV neutral particles enter the reactor plasma. Figure 3-7 is a schematic of this arrangement.

Four NBI's are used on the reactor; two at each end plug. At each end plug one is mounted vertically above the end plug coils and the other horizontally with both beams directed through the Yin-Yang coils center cavity. Figure 3-8 shows this configuration.

A choice was made to modularize components inside the NBI housing instead of considering the whole unit as a module for replacement purposes. Changing out the whole unit requires disconnecting many more services than a single component and also would result in a large facility and spares cost. In addition, the time required is expected to be at least as long as replacing a smaller internal module. Therefore, the internal components are combined into replaceable modules for maintenance. Anticipating the highest failure rate component to be the ion source, it was made the major element of one of the internal modules. Thus, only a quantity of ion source modules need be kept as spares; not entire NBI's. The ion source module actually includes more than just the ion source. A cesium charge exchanger, vacuum duct, negative acceleration grids, and negative electrostatic shields are also included to reduce the number of disconnects required while still keeping the size of the module to a reasonable level.

Also inside the NBI housing is another module containing the cesium plasma stripping cell, positive acceleration grids and positive electrostatic shields.

NEUTRAL BEAM INJECTOR SCHEMATIC
1.2-MeV Neutral-Beam Injector



FROM REFERENCE 2

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FIGURE 3–7

NEUTRAL BEAM INJECTORS–GENERAL ARRANGEMENT

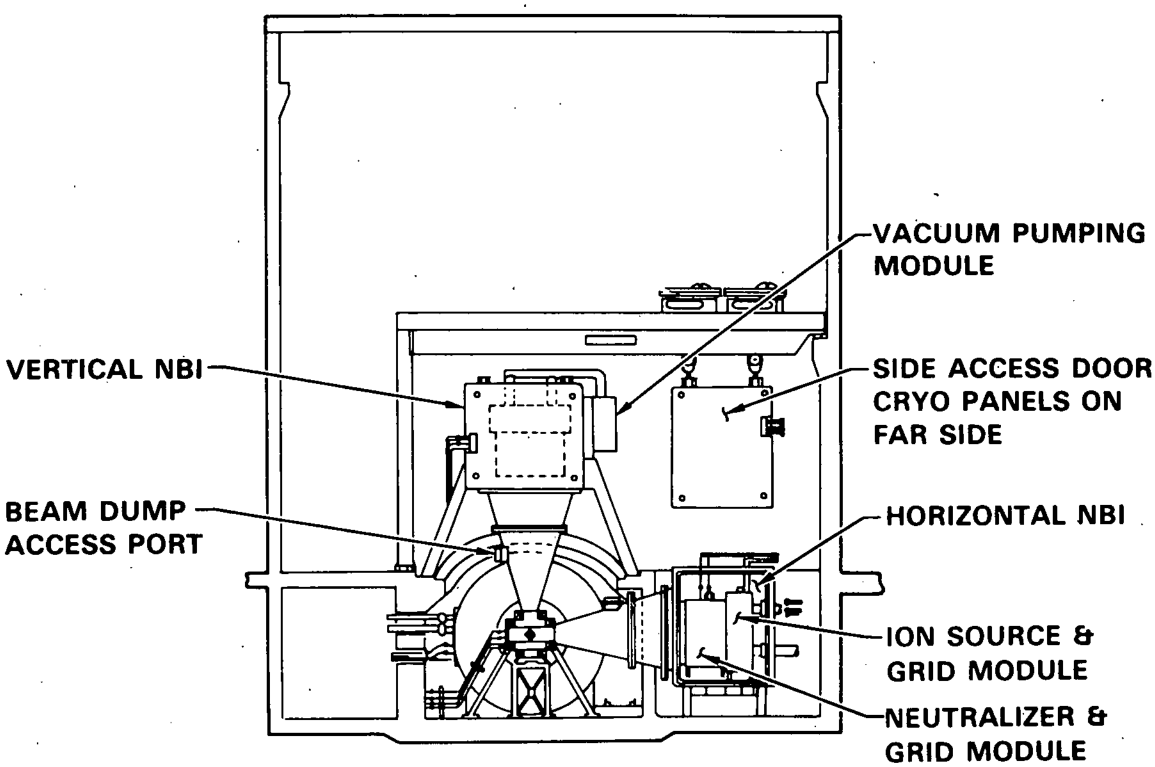

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FIGURE 3–8

The electrostatic shields are used to reduce the chance of arcing. The two modules are divided along the neutral potential line to simplify attaching each module to the NBI housing structure, which is also at neutral potential.

All cryopump panels in the NBI are attached to the side access doors. When a door is removed, one half of the cryopump panels are also removed with it. If necessary the entire door assembly can be replaced. Sliding gate or venetian blind type shutters are provided in front of each cryopump panel to isolate them from the rest of the chamber during pump regeneration. An alternate design which requires rotating the cryopump panels to allow regeneration has been considered but the design of a highly reliable liquid helium service line that would allow the rotation while not leaking in a high vacuum appears uncertain. The entire side panel of the NBI housing is removed to provide access to the NBI modules. The door seals are welded because the NBI's do not include a secondary vacuum zone.

The beam dump is a separate module which is mounted on the neutral beam duct. This module can also be removed through the side door of the NBI.

The power supplies and transformers are assumed to be external to the NBI. These are located together in an adjacent room which can have an inert atmosphere or other controlled environment conditions as required.

In summary, the Neutral Beam Injectors used on the TMR are much more complicated and also more difficult to service than those used on the tokamak. As an example, the tokamak NBI's each have three ion sources, externally located, each of which can be isolated and repaired without shutting down the NBI. An ion source failure in a TMR NBI requires shutting down the entire reactor and opening the NBI housing to access the ion source and replace it.

3.2.6 TMR Direct Converter - The direct converter design being used is essentially the same as that described in Reference 2. It is an elliptical grid of radiatively cooled carbon/carbon composite material vanes with additional grids at several potential levels. These vanes are strung vertically between the ends of the support structure and are used for capturing positive ions that escape from the end plugs. This method of generating electricity is highly efficient. The single stage system chosen recovers 60% of the energy in the charged particles escaping from the end plugs.

The grid of the direct converter is subdivided into 17 grid modules as shown in Figure 3-9. Each module consists of 40 sets of electron grid wires and ion collection vanes, a water cooled back panel, and coolant and electrical connections. Access is through three grid access doors above the modules. Each side door provides

DIRECT CONVERTER GRID MODULES

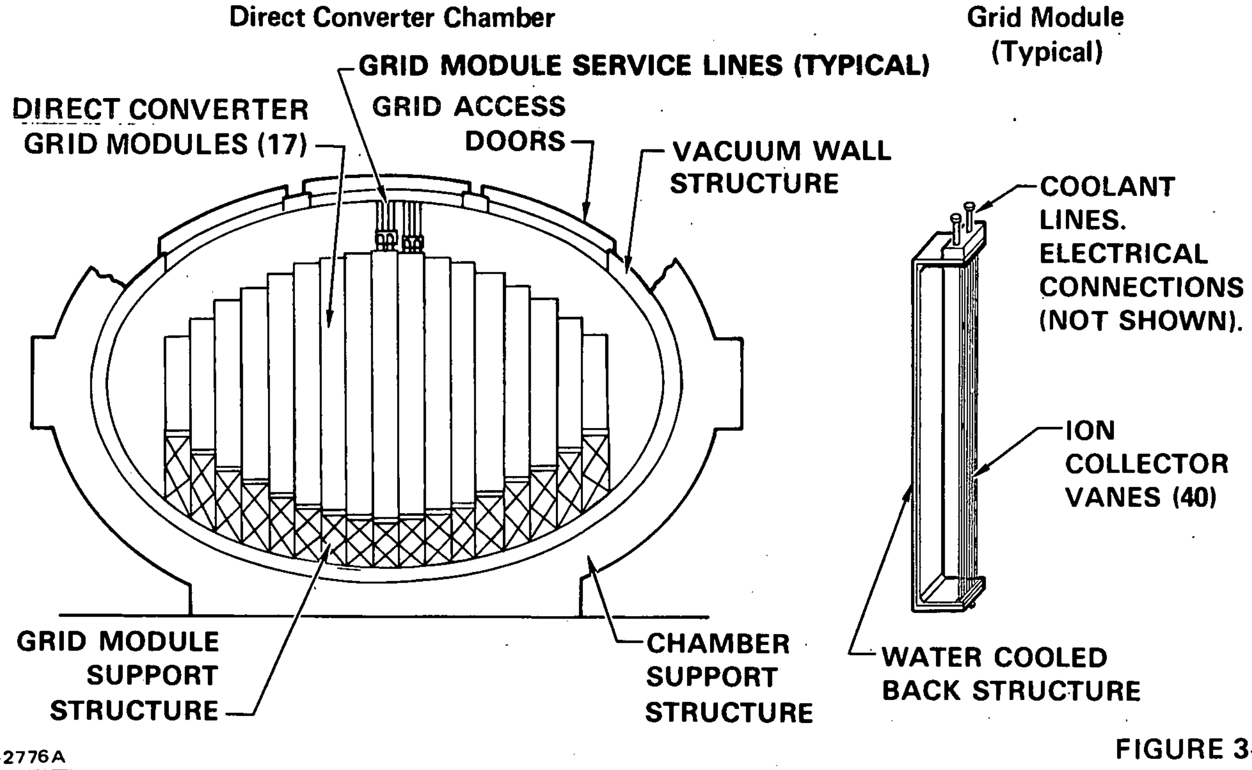

FIGURE 3–9

access to 5 modules and the center door provides access to 7. After these doors are removed the modules can be disconnected and lifted out for servicing. On top of the direct converter chamber and to one side is the hot cell station for repairing the grids. The long slender modules (20 m maximum length) would be difficult to design for supporting the grids in the horizontal attitude and for movement to the normal hot cell, so a special grid repair station is located nearby. Repair at this station can be accomplished with the modules vertical. Only the high bay overhead crane is needed to move a module from its location in the direct converter to a rack in the grid repair station.

The walls of the direct converter need to be cooled or shaded because of the high thermal radiation coming from the grid vanes. Figure 3-10 shows the arrangement of the water cooling panels used to shade the walls. These water cooling panels are also modularized and tracks are provided on the inside of the reactor to allow them to be accessed and removed.

Vacuum pumping of the central cell plasma chamber, end plug, and direct converter cavities is accomplished by the cryopump panels in the direct converter. These 50 cryopump panels function in the same manner as those in the neutral beam injector. The cryopumps must have some type of isolation valving to allow regeneration of some of them while the rest are exposed and maintain the vacuum.

DIRECT CONVERTER CHAMBER GENERAL ARRANGEMENT

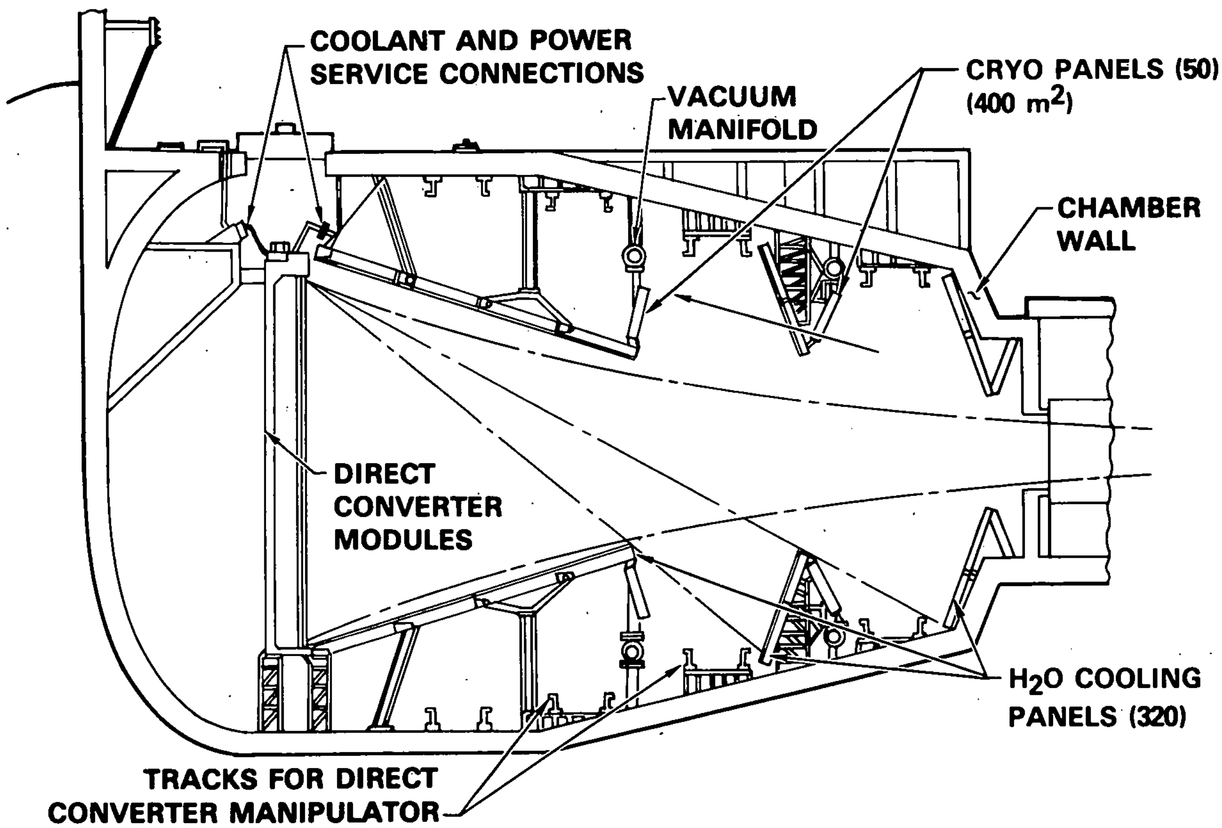

FIGURE 3–10

Additional access to the inside of the direct converter chamber is provided by a door in the inboard wall on the NBI side of the direct converter. This door, which opens into the trench area, allows maintenance equipment to enter the chamber and replace cooling panels or cryopump panels. Since both this door and the doors over the grid modules are vacuum barriers to a single vacuum zone a welded flange is used for sealing them.

The design of the direct converter chamber limits access by requiring entrance through the side door. This type of access means that coolant and cryopump panels have to be carried in and out by a remote manipulator transporter. Unfortunately, the size of the direct converter makes it impractical to have a large removable cover. Therefore, movement of components within the chamber cannot be accomplished by use of a crane. In addition to access problems, the design makes fault isolation difficult. With the cooling panels, cryopump panels and their associated hardware and plumbing inside the chamber, any failure, such as a leak in one of the many internal components, forces a reactor shutdown.

3.2.7 TMR Vacuum System Design - The vacuum wall arrangement in the baseline TMR differs from that of the IMS tokamak in some areas. Where the tokamak has a dual vacuum wall arrangement almost completely around the reactor (See Section 3.3.4), the baseline TMR has only a single vacuum wall in the direct converter region and in the NBI's. The same double vacuum wall arrangement does exist, however, in the central cell region. A stainless steel clad concrete trench is the primary (outer) vacuum wall in the central cell region. As shown in Figure 3-11 the area between the trench wall and the central cell sectors is maintained at 10^{-4} torr, and utilizes a mechanical seal around the trench cover. The 10^{-4} torr

CENTRAL CELL VACUUM ZONES

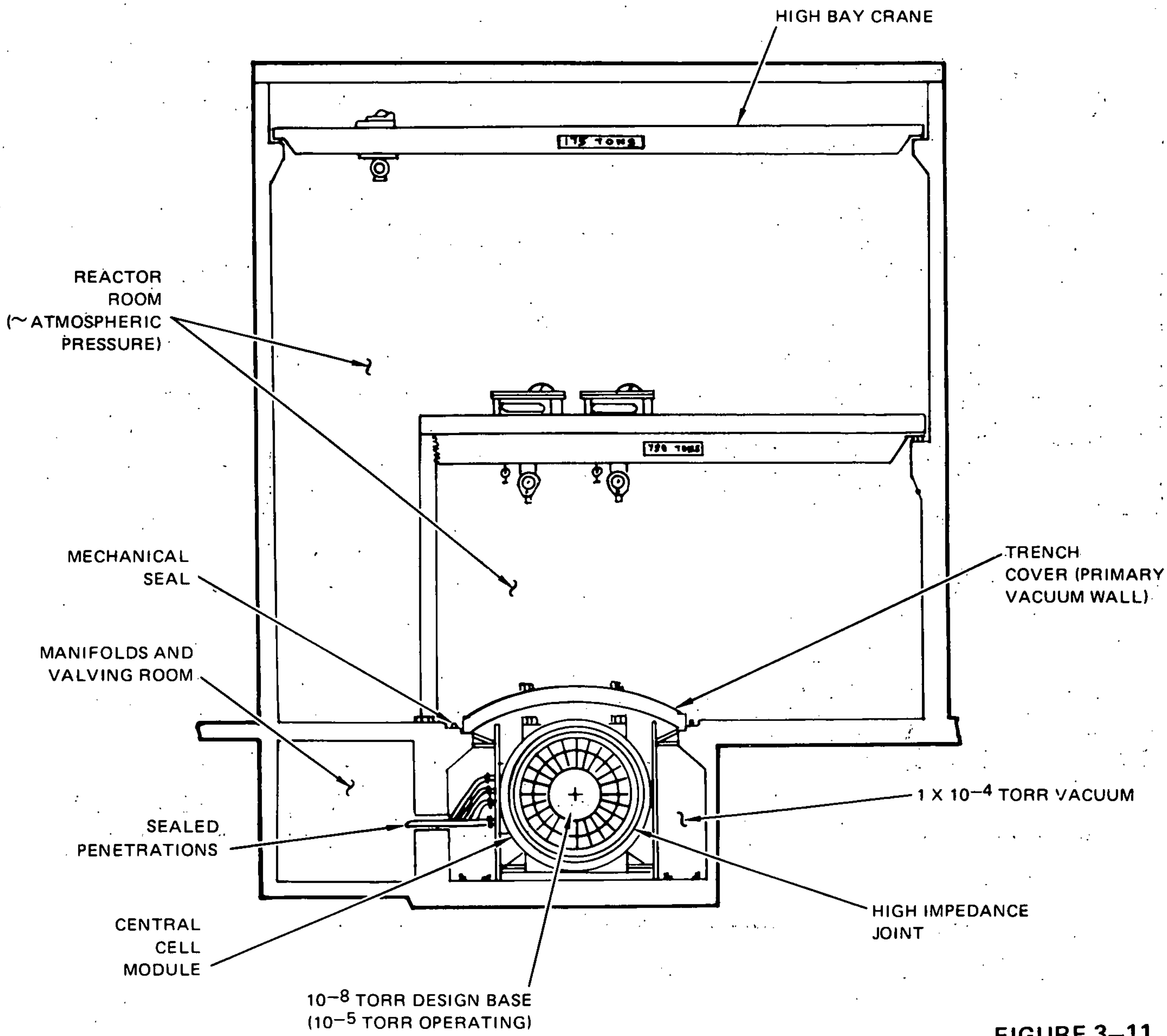

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FIGURE 3–11

pressure is selected because it is below the pressure where electrical discharge is a problem and results in molecular flow between the secondary and primary vacuum chambers. For this outer vacuum zone four vacuum pump sets similar to those shown in Figure 3-12 are used with two additional sets available as spares. A total of 360 horsepower (269 kW) is required to drive the 4 pump sets. Although achieving the 10^{-4} torr pressure may be optimistic with this pump set, it is selected for our baseline because it is also used for the IMS tokamak reactor.

ROUGHING AND REGENERATION VACUUM PUMP SET

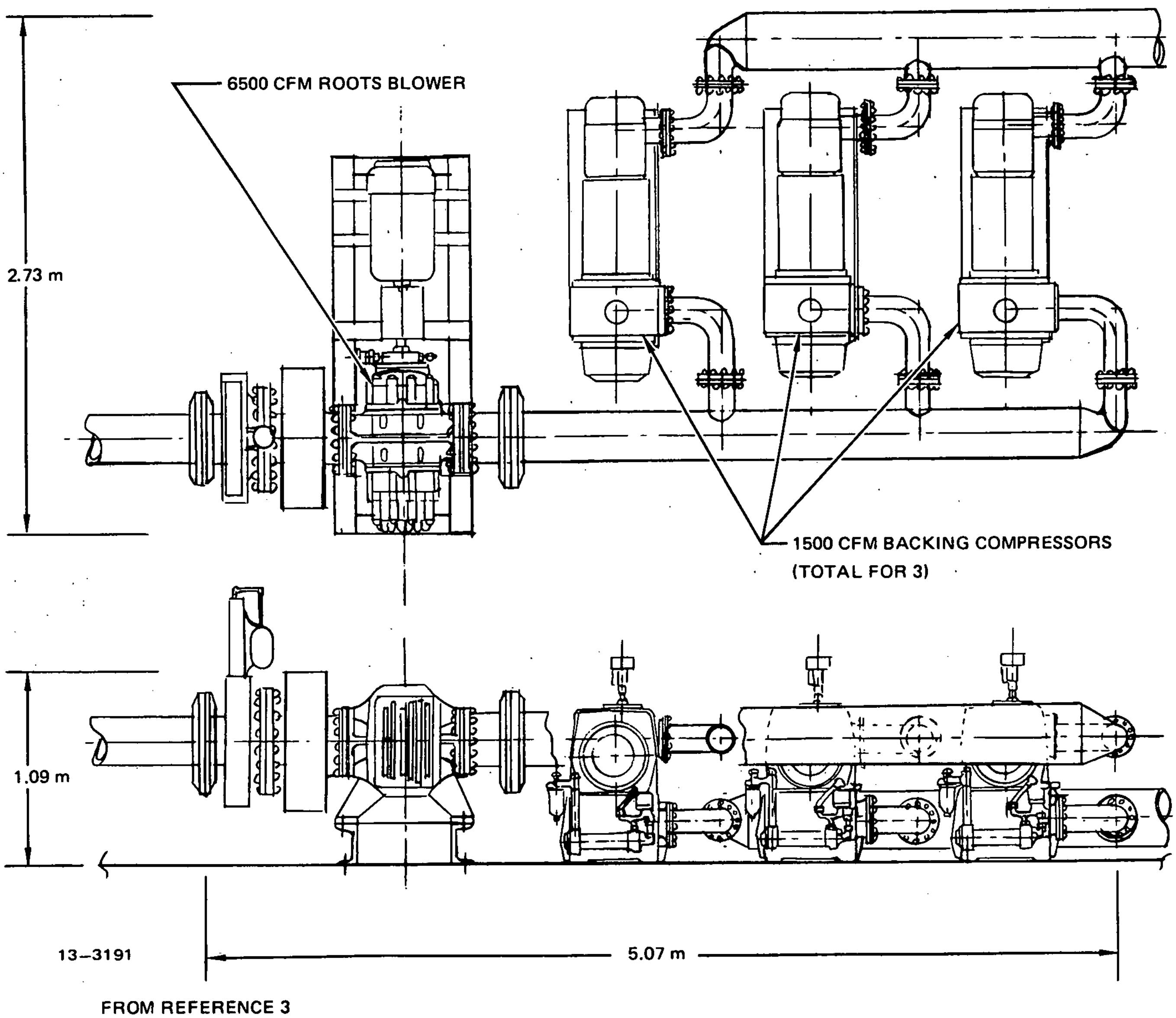


FIGURE 3–12

Between the outer vacuum zone and the central cell plasma vacuum zone are high impedance joints located between central cell sectors. Because of the low pressure differential between vacuum zones, a large load is not imposed on the plasma chamber vacuum system.

Vacuum pumping of the plasma chamber is through the end plugs to the cryopumps in the direct converters. For this vacuum system the location of the pumps suggested in Reference 2 is followed. It is assumed that there is enough conductance through the restrictions in the end plugs to adequately pump out the central cell region.

Direct converters, neutral beam injectors, and tritium injectors have only a single vacuum wall. Therefore, to reduce leakage problems, all access panels in these regions have welded seals. The specially designed flange shown in Figure 3-13 is considered for use in conjunction with automatic welding equipment to ensure quick cut-off and rewelding with proper alignment and positioning for these seals.

As mentioned before, the primary vacuum pumping system is located in the direct converter regions. Each direct converter chamber has 200 m^2 of active cryopump surface at any one time which requires a total active area of 400 m^2, or 800 m^2 total area for the entire system with both direct converters. This system assumes

VACUUM SEAL FLANGE CONCEPT

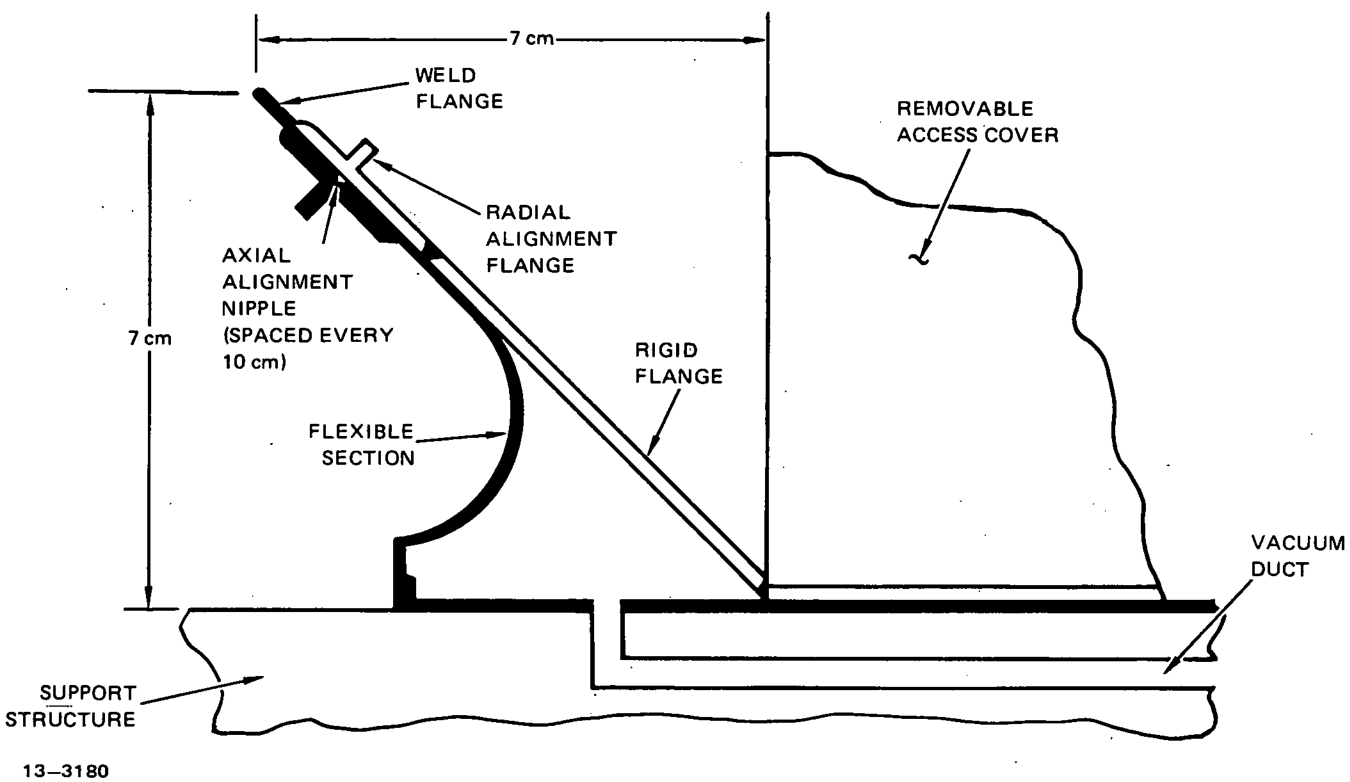


FIGURE 3–13

that the total regeneration time is equal to the operating time between the regeneration periods. The cryopump system has about the same total area as used on the IMS tokamak (see Section 3.3.4) and, by assuming the same chamber pressure levels (10^{-5} torr operating, 10^{-8} torr base), the same plasma chamber and regeneration pumping requirements can be used. Four of the same size pump sets used for the outer vacuum chamber are used for cryopump regeneration. Two additional sets are used for spares.

This cryopump system has been designed as a series of individual panels to enhance its maintainability. However, the IMS tokamak design is inherently more maintainable. The cylindrical tokamak cryopumps are externally mounted for ease of access and have a relatively simple isolation valve between the pump and the chamber. This arrangement allows the pump to be isolated and possibly even removed and replaced while the reactor is operating. The baseline TMR has the cryopump panels located inside the direct converter. The 50 flat modular units in each direct converter have venetion blind type louvres, slide valves, or something similar, to isolate the panel during regeneration. However, since there is only a high impedance seal in this area any major failure or gross leakage could not be isolated from the plasma. Additional maintenance difficulties arise because no work can be accomplished on a panel while the reactor is operating. All regeneration, cryogenic and vacuum valving mechanisms as well as the cryopump panel shutter mechanisms are inside the reactor and must operate in a hard vacuum. If the conductance is satisfactory, the alternate arrangement with the circular cryopumps located outside of the direct converter chamber with an intervening isolation valve, similar to the tokamak arrangement should be considered.

3.2.8 TMR Cooling Systems - Although requiring 20% less capacity, the primary blanket cooling system used on the baseline TMR is essentially identical to that of the IMS tokamak; helium is used in the primary coolant loop and sodium in the intermediate coolant loop. One difference is that the TMR system uses only 6 loops, handling 2030 MW_{th} of energy from the first wall blanket, while the IMS uses 8 loops to handle 2540 MW_{th}. Another difference is that there is no need for hot sodium storage in the baseline TMR. It operates continuously and doesn't need the thermal storage capacity to provide heat at a constant rate to the steam cycle as is the case for the tokamak reactor. The rationale for choosing a helium/sodium system is the same as that discussed in Section 3.3.5 and in Reference 3.

In addition to cooling the first wall blanket, the direct converter and central cell shielding are cooled by water. Although a detailed analysis of these systems has not been performed, it is estimated that the 410 MW_{th} removed from the direct converter water cooled panels will yield 164 MW of electrical power.

3.3 IMS TOKAMAK SELECTED SYSTEM DESIGN - The following is a brief summary of the design of some of the mechanical systems of the IMS tokamak fusion reactor. Sections 3.0 and 6.0 of Reference 3 contain more detail and many of the reasons for the design. This summary highlights the features to be compared with the TMR and the systems selected for the IMS tokamak that are not specifically defined in Reference 3.

3.3.1 IMS Tokamak General Arrangement - The general arrangement of the IMS tokamak is shown in Figure 3-14. This is basically the Culham Mark II reactor concept with a plasma major radius of 7.5 m. Table 3-2 lists the characteristics of this reactor.

The reactor is located in an 85 m diameter domed, reactor room 90 m high. This gives 5,700 m^2 of floor space and 510,000 m^3 internal volume. Two transfer locks and a decontamination room are provided to allow access of maintenance equipment to the room.

The toroidal reactor structure is subdivided into 16 removable first wall/blanket sectors which include an inner shield. These sectors are surrounded by a fixed outer shield wall to which access is gained through 16 doors large enough to pass the first wall/blanket sectors. These doors include the outer shield and lateral support panel for the toroidal field magnets. These assemblies rotate down and out of the way for access to the removable sectors. Surrounding this inner structure are sixteen superconducting toroidal field (TF) magnets and fifteen superconducting poloidal field (PF) magnets. Six of the PF magnets are located outside the TF "D" shaped magnets while the remaining 10 are "trapped" by the TF magnets. Retractable cylinders support the outer PF magnets allowing them to be moved vertically out of the way for access. The PF magnets within the bore of the TF magnets are assumed to be normal and segmented. In the central core of the reactor are transformer (ohmic heating) coils attached to the inside of the structural bucking cylinder.

Twenty cylindrical cryopumps are mounted on a common plenum chamber above the divertor and the TF magnets, and twelve neutral beam injectors are located radially around the periphery of the torus.

3.3.2 First Wall/Blanket Sector Design - The Culham first wall/blanket design concept has been used basically without change on the IMS tokamak. About 175 blanket/inner shield modules are attached to the structure of each of the 16 sectors. A single sector support structure with typical first wall blanket breeding cells is

IMPROVED MAINTENANCE SYSTEM (IMS) TOKAMAK

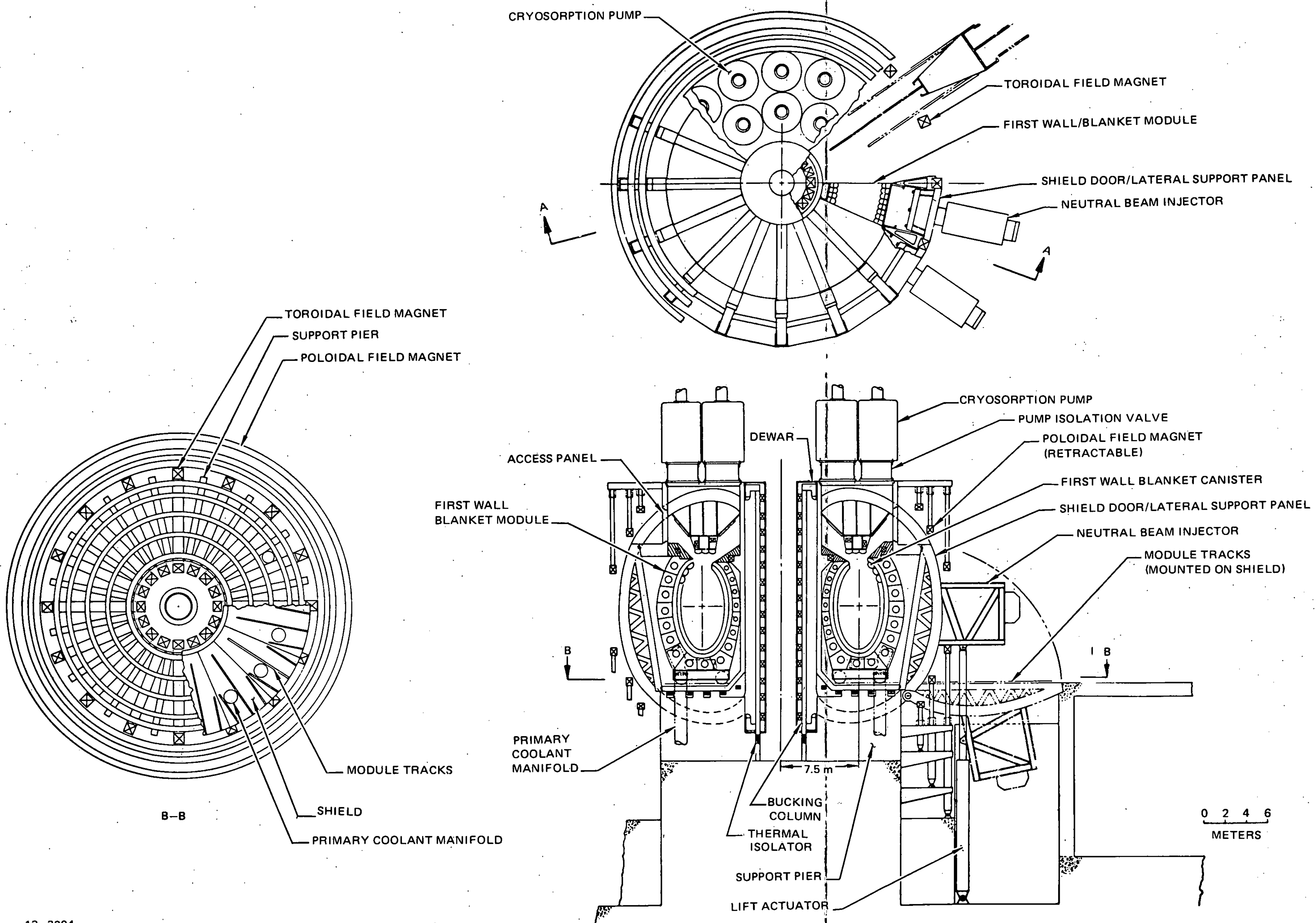


FIGURE 3–14

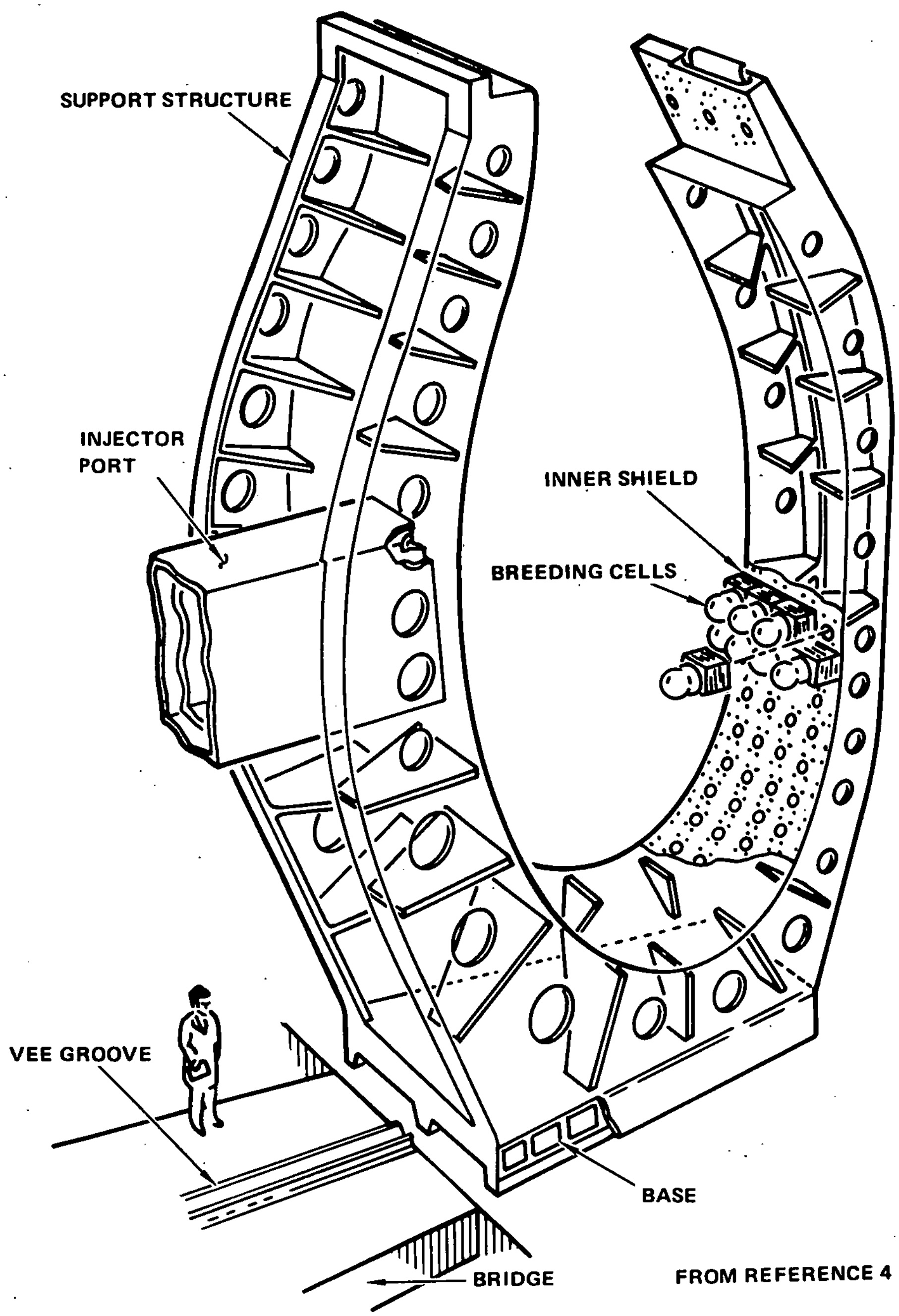
13–3204

TABLE 3–2
IMS TOKAMAK CHARACTERISTICS

	CULHAM & IMS
POWER , MW_{th}	3000
NET ELECTRICAL POWER, MW_e	962
FIRST WALL/BLANKET CONFIGURATION	CANISTER
FIRST WALL COOLANT	HELIUM
DIVERTOR COOLANT	LITHIUM
AUXILIARY HEATING	NBI
VACUUM SYSTEM	UWMAK-III TYPE
DIVERTOR	SINGLE NULL
TF MAGNETS, NUMBER	16
MAX. TOROIDAL FIELD STRENGTH (B_{max}), TESLA	8.66
FIELD STRENGTH ON AXIS (B_o) TESLA	3.871
PLASMA STABILITY FACTOR	2.5
PLASMA BURN TIME, SEC	3600
PLASMA REJUVENATION TIME, SEC	100
PLASMA ECCENTRICITY	2
PLASMA MAJOR RADIUS, M	7.5
PLASMA MINOR RADIUS, M	1.924
PLASMA VOLUME, m^3	1096.0
WALL AREA, m^2	990.8
POLOIDAL BETA	3.906 (A)
NEUTRON WALL LOADING, MW/m^2	2.121
ION TEMPERATURE, T_i, KeV	12.9
ELECTRON TEMPERATURE, T_e, KeV	13.8
DENSITY, n_i PARTICLES/m^2	1.31×10^{20}
CONFINEMENT TIME τ_p, SEC	2.72
$n_i \tau_p$ PARTICLE-SEC/m^3	3.57×10^{20}
FUSION REACTION RATE, $\langle \sigma v \rangle$ m^3/SEC	2.05×10^{-22}
THRUPUT, TORR-L/SEC	2116
CRYOPANEL AREA, m^2 (OPERATING FACE AREA)	420
WALL LIFE, YRS.	7.543
A = ASPECT RATIO	

shown in Figure 3-15. This modular structural unit is designed to be moved radially outward along rails and over the shield door when the door is in the horizontal position. From this point it can be lifted to the hot cell for inner wall repair or replacement, while a spare structural unit is installed.

TYPICAL CULHAM REACTOR SECTOR STRUCTURE



13–3174

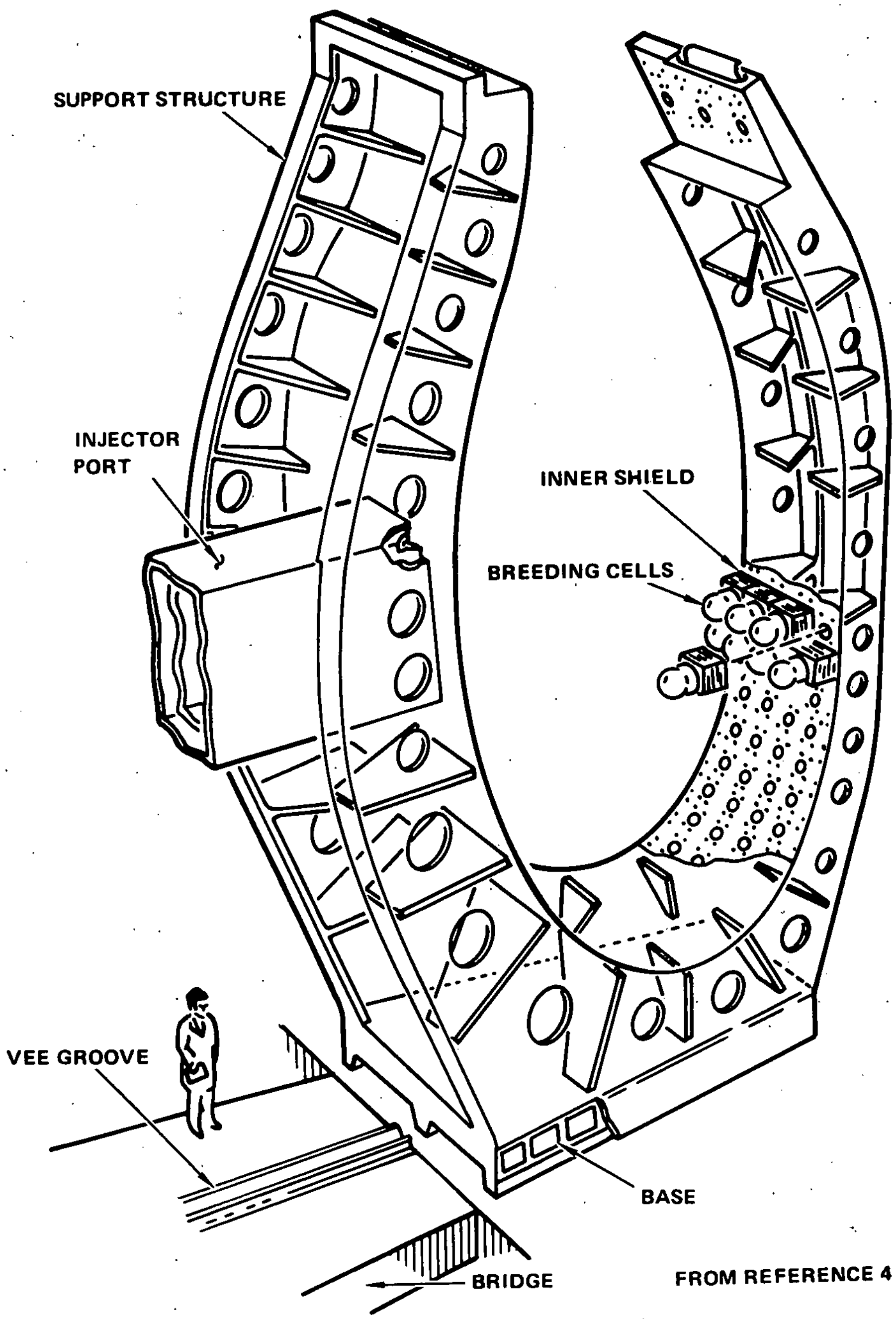
FIGURE 3–15

TABLE 3–2
IMS TOKAMAK CHARACTERISTICS

	CULHAM & IMS
POWER , MW_{th}	3000
NET ELECTRICAL POWER, MW_e	962
FIRST WALL/BLANKET CONFIGURATION	CANISTER
FIRST WALL COOLANT	HELIUM
DIVERTOR COOLANT	LITHIUM
AUXILIARY HEATING	NBI
VACUUM SYSTEM	UWMAK-III TYPE
DIVERTOR	SINGLE NULL
TF MAGNETS, NUMBER	16
MAX. TOROIDAL FIELD STRENGTH (B_{max}), TESLA	8.66
FIELD STRENGTH ON AXIS (B_o) TESLA	3.871
PLASMA STABILITY FACTOR	2.5
PLASMA BURN TIME, SEC	3600
PLASMA REJUVENATION TIME, SEC	100
PLASMA ECCENTRICITY	2
PLASMA MAJOR RADIUS, M	7.5
PLASMA MINOR RADIUS, M	1.924
PLASMA VOLUME, m^3	1096.0
WALL AREA, m^2	990.8
POLOIDAL BETA	3.906 (A)
NEUTRON WALL LOADING, MW/m^2	2.121
ION TEMPERATURE, T_i, KeV	12.9
ELECTRON TEMPERATURE, T_e, KeV	13.8
DENSITY, n_i PARTICLES/m^2	1.31×10^{20}
CONFINEMENT TIME τ_p, SEC	2.72
$n_i\ \tau_p$ PARTICLE-SEC/m^3	3.57×10^{20}
FUSION REACTION RATE, $\langle \sigma v \rangle$ m^3/SEC	2.05×10^{-22}
THRUPUT, TORR-L/SEC	2116
CRYOPANEL AREA, m^2 (OPERATING FACE AREA)	420
WALL LIFE, YRS.	7.543
A = ASPECT RATIO	

shown in Figure 3-15. This modular structural unit is designed to be moved radially outward along rails and over the shield door when the door is in the horizontal position. From this point it can be lifted to the hot cell for inner wall repair or replacement, while a spare structural unit is installed.

TYPICAL CULHAM REACTOR SECTOR STRUCTURE



FROM REFERENCE 4

13—3174

FIGURE 3—15

3.3.3 <u>IMS Tokamak Neutral Beam Injector</u> - A design developed and described in Reference 5 by LBL/LLL for the Tokamak Fusion Test Reactor (TFTR) was used as a baseline for the IMS tokamak neutral beam injector (NBI). Twelve units are used on each reactor, each with an output of 5-6 MW, yielding a total of 60 MW minimum of 120 KeV neutral atoms per reactor.

Each NBI is about 3 m wide x 6 m long x 5 m high and weighs about 135 tonnes, including an estimate for shielding. The twelve units are located radially around the perimeter of the toroid, with the power supplies located remotely. A valve is installed between the reactor vacuum wall and the NBI housing, allowing the NBI to be isolated, if necessary, during reactor operations. Figure 3-16 and 3-17 show the location and interfaces of the three ion sources that are mounted externally on the NBI housing. Each ion source is separated from the NBI housing by an isolation valve, which allows ion source replacement while the NBI is operating.

TOKAMAK NBI ISOLATION VALVE LOCATION

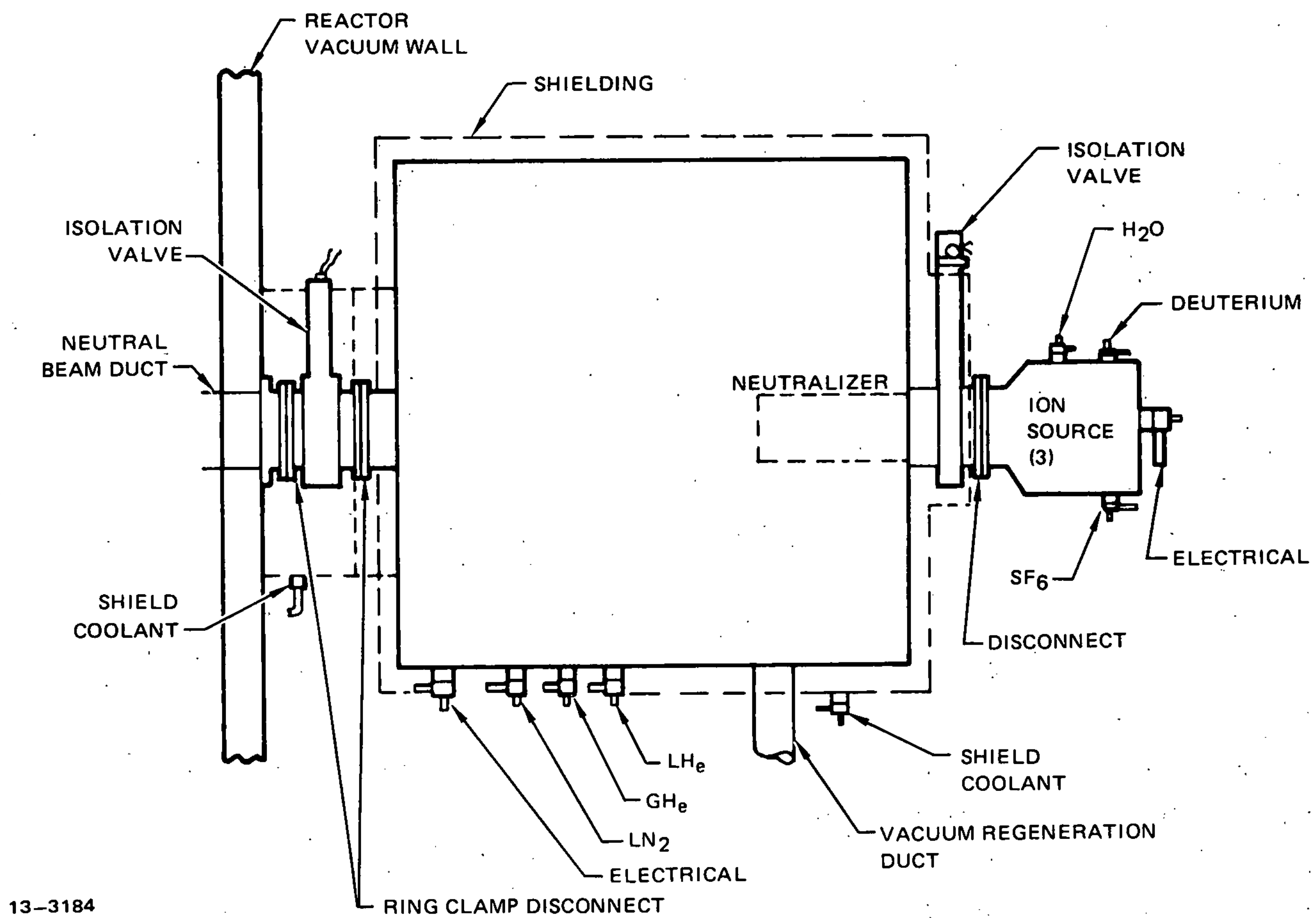


FIGURE 3–16

IMS TOKAMAK ION SOURCE CONCEPTUAL DISCONNECT ARRANGEMENT

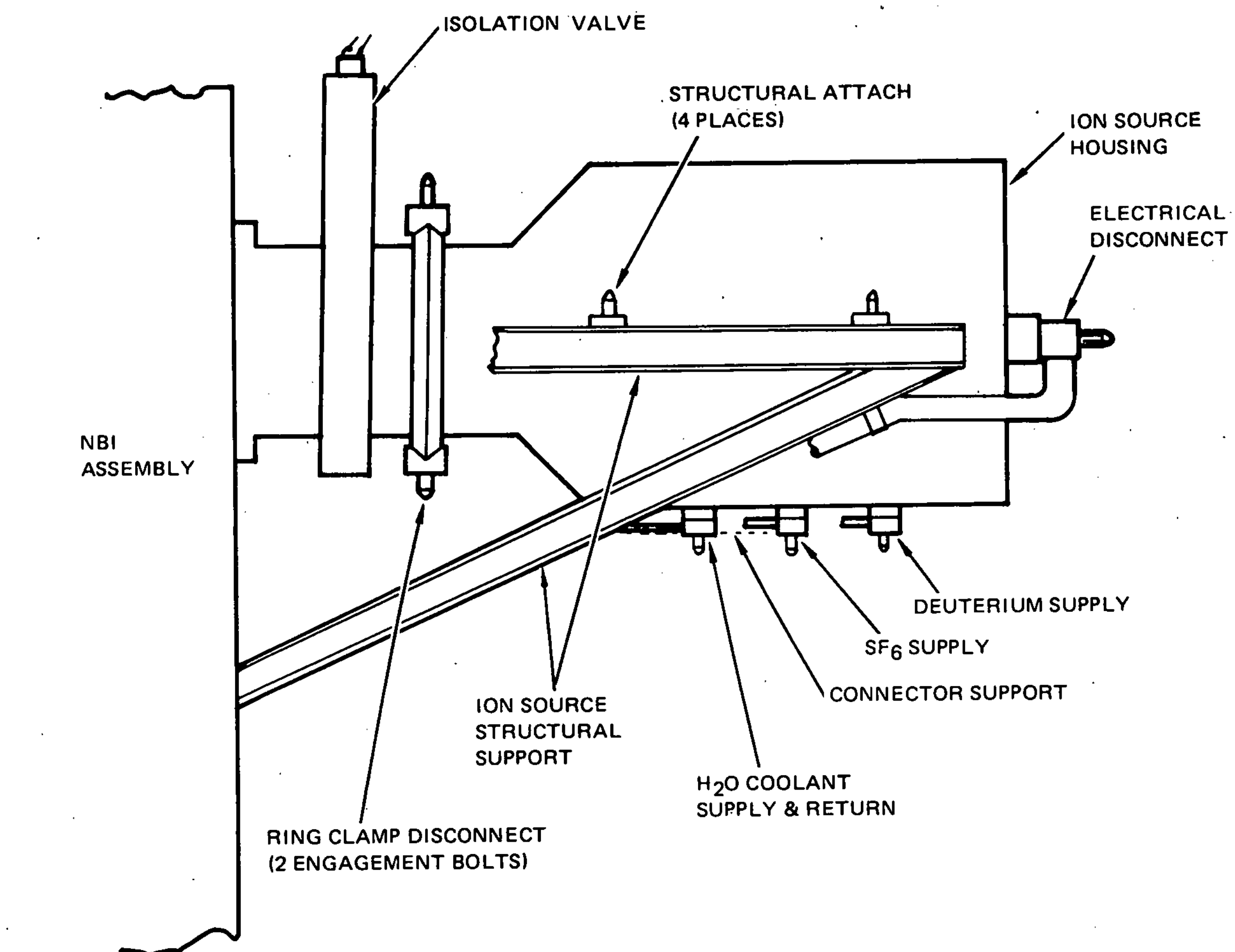


FIGURE 3–17

Two basic maintenance activities are considered in the design of the NBI. These are (1) to repair or replace the NBI itself, and (2) the movement of the entire NBI assembly to allow access to other systems.

In-place repairing of an NBI is practical because of the modularity of the unit. For example, any one of the three ion sources can be isolated and replaced without shutting down the NBI. Any repair other than replacement of ion sources, i.e., replacing the neutralizer, cryopump panels, etc., requires that the entire NBI is isolated before the modules can be accessed.

The second activity, moving the NBI to gain access to other systems, was addressed in detail in the earlier study of tokamak reactors (Reference 3). The IMS tokamak reactor utilizes the concept where the shield door, lateral support access panel, and NBI are combined into one integral unit that pivots to a position below the main reactor room floor. The internal surface of the shield then forms a surface with integral tracks available for module removal as shown in Figure 3-2.

3.3.4 IMS Tokamak Vacuum System Design - Earlier tokamak studies (Reference 3) indicate that downtime savings exist for dual vacuum zones with the primary vacuum wall at the reactor room wall as was originally prescribed for the IMS concept. However, almost as much time is saved if a double vacuum zone is used with the primary wall in the region of the TF magnets. This arrangement has the added advantages of accessing such components as the NBI ion sources without pressurizing the main vacuum zones and that equipment or electric cabling in the reactor room need not be designed for vacuum operation. Therefore, a dual vacuum wall arrangement is used with the reactor room at nearly ambient pressure and with the primary vacuum wall at the outer shield. The outer seal is a mechanical seal in the outer shield area and the inner seal is a high impedance joint between the first wall/blanket sectors. The volume between the two seals is maintained at 10^{-4} torr and the plasma chamber is designed for a base pressure of 10^{-8} torr. Table 3-3, taken from Reference 3, is a summary of the vacuum system and pumping requirements.

The roughing pump sets used here and on the TMR are the same except that not as many are used (8 sets + 4 spare sets on TMR vs. 6 sets + 2 spare sets here). The composition and performance of each pump set is the same for both cryopump regeneration pumping and secondary vacuum chamber pumping.

Twenty cylindrical cryopumps are mounted on a common plenum chamber above the divertor to provide the primary pumping capacity that is required. Each pump has an isolation valve between it and the plenum which allows for regeneration, failure isolation, or even removal and replacement of the pump during reactor operations. The installation is shown in Figure 3-18.

3.3.5 IMS Tokamak Cooling System - Helium coolant has been selected for the IMS tokamak primary coolant loop in preference to either liquid sodium or lithium for both maintenance and safety considerations. Draining and filling the first wall/blanket sectors with helium is relatively simple in comparison with the liquid metals and cleanup operations are not required in the event of a rupture in the first wall/blanket or coolant lines. Cleaning up a spill of either liquid metal is very difficult. These metals tend to penetrate cracks and crevices making them difficult to remove. Any residue left tends to outgas when subjected to a vacuum and elevated temperatures.

While helium is used to cool the first wall/blanket and inner shield, water is used as the outer shield coolant. This is the system selected in Reference 3.

TABLE 3–3
IMS TOKAMAK VACUUM SYSTEMS

PRIMARY VACUUM SYSTEM	
PLASMA CHAMBER & CRYOPUMP REQUIREMENTS	
NUMBER OF PUMPS (TOTAL/ACTIVE)	32/16
THRUPUT @ 300°K, TORR-L/SEC	2100
PUMPING SPEED, L/SEC	2.1×10^7
CRYOPANEL AREA, m^2	
ACTIVE	420
TOTAL	840
CHAMBER OPERATING PRESSURE, TORR	1×10^{-5}
CHAMBER BASE PRESSURE, TORR	1×10^{-8}
REJUVENATION PERIOD, HRS.	6
GAS VOLUME/6 HRS (STP), LITERS	60000
OUTER CHEVRON TEMP, °K	80
INNER CHEVRON TEMP, °K	20
MOLECULAR SIEVE TEMP, °K	4.2
TOTAL MOLECULAR SIEVE MTL, Kg.	2100
ABSORPTION CAPACITY, 5°K (STP), L/SEC	3.15×10^5
NUMBER OF BURN CYCLES TO SATURATE PUMPS	31
REGENERATION PUMPING	
NUMBER OF PUMP SETS/SPARES	4/1
PUMPS/SET	
L-H RA 9001 ROOTS BLOWER	1
L-H TR 630 ROTARY PISTON PUMPS	3
TOTAL EFFECTIVE PUMPING SPEED, CFM	6000
PUMP DOWN TIME (REGENERATION)	
CRYOSORPTION PUMP, GAS @ 100 TORR, HRS.	.1
PUMP DOWN 100 TORR TO 1×10^{-1} TORR, HRS.	3.3
WARMUP AND COOL CRYOPANELS, HRS.	2.0
TOTAL	5.4
PUMP DRIVE POWER/SET, HP	90
TOTAL GAS VOLUME (STP), LITERS	60000
PUMPING TEMPERATURE, °K	300
PLENUM PRESSURE, TORR	100
FINAL PRESSURE, TORR	1×10^{-1}
PUMP DOWN VOLUME, TOTAL, m^3	9400
PER REGENERATION*, m^3	8100
SECONDARY VACUUM CHAMBER PUMPING SYSTEM	
NO. OF PUMP SETS/SPARES	2/1
PUMPS/SET	SAME AS REGENERATION
TOTAL PUMPING TIME 760 TO 10^{-4} TORR, HRS.	12.2

* DOES NOT INCLUDE PLASMA CHAMBER

IMS TOKAMAK CRYOPUMP CONNECTION ARRANGEMENT

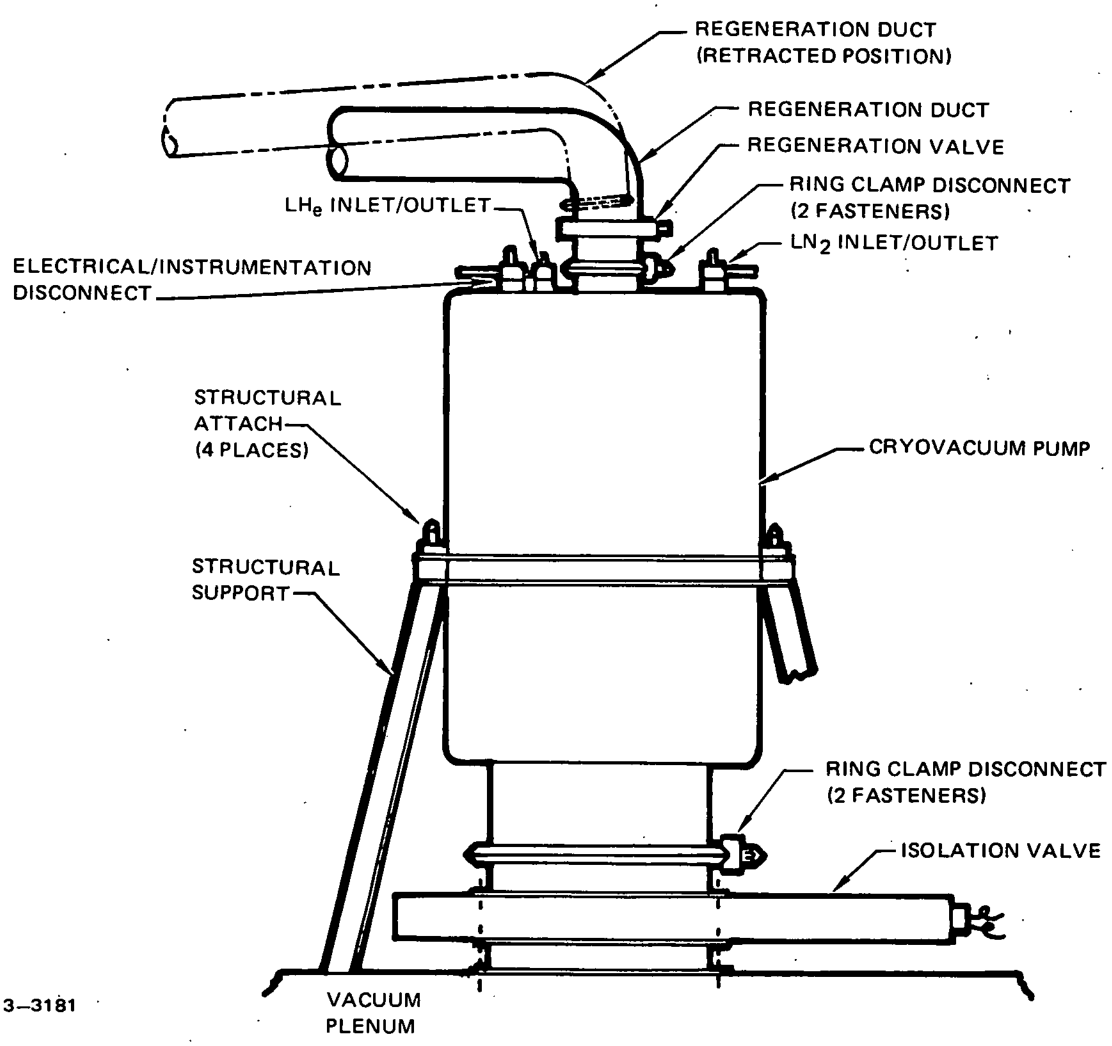


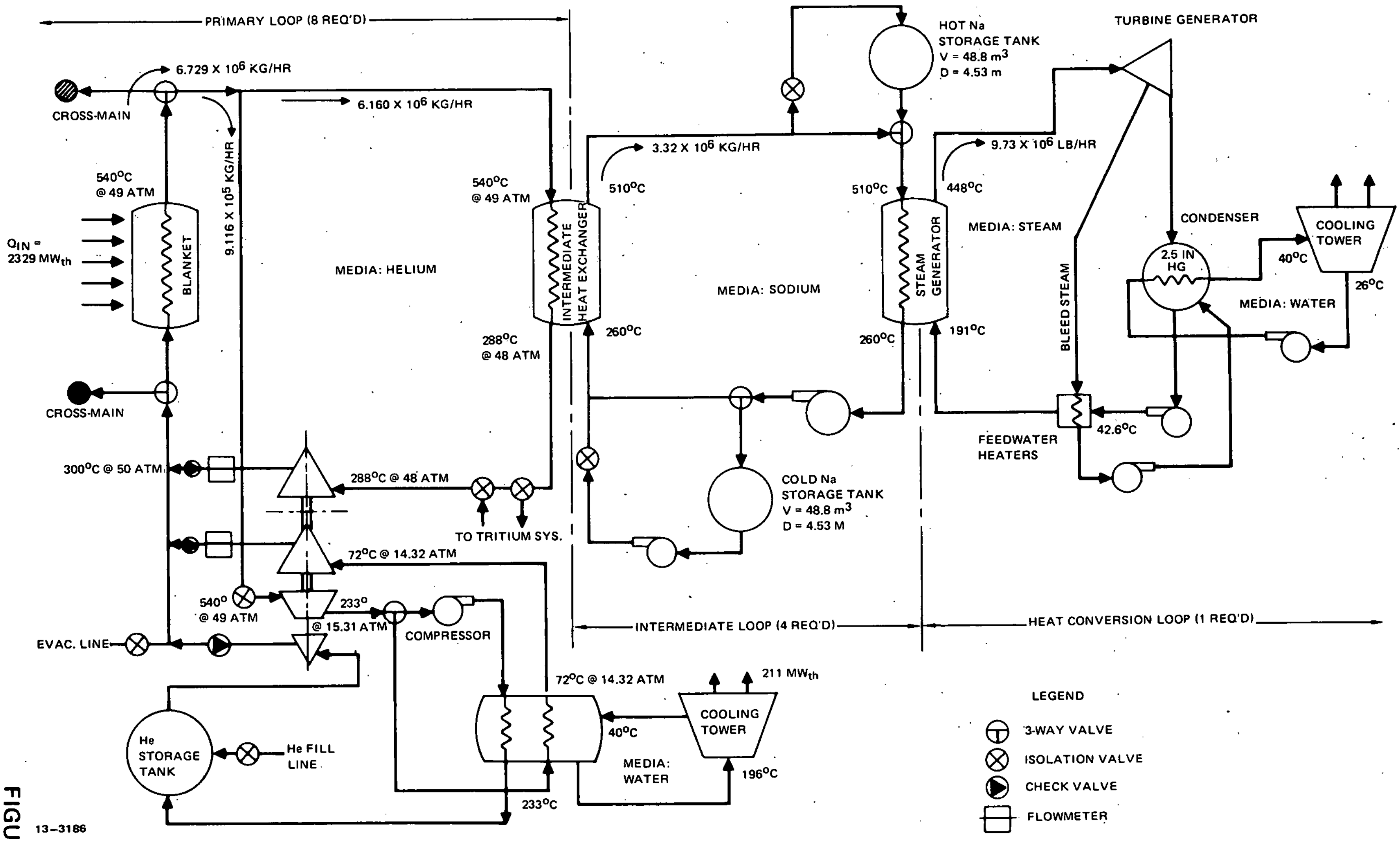
FIGURE 3–18

Eight primary He cooling loops feed eight sodium intermediate cooling loops which in turn are used to generate steam to run the turbine generator. Figure 3-19 is a flow diagram of one loop in this system. The system is also described in further detail in Reference 3.

The divertor bombardment plate coolant selection presents a special problem since the plate size becomes so large if helium is used as a coolant that it doesn't fit in the space available. For this reason, the primary cooling loop in the divertor uses sodium. A sodium secondary coolant loop is also used for the divertor in the same manner as the intermediate cooling loops defined for the first wall/blanket cooling system shown in Figure 3-19.

3000 MW_t POWER CONVERSION SYSTEM

Primary Loop Media: Helium



FROM REFERENCE 3

FIGURE 3–19

3.4 EMPLOYMENT OF REDUNDANCY IN THE BASELINE DESIGNS - For both baseline design concepts an attempt was made to identify which components could be made redundant and, thereby, reduce the requirements for forced outages and increase overall system reliability. For both reactors redundant components and subsystems are assumed to exist wherever redundancy is estimated to be of value in achieving reduced outage downtime and wherever it is feasible. Detailed analysis and iteration of such assumptions is unwarrented with the level of system definition available. Some of the rationale used in selecting redundancy for these baseline configurations is discussed in the following sections.

3.4.1 TMR Redundancy - The major emphasis in applying redundancy to the TMR was in the cooling systems, vacuum systems, power supplies and instrumentation and control systems although the design does not allow for redundancy of some items. As shown later in Tables 4-31 and 4-32, some of the major systems and components of the reactor to which redundancy could not be applied are the first wall/blanket, magnets, internal mechanical connections, neutral beam injectors and their internal components, direct converter collector grids, and direct converter thermal panels.

The first wall/blanket inherently cannot be redundant. Magnets have too low a failure rate and too long a life to justify redundancy as well as some being too large to allow inclusion of redundant units. All internal fluid connections are also inherently incapable of being redundant unless they are part of a secondary or redundant loop.

The neutral beam injectors in the end plugs, including their internal components, are also deemed incapable of being made redundant. One exception is the cryopump panels installed in the NBI housings. All four NBI's are needed and no more can be added because of restricted access to the Yin-Yang plug region. Inside the NBI the beam duct geometry provides space for only one set of ion sources without redundancy unless a failure of some of the individual cells can be tolerated. Because of the arc supression grids inside the module all ion sources must be removed at one time.

Redundancy cannot be applied to the direct converter power grids and thermal panels same reason as the first wall/blanket, i.e., they must intercept all incident radiation on an area of the direct converter chamber. If a failure occurs in these components the thermal radiation or ion impingement on the area covered by that component would damage the chamber in that area unless the reactor is shut down. The use of automatically replacable components would increase the complexity to a point where reliability would probably be reduced.

Among reactor components or systems that are assumed to be redundant are the cryopump panels inside the NBIs and direct converters. Although the cryopump panels are inside the reactor and cannot be isolated if there is a failure, they can be made redundant in their expected principal failure mode. This failure mode is assumed to be a mechanical failure in the regeneration isolation shutters or slide valves, or an internal failure in the fluid system (inoperable isolation valve, clogged plumbing, etc.). This type of failure, which would make the individual cryopump panel useless but not cause a reactor forced outage, is assumed to be the only failure mode encountered in the cryopumps. Based on this premise, 100 percent redundancy has been incorporated in the system.

Adding redundant cooling loops (or critical components within the cooling loops) and redundant control and instrumentation systems will increase the cost of the reactor but can be readily accomplished within the overall reactor configuration tion. Therefore, redundancy has been added to increase the reliability in these systems.

Because of the lower energy levels required and the space available, it is possible to add redundant ion sources to the neutral beam fuel injection units. An entire fuel injection NBI can be added as a back up if it is needed, however, this is considered unnecessary without further analysis.

Redundancy is added to reactor support systems only when an outage would shut down the reactor. Since the design of these systems is somewhat independent of the design of the reactor a number of support systems are not made redundant because they can be repaired while the reactor is operating. Some of the support systems which require redundancy either in their components or for significant system subassemblies are the roughing and regeneration vacuum systems, primary cooling systems outside of the reactor room, NBI and magnet power supplies, power conditioning equipment, and cryogen refrigeration systems.

3.4.2 IMS Tokamak Redundancy - In the tokamak reactor, redundancy can be designed into many of the reactor systems. One of the more important is the NBI ion sources. Because of the low energy requirements and the NBI location and beam duct design, NBI's with redundant ion sources or even the use of redundant NBI's appears feasible.

Also, redundancy can be included in the primary vacuum system. Separate external cryopumps are used. These cryopumps can be completely separated from the reactor by closing isolation valves, so that even a massive leak could be contained and reactor operations could continue. This arrangement provides not only redundancy but also permits the cryopumps to be changed out while the reactor is operating.

Redundancy is also designed into the reactor in the internal cooling loops, instrumentation and control system, and built-in maintenance equipment.

Redundancy is added to the support systems on the same basis as for the TMR. This results in redundancy being added to the cryogenic refrigeration systems, roughing and regeneration vacuum systems, power conditioning equipment, NBI and magnet power supplies, coolant systems external to the reactor, and fuel handling and injection systems. The details of the redundancy included in the IMS Tokamak design are shown later in Table 4-57.

As in the TMR, no redundancy can be designed into the first wall/blanket or the magnets of the IMS tokamak reactor. A failure in any of these results in a forced outage. Failures in piping and at mechanical joints in fluid lines are in the same category; no redundancy was assumed because their dominant failure mode, i.e., a leak, most probably will cause a reactor shutdown. Tokamak reactors also have a divertor system which, like the first wall/blanket, inherently cannot have any redundancy.

3.5 ADVANCED TMR DESIGN - The Lawrence Livermore Laboratory (LLL) is currently developing a commercial tandem mirror reactor conceptual design which utilizes thermal barriers in the end plug regions. The principles incorporated in this advanced TMR design are described further in Reference 6.

Since the LLL design concepts described in Reference 6 have been sized for either 527 MW or 1130 MW net power output, the advanced TMR comparison with the baseline TMR requires resizing this concept to a reactor configuration producing close to 1000 MWe. Figure 3-20 is a power flow diagram of the resized advanced TMR used for comparison. Because the thermal barrier plugs are highly efficient, this reactor has a recirculating power fraction (power consumed/gross electrical power) of only 0.25.

Figure 3-21 shows the reactor as defined for this study. The major difference between this reactor and those defined by LLL is in the central cell length, this being 88 m long with 44 sectors and producing 970 MWe, while the reactor designs in the reference study are 56 m long with 28 sectors (527 MWe) and 100 m long with 50 sectors (1130 MWe).

The advanced TMR is estimated to be 183 m in overall length and is subdivided into 5 major sections. These include a central cell region, two 31 m long end plug regions, and two 17 m long direct converters. The reactor building is shown

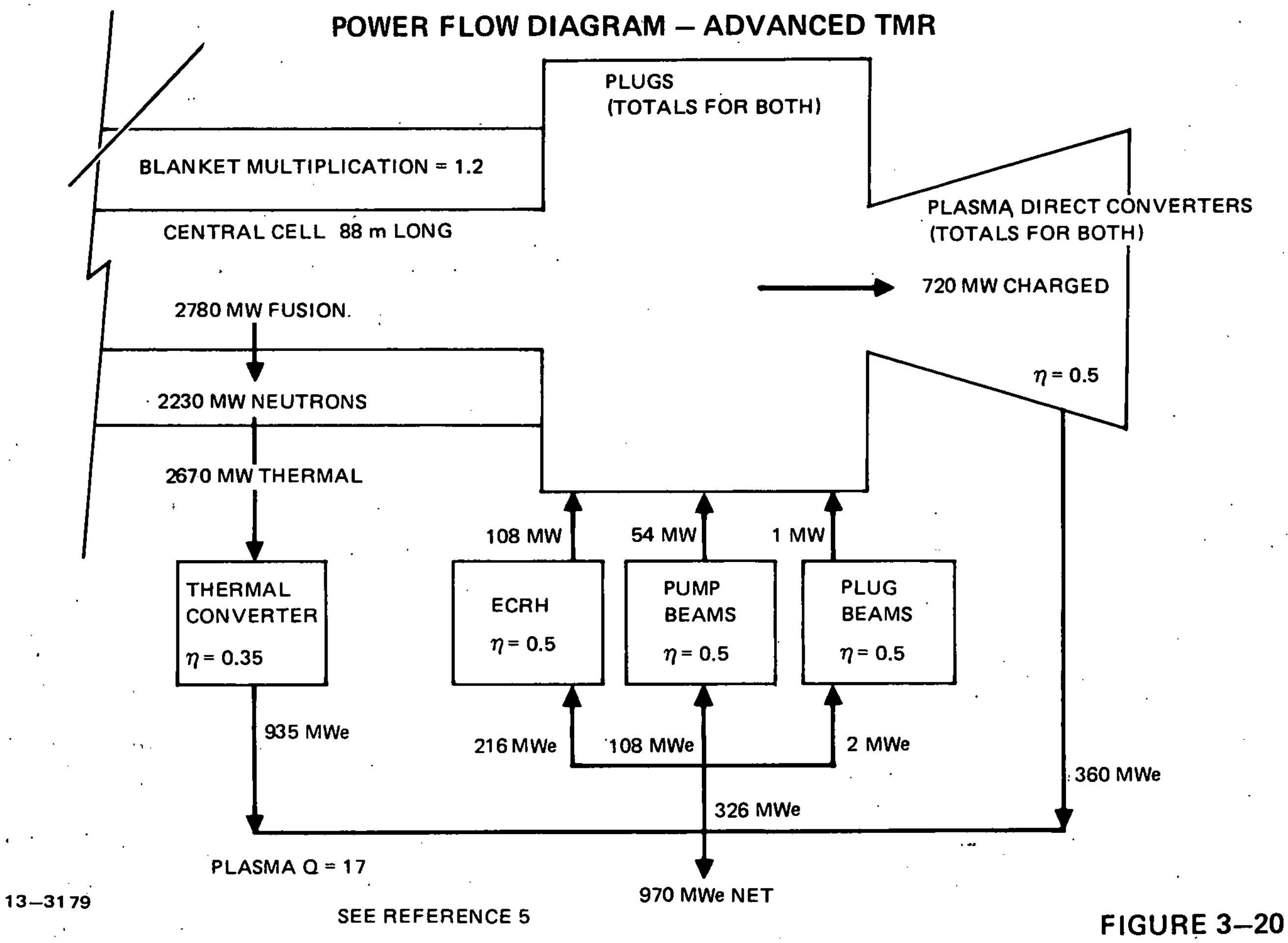


FIGURE 3–20

in Figure 3-22. It is 220 m long with 8800 m^2 of floor space and a volume of 350,000 m^3.

Each central cell sector is about 8 m in diameter, 2 m long and weighs approximately 500 tonnes. The blanket and shield in each sector consists of 24 blanket pod clusters, surrounded by shielding, two niobium-titanium superconducting coils, manifolds, and structure. While the blanket pod clusters are designed for remote removal and replacement from within the reactor during a forced outage, the comparisons conducted in this analysis are limited to changing out an entire central cell module in the reactor room.

An advanced seal concept between central cell sectors is utilized which reduces the time required to replace the sectors. This new seal design is gas actuated as shown in Figure 3-23 and reduces the requirements imposed on removable shield segments. Spacing and shielding blocks are still required between cell modules, partially offsetting the time advantage realized by the advanced seal design.

Serviceability of end plug magnets and shielding segments is a problem in the baseline TMR design concept. In the baseline design the solenoid magnets are very

ADVANCED TANDEM MIRROR REACTOR

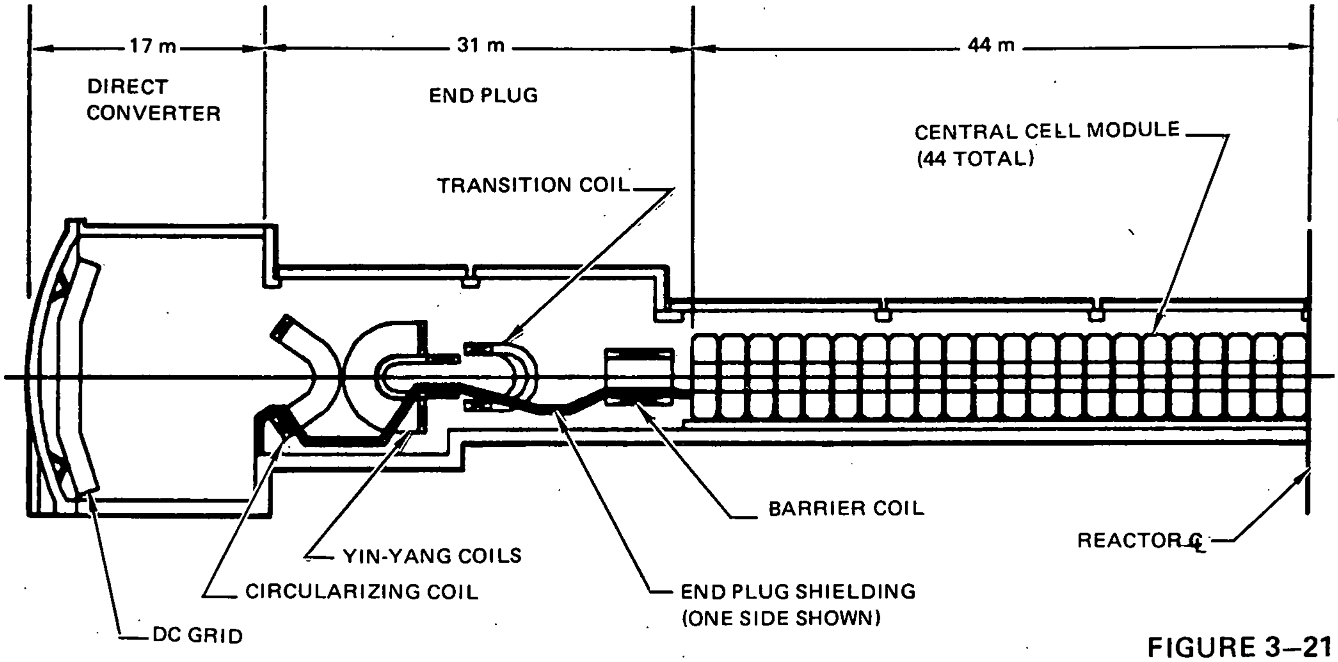


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FIGURE 3–21

ADVANCED TMR REACTOR BUILDING

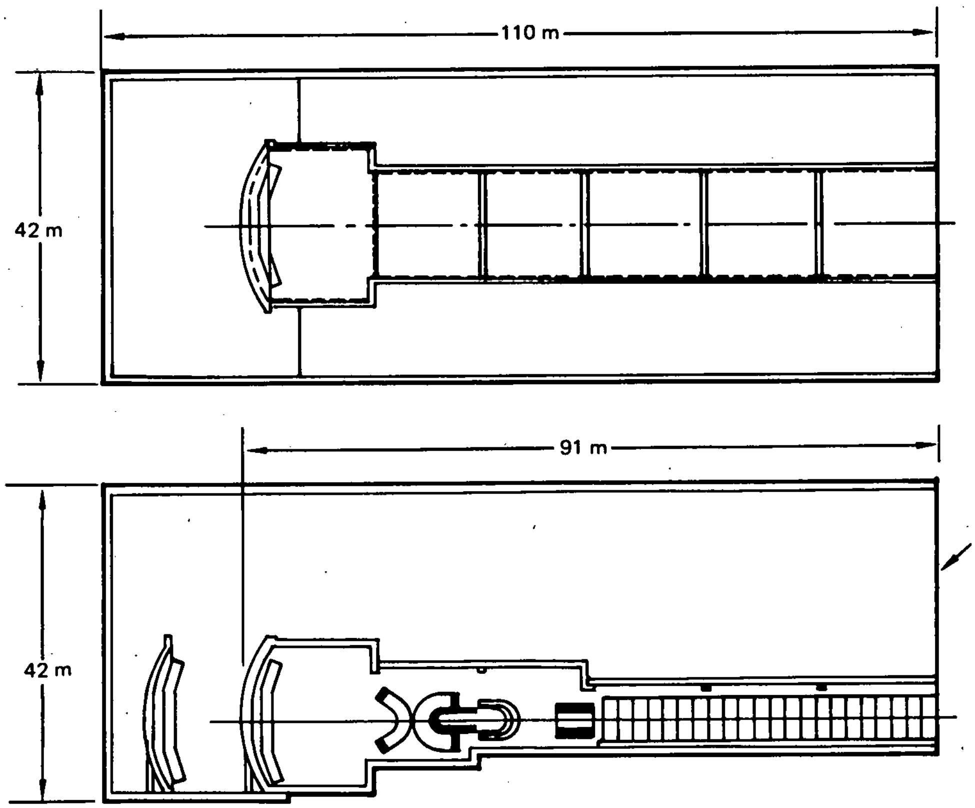

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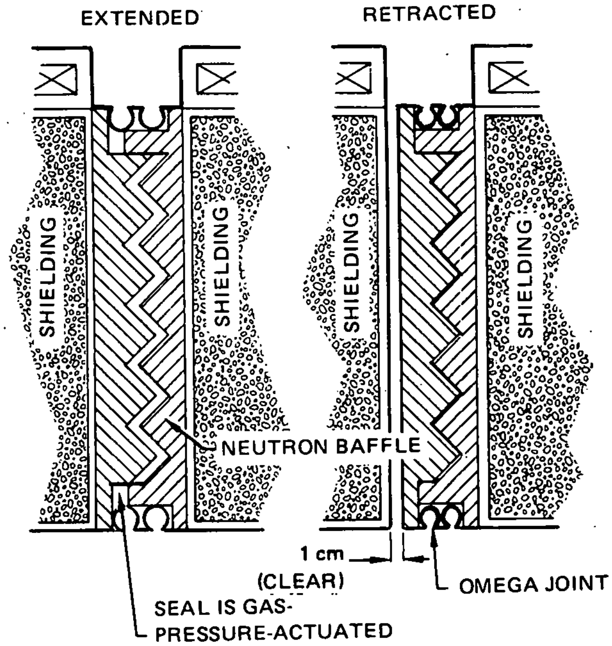
FIGURE 3–22

SECTOR-TO-SECTOR SEAL CUSHION



13–3187 FROM REFERENCE 5

FIGURE 3–23

large and making handling difficult; magnets are located within magnets which limits access and complicates repair procedures. The advanced TMR design concept eliminates many of these problems. All magnets are easily accessible and none are nested within another nor are any too large to be lifted by the central cell cranes. However, to lift the larger magnets, such as an individual Yin-Yang coil, the inner shielding must be removed to bring the magnet weight within the crane capacity. The shield modules are removed in the same manner as defined for the baseline TMR, i.e., by moving horizontally then lifting.

The use of thermal barriers in the end plugs allows the end plug neutral beam power requirements to be greatly reduced. Each plug needs only 250 KW of 400 KeV neutral particles trapped in the plasma. To provide this requirement only one NBI is required for each end plug. With these limited requirements it appears possible to install redundant end plug heating capability by either using two NBI's at each end plug or by installing several ion sources in the one NBI. This redundancy could not be provided on earlier TMR NBI's because of the volume required for the suppression grids that had to be used. Eliminating the grids at the ion source and their associated complexity makes the NBI on the advanced TMR much easier to service.

The end plug region also requires the installation of barrier pump neutral beam injectors and waveguides for the ECRH. Since these modules are smaller than the end plug NBI, they can be replaced as a unit should a failure occur.

By using a circularizing coil between the Yin-Yang coils and the direct converter, a circular direct converter design is possible. The converter face is then only 16 m in dia. and receives a total of approximately 730 MW of incident energy at both ends of the TMR. The direct converter face is subdivided into a central module and 6 identical trapezoidal shaped modules around the outside. The circular shape permits the use of a smaller volume, cylindrical direct converter chamber and reduces spares requirements since most modules are identical. The ion collector plates are actively cooled. Therefore, active cooling of the direct converter chamber walls is not required.

The cryopump panels are installed on the inner wall of the direct converter with a minimum of baffle shielding to protect them from the direct converter radiation. The same area (400 m^2) is used in each direct converter as for the baseline TMR. This allows for one half of the cryopump panels to be regenerating at one time and also includes 100% redundancy. Access to the inside of the direct converter is through a large removable door at the end of the chamber. This door has the direct converter modules mounted on it. Such an arrangement appears preferable to the limited access available for the baseline TMR's direct converter.

In summary, the advanced TMR is smaller and appears simpler than the baseline TMR and is potentially more serviceable and reliable.

4.0 MAINTENANCE PLAN DEVELOPMENT

Maintenance plans have been developed for both the TMR and the tokamak baseline reactors. The requirements of these plans provide the basis for the comparative analyses described in the next secton of the report (Section 5.0). The plans defined in this section consider only the reactor systems but are a relatively complete definition of the maintenance activities required. These plans include the maintenance actions involved in scheduled maintenance and forced outages, the use of redundancy, the maintenance equipment required and the influence of maintenance equipment failures. A brief explanation of the maintenance characteristics of an advanced TMR concept is also included.

4.1 APPROACH TO MAINTENANCE PLAN DEVELOPMENT - Three basic steps have been used to develop maintenance plans for this study. These are outlined in Table 4-1

TABLE 4—1
MAINTENANCE PLAN DEVELOPMENT APPROACH

DEVELOP COMPONENT (SUBASSEMBLY) MAINTENANCE REQUIREMENTS
- o ASSIGN FORCED AND/OR SCHEDULED OUTAGES
  - INCLUDE REDUNDANCY
  - MAINTENANCE WHILE OPERATING
- o DEVELOP SCENARIOS FOR SIGNIFICANT COMPONENTS

DEVELOP SCHEDULED MAINTENANCE REQUIREMENTS
- o USE MANAGEMENT SCHEDULING AND CONTROL SYSTEM (MSCS)
  - INTEGRATE SCHEDULED DOWNTIME
  - ASSIGN RESOURCE USAGE
- o USE MICOMO OR TOCOMO
  - OPTIMIZE SCHEDULED DOWNTIME
  - DEFINE AVAILABILITY
  - DEFINE COST OF ELECTRICITY (COE)

ALLOCATE FORCED OUTAGE REQUIREMENTS
- o SELECT GOALS
  - COE AND AVAILABILITY
- o DEFINE COMPONENT REQUIREMENTS
  - UNAVAILABILITY
  - FAILURE RATES

and include the definition of individual maintenance action scenarios, the combination of these maintenance actions to establish scheduled maintenance requirements, and the allocation of forced outage downtimes to system components based on selected Cost of Electricity (COE) goals or availability goals.

The general approach first requires the development of a scheduled maintenance plan; then, subtracting the scheduled maintenance time from the total downtime available with the selected goal yields the total allowable forced outage downtime from which the allocation to components can be made.

4.1.1 Maintenance Action Selection for Detailed Analyses - Maintenance action scenarios can only be defined for a limited number of specific maintenance actions. The selection of the maintenance actions to be examined is limited to those construed to require either the largest effort, the longest downtime or to occur frequently. For this study, maintenance actions considered are limited to the reactor systems since the balance of plant is assumed to be identical for the TMR and tokamak reactor systems and, therefore, will have the same influence on both.

The process used to select maintenance actions first requires definition of as many as possible of the replaceable units in each reactor system. The redundancy of each unit is initially defined and the reactor operating condition during maintenance is assigned. The latter operating conditions are limited to (1) maintenance during a scheduled outage, (2) maintenance while the reactor is operating, and (3) maintenance requiring a forced outage. The subsystem designs discussed briefly in the previous section of this report and in References 2 and 3 serve as the base for defining component breakdowns and assigning redundant components to each subsystem. Since detailed system designs are not available, the number of units included in each subsystem are coarse estimates in some cases.

Tables 4-2, 4-3 and 4-4 indicate component breakdown and the number of units considered for the TMR and the tokamak reactor systems. The reactor operating condition deemed most probable for maintenance actions is also indicated. Tables 4-2 and 4-3 define the TMR central cell components and the TMR end plug components, respectively. Table 4-4 defines the Improved Maintenance System (IMS) tokamak reactor which is used for comparison with the TMR. The total number of units shown is the number of operating units plus the number of redundant units. Several types of redundancy are used, depending on the system postulated. For example, the primary cooling system in the central cell region assumes that completely redundant loops are used. Fon valves and electrical cables, redundancy is considered to be for specific units on a one for one basis.

TABLE 4–2
TMR CENTRAL CELL MAINTENANCE MODES

COST ACCOUNT NUMBER	MAINTENANCE COMPONENT (SUBASSEMBLY)	SCHEDULED MAINTENANCE ACTION	NUMBER OF UNITS (TOTAL)	MAINTENANCE MODE		
				SCHEDULED OUTAGE	WHILE OPERATING	FORCED OUTAGE
22	REACTOR PLANT EQUIPMENT					
22.01	REACTOR EQUIPMENT					
22.01.01	BLANKET AND FIRST WALL					
	FIRST WALL AND STRUCTURE	REPLACE FW/B CENTER CELL	36*	X	-	X
	ATTENUATORS	(NOT APPLICABLE)				
	WALL MODIFIERS (COATINGS)	RECOAT FIRST WALL	-	-	X	X
22.01.02	PRIMARY SHIELD	(WITH FW/B CENTER CELL)	36*	-	-	X
22.01.03	FIELD MAGNETS	(WITH FW/B CENTER CELL)	36	X	-	X
	POWER LEADS	NONE	72	-	-	X
22.01.04	SUPPLEMENTAL HEATING	(NOT APPLICABLE)				
22.01.05	STRUCTURE AND SUPPORT	(NOT INCLUDED)				
22.01.06	VACUUM SYSTEMS					
22.01.06.01	PLASMA CHAMBER VACUUM	(SEE END PLUGS)				
22.01.06.02	MAGNET DEWAR VACUUM					
	PUMPS/COMPRESSORS	PERIODIC REPLACEMENT	2	-	X	-
	PIPING, CONNECTIONS	INSPECTION	152	-	X	-
	EXTERNAL VALVES	INSPECTION	76	-	X	-
22.01.06.03	SUPPLEMENTAL HEATING - VACUUM	(FOR FUEL INJECTION BEAMS)				
	CRYOPUMPS	REPLACE PANELS	8	X	-	X
	MECHANICAL PUMPS	(USE DIRECT CONVERTER PUMPS)				
	CRYOGEN PIPING, CONNECTIONS	INSPECTION	144	-	X	X
	CRYOGEN VALVES, CONTROL	INSPECTION	8	X	-	X
	VACUUM PIPING, CONNECTIONS	INSPECTION	4	-	X	X
	VACUUM VALVES, REGEN.	INSPECTION	2	-	X	X
	CRYOGEN VALVES, ISO	INSPECTION	54	-	X	-
22.01.06.04	DIRECT CONVERTER VACUUM	(SEE END PLUGS)				
22.01.06.05	REACTOR VACUUM SYSTEM	(FOR REACTOR ROOM)				
	PUMPS/COMPRESSORS	PERIODIC REPLACEMENT	6 SETS	-	X	-
	PIPING, CONNECTIONS	INSPECTION	24	-	X	-
	EXTERNAL VALVES	INSPECTION	12	-	X	-
22.01.06.06	REACTOR VACUUM WALL					
	PENETRATIONS	REPLACE SEALS	4	X	-	X
22.01.07	POWER SUPPLY, ENERGY STORAGE					
	DIESEL GENERATORS	TEST/INSPECTION	3	-	X	-
	CABLES, METERS	INSPECTION	6000	X	X	X
	POWER CONDITIONING					
	POWER SUPPLIES, MAGNET	INSPECTION	18	-	X	-
	CONTROLLERS	INSPECTION	42	-	X	-
	SWITCHES/CIRCUIT BREAKER	INSPECTION	42	-	X	-
	DIAGNOSTIC POWER CONDITIONING	INSPECTION	2 SETS	-	X	-
	FUEL INJECTION POWER	CALIBRATION	3	-	X	-
22.01.08	IMPURITY CONTROL	(NOT APPLICABLE)				
22.01.09	DIRECT ENERGY CONVERTER	(SEE END PLUGS)				
22.02	MAIN HEAT TRANSPORT SYSTEMS					
22.02.01	PRIMARY COOLANT SYSTEM					
22.02.01.01	PUMPS AND DRIVES	PERIODIC REPLACE	7	-	X	-
22.02.01.02	PIPING, CONNECTIONS	INSPECTION	518	-	X	X
	ISOLATION VALVES	INSPECTION	7 SETS	-	X	X
	CONTROL VALVES	INSPECTION	72	X	-	X
22.02.01.03	HEAT EXCHANGER	PERIODIC CLEANING	14	-	X	-
22.02.01.04	TANKS	INSPECTION	7	-	X	-
22.02.01.05	CLEAN-UP SYSTEM	INSPECTION	7	-	X	-
22.02.01.06	THERMAL INSULATION	(SEE PIPING, ABOVE)				
22.02.01.07	TRITIUM EXTRACTION	(SEE TRITIUM RECOVERY)				

*SECTOR MODULE

TABLE 4–2
TMR CENTAL CELL MAINTENANCE MODES (CONT.)

COST ACCOUNT NUMBER	MAINTENANCE COMPONENT (SUBASSEMBLY)	SCHEDULED MAINTENANCE ACTION	NUMBER OF UNITS (TOTAL)	MAINTENANCE MODE		
				SCHEDULED OUTAGE	WHILE OPERATING	FORCED OUTAGE
22.02.02	INTERMEDIATE COOLANT SYSTEM					
22.02.02.01	PUMPS AND DRIVES	PERIODIC OVERHAUL	7	-	X	-
22.02.02.02	PIPING, CONNECTIONS	INSPECTION	98	-	X	X
	ISOLATION VALVES	INSPECTION	14	-	X	X
	CONTOL VALVES	INSPECTION	14	X	-	X
22.02.02.03	STEAM GENERATOR	PERIODIC OVERHAUL	7	-	X	-
22.02.02.04	TANKS	INSPECTION	7	-	X	-
22.02.02.05	CLEAN-UP SYSTEM	INSPECTION	7	-	X	-
22.03	AUXILIARY COOLING SYSTEMS					
22.03.01	MAGNET COOLING					
	H_2 REFRIGERATION SYSTEM	PERIODIC OVERHAUL	1 UNIT	-	X	-
	N_2 REFRIGERATION SYSTEM	PERIODIC OVERHAUL	1 UNIT	-	X	-
	PIPING, CONNECTIONS	INSPECTION	566	-	X	X
	TANKS/CONTAINERS	INSPECTION	74	-	X	-
22.03.02	SHIELD COOLING	(SEE PRIMARY COOLANT)				
22.03.03	SUPPLEMENTAL HEATING COOLING	(FOR FUEL INJECTION BEAMS)				
	H_e REFRIGERATION SYSTEM	PERIODIC OVERHAUL	1 UNIT	-	X	-
	N_2 REFRIGERATION SYSTEM	PERIODIC OVERHAUL	1 UNIT	-	X	-
	PUMPS AND DRIVES, WATER	PERIODIC OVERHAUL	2	-	X	-
	PIPING, CONNECTIONS	INSPECTION	32	-	X	X
	VALVES, CONTROL	INSPECTION	8	X	-	X
22.03.04	POWER SUPPLY COOLING	(NOT INCLUDED)				
22.04	RADIOACTIVE WATER TREATMENT	(NOT INCLUDED)				
22.05	FUEL HANDLING AND STORAGE					
22.05.01	FUEL PURIFICATION SYSTEM	(SEE END PLUGS)				
22.05.02	LIQUIDATION	(NOT APPLICABLE)				
22.05.03	FUEL PREPARATION	(SEE FUEL INJECTION, BELOW)				
22.05.04	FUEL INJECTION					
	ION SOURCES	PERIODIC REPLACEMENT	12	X	-	X
	ION BEAM DUMP	INSPECTION	2	X	-	X
	ION DUMP MAGNETS	NONE	2	-	-	X
22.05.05	FUEL STORAGE/PIPING	INSPECTION	2	-	X	X
22.05.06	TRITIUM RECOVERY	REPLACE ABSORBERS	-	-	X	-
22.05.07	EMERGENCY AIR DETRITIATION	NONE	-	-	X	-
22.06	OTHER REACTOR EQUIPMENT					
22.06.01	MAINTENANCE EQUIPMENT					
	CENTER OVERHEAD CRANE	ADJUST/LUBE		X	-	X
	MAGNET COOLING MODULE	ADJUST/LUBE		-	X	X
	TRENCH ROBOT	ADJUST/LUBE		-	X	X
	OVERHEAD MANIPULATOR	ADJUST/LUBE	SEE DETAILED LIST	-	X	X
	TOOLS (AUTOMATIC WELDERS)	ADJUST/LUBE		-	X	X
	(VACUUM SEAL WELDERS)	ADJUST/LUBE				
	FIXTURES	NONE		-	X	X
	TUGS AND DOLLIES	ADJUST/LUBE		-	X	X
	VIEWING SYSTEMS	PERIODIC REPLACEMENT		X	X	X
	ENTRANCE AND EGRESS LOCKS	ADJUST/LUBE		-	X	X
22.06.02	SPECIAL HEATING SYSTEMS	(NOT INCLUDED)				
22.06.03	COOLANT STORAGE AND MAKEUP	(NOT INCLUDED)				
22.06.04	GAS SYSTEMS	(NOT INCLUDED)				
22.06.05	BUILDING VENTILATION SYSTEM					
	FANS	LUBRICATION	NOT DEFINED	-	X	-
	FILTERS AND SCRUBBERS	PERIODIC CLEANING		-	X	-
22.07	INSTRUMENTATION AND CONTROL					
22.07.01	REACTOR I&C EQUIPMENT					
	PROBES (PERFORMANCE MONITORING SYS)	PERIODIC REPLACEMENT	NOT DEFINED	X	X	-
	INTEGRAL INSTRUMENTS (REACTOR STATUS SYS)	REPLACEMENT W/UNIT		X	X	-
	EXTERNAL INSTRUMENTS (PLASMA CONTROL SYSTEM)	PERIODIC OVERHAUL		X	X	-
	CONTROL ROOM EQUIPMENT	CALIBRATION		-	X	-
	COMPUTERS	NONE		-	X	-
22.07.02	RADIATION MONITORING SYSTEM	NONE		X	X	-
22.07.03	ISOLATED GAUGES	(NOT INCLUDED)				

TABLE 4–3
TMR END PLUG MAINTENANCE MODES

COST ACCOUNT NUMBER	MAINTENANCE COMPONENT (SUBASSEMBLY)	SCHEDULED MAINTENANCE ACTION	NUMBER OF UNITS (TOTAL)	MAINTENANCE MODE		
				SCHEDULED OUTAGE	WHILE OPERATING	FORCED OUTAGE
22	REACTOR PLANT EQUIPMENT					
22.01	REACTOR EQUIPMENT					
22.01.01	BLANKET AND FIRST WALL					
	FIRST WALL AND STRUCTURE	REPLACE WALL	24	X	-	X
	ATTENUATORS	(NOT APPLICABLE)				
	WALL MODIFIERS	(NOT APPLICABLE)	-	-	X	X
22.01.02	PRIMARY SHIELD	(WITH PLUG WALL)	-	-	-	X
22.01.03	MAGNETS					
	SOLENOID	NONE	4	X	-	X
	YIN YANG	NONE	4	X	-	X
	TRANSFER	NONE	2	X	-	X
	POWER LEADS	NONE	20	-	-	X
22.01.04	SUPPLEMENTAL HEATING					
22.01.04.01	NEUTRAL BEAM HEATING					
	ION SOURCES	PERIODIC REPLACEMENT	4	X	-	X
	ION BEAM DUMP PLATES	INSPECTION	4	-	-	X
	PLASMA STRIPPING CELL	PERIODIC REPLACEMENT	4	-	-	X
	ION DUMP MAGNETS	NONE	4	-	-	X
	D_2 MERCURY PUMPS	REPLACE ABSORBMENT	8	-	-	X
	Na COOLANT SYSTEM	INSPECTION	2	-	X	X
22.01.05	PRIMARY STRUCTURE AND SUPPORT	(NOT INCLUDED)				
22.01.06	VACUUM SYSTEMS					
22.01.06.01	PLASMA CHAMBER VACUUM	(WITH DIRECT CONVERTER VAC.)				
22.01.06.02	MAGNET DEWAR VACUUM					
	PUMPS/COMPRESSORS	(USE CENTRAL CELL PUMPS)				
	PIPING, CONNECTIONS	INSPECTION	48	-	X	-
	EXTERNAL VALVES	INSPECTION	24	-	X	-
22.01.06.03	SUPPLEMENTAL HEATING - VACUUM					
	CRYOPUMPS	REPLACE PANELS	30	X	-	X
	MECHANICAL PUMPS	(USE DIRECT CONVERTER PUMPS)				
	CRYOGEN PIPING, CONNECTIONS	INSPECTION	240	-	X	X
	CRYOGEN VALVES, LHe CONTROL	INSPECTION	60	X	-	X
	VACUUM PIPING, CONNECTIONS	INSPECTION	4	-	X	X
	VACUUM VALVES, REGEN.	INSPECTION	2	-	X	X
	CRYOGEN VALVES, ISO	INSPECTION	90	-	X	-
22.01.06.04	DIRECT CONVERTER VACUUM					
	CRYOPUMPS	REPLACE PANELS	100	X	-	X
	MECHANICAL PUMPS	PERIODIC REPLACEMENT	3 SETS	-	X	-
	CRYOGEN PIPING, CONNECTIONS	INSPECTION	136	-	X	X
	CRYOGEN VALVES LHe CONTROL	INSPECTION	200	X	-	X
	VACUUM PIPING, CONNECTIONS	INSPECTION	4	-	X	X
	VACUUM VALVES	INSPECTION	2	-	X	X
	VACUUM VALVES, ISO	INSPECTION	150	-	X	-
22.01.06.05	REACTOR VACUUM SYSTEM	(SEE CENTRAL CELL SYSTEM)				
22.01.06.06	VACUUM WALL (PENETRATIONS)					
	DIRECT CONVERTER	REPLACE SEALS	6	X	-	X
	PLUG REGION	REPLACE SEALS	2	X	-	X
	SUPPLEMENTAL HEATING	REPLACE SEALS	8	X	-	X
22.01.07	POWER SUPPLY, ENERGY STORAGE					
	DIESEL GENERATORS	(USE CENTRAL CELL UNITS)				
	CABLES, METERS	INSPECTION	4750	X	X	X
	POWER CONDITIONING					
	POWER SUPPLIES, NBI	INSPECTION	75	-	X	-
	CONTROLLERS	INSPECTION	18	-	X	-
	SWITCHES/CIRCUIT BREAKER	INSPECTION	18	-	X	-
	DIAGNOSTIC POWER CONDITIONING	INSPECTION	2 SETS	-	X	-
	FUEL INJECTION POWER	(SEE CENTRAL CELL)				
22.01.08	IMPURITY CONTROL	(NOT APPLICABLE)				

TABLE 4–3
TMR END PLUG MAINTENANCE MODES (CONT.)

COST ACCOUNT NUMBER	MAINTENANCE COMPONENT (SUBASSEMBLY)	SCHEDULED MAINTENANCE ACTION	NUMBER OF UNITS (TOTAL)	MAINTENANCE MODE		
				SCHEDULED OUTAGE	WHILE OPERATING	FORCED OUTAGE
22.01.09	DIRECT ENERGY CONVERTER					
22.01.09.01	VACUUM TANK	(SEE VACUUM WALLS)				
22.01.09.02	DIRECT CONVERTER MODULES	PERIODIC REPLACEMENT	34	X	-	X
22.01.09.03	THERMAL PANELS	PERIODIC REPLACEMENT	640	X	-	X
22.01.09.04	POWER CONDITIONING EQ.	CALIBRATION	6	-	X	-
22.02	MAIN HEAT TRANSPORT SYSTEMS					
22.02.01	PRIMARY COOLANT SYSTEM	(SEE CENTRAL CELL)				
22.02.02	INTERMEDIATE COOLANT SYSTEM	(SEE CENTRAL CELL)				
22.03	AUXILIARY COOLING SYSTEMS					
22.03.01	MAGNET COOLING	INSPECTION	10	-	-	X
22.03.02	SHIELD COOLING, WATER					
22.03.02.01	REFRIGERATION	(NOT APPLICABLE)				
22.03.02.02	PIPING CONNECTIONS	INSPECTION	132	-	X	X
	HEAT EXCHANGER	CLEANOUT	3	-	X	-
	VALVES, CONTROL	INSPECTION	24	X	-	X
22.03.02.03	PUMPS AND DRIVES	PERIODIC REPLACEMENT	2 SETS	-	X	-
22.03.02.05	CLEAN-UP SYSTEM	INSPECTION	NOT DEFINED	-	X	-
22.03.03	SUPPLEMENTAL HEATING COOLING					
	H_e REFRIGERATION SYSTEM	PERIODIC OVERHAUL	4	-	X	-
	N_2 REFRIGERATION SYSTEM	PERIODIC OVERHAUL	4	-	X	-
	PUMPS AND DRIVES, WATER	(USE SHIELD COOLANT)				
	PIPING CONNECTIONS	INSPECTION	32	-	X	X
	VALVES, CONTROL	INSPECTION	8	X	-	X
22.03.04	POWER SUPPLY COOLING	(NOT INCLUDED)				
22.03.05	DIRECT CONVERTER COOLING					
	PUMPS AND DRIVES	PERIODIC REPLACEMENT	2 SETS	-	X	-
	PIPING, CONNECTIONS	INSPECTION	20	-	X	X
	VALVES, CONTROL	INSPECTION	58	X	-	X
	HEAT EXCHANGER	INSPECTION	2	-	X	-
	CLEAN-UP SYSTEM	(NOT INCLUDED)				
22.04	RADIOACTIVE WATER TREATMENT	(NOT INCLUDED)				
22.05	FUEL HANDLING AND STORAGE					
22.05.01	FUEL PURIFICATION SYSTEM	REPLACE PURIFIER	9	-	X	-
22.05.02	LIQUIDATION	(NOT APPLICABLE)				
22.05.03	FUEL PREPARATION	(SEE CENTRAL CELL)				
22.05.04	FUEL INJECTION	(SEE CENTRAL CELL)				
22.05.05	FUEL STORAGE/PIPING	INSPECTION	26	-	X	X
22.05.06	TRITIUM RECOVERY	REPLACE ABSORBERS	6	-	X	-
22.05.07	EMERGENCY AIR DETRITIATION	NONE	NOT DEFINED	-	X	-
22.06	OTHER REACTOR EQUIPMENT					
22.06.01	MAINTENANCE EQUIPMENT					
	HIGH BAY CRANE	ADJUST/LUBE	SEE DETAILED LIST	-	-	X
	SHIELDING MANIPULATOR	ADJUST/LUBE		-	X	X
	NBI MANIPULATOR	ADJUST/LUBE		-	X	X
	DIRECT CONVERTER MANIPULATOR	ADJUST/LUBE		-	X	X
	TOOLS (WELDERS)	ADJUST/LUBE		-	X	X
	FIXTURES	NONE		-	X	X
	TUGS AND DOLLIES	ADJUST/LUBE		-	X	X
	VIEWING SYSTEMS	PERIODIC REPLACEMENT		X	X	X
	ENTRANCE AND EGRESS LOCKS	ADJUST/LUBE		-	X	X
22.06.02	SPECIAL HEATING SYSTEMS	(NOT INCLUDED)				
22.06.03	COOLANT STORAGE AND MAKEUP	(NOT INCLUDED)				
22.06.04	GAS SYSTEMS	(NOT INCLUDED)				
22.06.05	BUILDING VENTILATION SYSTEM					
	FANS	LUBRICATION	NOT DEFINED	-	X	-
	FILTERS AND SCRUBBERS	PERIODIC CLEANING		-	X	-

TABLE 4–3
TMR END PLUG MAINTENANCE MODES (CONT.)

COST ACCOUNT NUMBER	MAINTENANCE COMPONENT (SUBASSEMBLY)	SCHEDULED MAINTENANCE ACTION	NUMBER OF UNITS (TOTAL)	MAINTENANCE MODE		
				SCHEDULED OUTAGE	WHILE OPERATING	FORCED OUTAGE
22.07	INSTRUMENTATION AND CONTROL					
22.07.01	REACTOR I&C EQUIPMENT					
	PROBES (PERFORMANCE MONITORING SYS)	PERIODIC REPLACEMENT	NOT DEFINED	X	X	-
	INTEGRAL INSTRUMENTS (REACTOR STATUS SYS)	REPLACEMENT W/UNIT		X	X	-
	EXTERNAL INSTRUMENTS (PLASMA CONTROL SYSTEM)	PERIODIC OVERHAUL		X	X	-
	CONTROL ROOM EQUIPMENT	CALIBRATION		-	X	-
	COMPUTERS	NONE		-	X	-
22.07.02	RADIATION MONITORING SYSTEM	NONE		X	X	-
22.07.03	ISOLATED GAUGES	(NOT INCLUDED)				

TABLE 4–4
IMS TOKAMAK MAINTENANCE MODES

COST ACCOUNT NUMBER	MAINTENANCE COMPONENT (SUBASSEMBLY)	SCHEDULED MAINTENANCE ACTION	NUMBER OF UNITS (TOTAL)	MAINTENANCE MODE		
				SCHEDULED OUTAGE	WHILE OPERATING	FORCED OUTAGE
22	REACTOR PLANT EQUIPMENT					
22.01	REACTOR EQUIPMENT					
22.01.01	BLANKET AND FIRST WALL					
	FIRST WALL AND STRUCTURE	REPLACE WALL SECTOR	16	X	-	X
	WALL MODIFIERS (COATINGS)	RECOAT FIRST WALL	-	-	X	X
22.01.02	SHIELD					
	PRIMARY (INNER)	NONE	16	-	-	X
	SECONDARY (OUTER)	NONE	16	-	-	X
22.01.03	MAGNETS					
	TOROIDAL FIELD MAGNETS	NONE	16	X	-	X
	POLOIDAL FIELD MAGNETS	NONE	15	X	-	X
	OMNIC HEATING COILS	NONE	14	X	-	X
	POWER LEADS	NONE	90	-	-	X
22.01.04	SUPPLEMENTAL HEATING					
22.01.04.01	NEUTRAL BEAM HEATING					
	ION SOURCES	PERIODIC REPLACEMENT	36	X	-	X
	ION BEAM DUMP PLATES	INSPECTION	12	-	-	X
	ION DUMP MAGNETS	NONE	12	-	-	X
	ISOLATION VALVE	PERIODIC REPLACEMENT	12	X	-	X
22.01.05	STRUCTURE AND SUPPORT					
	MAGNET RETRACTION SYSTEM	INSPECTION ADJUSTMENT	6	X	-	X
22.01.06	VACUUM SYSTEMS					
22.01.06.01	PLASMA CHAMBER VACUUM	(AT DIVERTORS)				
	CRYOPUMPS	REPLACE PUMP ASSY.	20	X	-	X
	MECHANICAL PUMPS	PERIODIC OVERHAUL	5	-	X	-
	CRYOGEN PIPING, CONNECTIONS	NONE	160	-	X	X
	CRYOGEN VALVES, CONTROL	INSPECTION	20	X	-	X
	VACUUM PIPING, CONNECTIONS	NONE	40	-	X	X
	VACUUM VALVES, REGEN.	INSPECTION	20	X	-	X
	CRYOGEN VALVES, ISOLATION	INSPECTION	60	-	X	-
22.01.06.02	MAGNET DEWAR VACUUM					
	PUMPS/COMPRESSORS	PERIODIC REPLACEMENT	2	-	X	-
	PIPING, CONNECTIONS	NONE	188	-	X	-
	VALVES, EXTERNAL	INSPECTION	94	-	X	-
22.01.06.03	SUPPLEMENTAL HEATING VACUUM					
	CRYOPUMPS	REPLACE PANELS	18	X	-	X
	MECHANICAL PUMPS	(USE PLASMA CHAMBER PUMPS)				
	CRYOGEN PIPING, CONNECTIONS	NONE	144	-	X	X
	CRYOGEN VALVES, CONTROL	INSPECTION	18	X	-	X
	VACUUM PIPING, CONNECTIONS	NONE	4	-	X	X
	VACUUM VALVES, REGEN.	INSPECTION	12	X	-	X
	CRYOGEN VALVES, ISOLATION	INSPECTION	54	-	X	-
22.01.06.04	DIRECT CONVERTER VACUUM	(NOT APPLICABLE)				
22.01.06.05	REACTOR VACUUM SYSTEM	(SECONDARY VACUUM ZONE)				
	PUMPS/COMPRESSORS	PERIODIC OVERHAUL	3	-	X	-
	PIPING, CONNECTIONS	NONE	12	-	X	-
	VALVES, EXTERNAL	INSPECTION	6	-	X	-
22.01.06.06	REACTOR VACUUM WALL					
	PENETRATIONS (DOORS)	REPLACE SEALS	32	X	-	X
22.01.07	POWER SUPPLY, ENERGY STORAGE					
	DIESEL GENERATORS	TEST/INSPECTION	3	-	X	-
	CABLES, METERS	NONE	6000	X	X	X
	POWER CONDITIONING					
	POWER SUPPLIES, (NBI MAGNETS)	INSPECTION	71	-	X	-
	ENERGY STORAGE EQUIP.	INSPECTION	3	-	X	-
	SUPPLEMENTAL HEATING POWER	CALIBRATION	5	-	X	X

TABLE 4–4
IMS TOKAMAK MAINTENANCE MODES (CONT.)

COST ACCOUNT NUMBER	MAINTENANCE COMPONENT (SUBASSEMBLY)	SCHEDULED MAINTENANCE ACTION	NUMBER OF UNITS (TOTAL)	MAINTENANCE MODE		
				SCHEDULED OUTAGE	WHILE OPERATING	FORCED OUTAGE
22.01.08	IMPURITY CONTROL					
	DIVERTORS					
	SLOT LINERS, SETS	PERIODIC REPLACEMENT	16	X	-	X
	BOMBARDMENT PLATES	PERIODIC REPLACEMENT	32	X	-	X
	PLATE COOLANT SYSTEM	CLEAN HEAT EXCHANGER	1 SYS	-	X	X
22.01.09	DIRECT ENERGY CONVERTER	(NOT APPLICABLE)				
22.02	MAIN HEAT TRANSPORT SYSTEMS					
22.02.01	PRIMARY COOLANT SYSTEM					
22.02.01.01	PUMPS AND DRIVES	PERIODIC OVERHAUL	9	-	X	-
22.02.01.02	PIPING, CONNECTIONS	NONE	396	-	X	X
	ISOLATION VALVES	INSPECTION	162	-	X	X
	CONTROL VALVES	INSPECTION (REPLACE)	36	X	-	X
22.02.01.03	HEAT EXCHANGER (INTERMEDIATE)	PERIODIC CLEANING	18	-	X	X
22.02.01.04	TANKS	INSPECTION	9	-	X	-
22.02.01.05	CLEAN-UP SYSTEM	INSPECTION	9	-	X	-
22.02.01.06	THERMAL INSULATION	(SEE PIPING, ABOVE)				
22.02.01.07	TRITIUM EXTRACTION	(SEE TRITIUM RECOVERY)				
22.02.02	INTERMEDIATE COOLANT SYSTEM					
22.02.02.01	PUMPS AND DRIVES	PERIODIC OVERHAUL	9	-	X	-
22.02.02.02	PIPING, CONNECTIONS	INSPECTION (RADIATION)	126	-	X	X
	ISOLATION VALVES	INSPECTION	18	-	X	X
	CONTROL VALVES	INSPECTION (REPLACE)	36	X	-	X
22.02.02.03	STEAM GENERATOR	PERIODIC OVERHAUL	9	-	X	-
22.02.02.04	TANKS	INSPECTION	9	-	X	-
22.02.02.05	CLEAN-UP SYSTEM	INSEPCTION	9	-	X	-
22.03	AUXILIARY COOLING SYSTEMS					
22.03.01	MAGNET COOLING					
	H_2 REFRIGERATION SYSTEM	PERIODIC OVERHAUL	1	-	X	-
	N_2 REFRIGERATION SYSTEM	PERIODIC OVERHAUL	1	-	X	-
	PIPING, CONNECTIONS	INSPECTION	360	-	X	X
	TANKS/CONTAINERS	INSPECTION	92	-	X	-
22.03.02	SHIELD COOLING, WATER					
	INNER SHIELD	(SEE PRIMARY COOLANT)				
	OUTER SHIELD (WATER COOLANT)					
	PIPING, CONNECTIONS	INSPECTION (RADIATION)	76	-	X	X
	VALVES, CONTROL	PERIODIC REPLACEMENT	38	X	-	X
	HEAT EXCHANGER	PERIODIC CLEANUP	2	-	X	-
	PUMPS AND DRIVES	PERIODIC OVERHAUL	2	-	X	-
22.03.03	SUPPLEMENTAL HEATING COOLING					
	H_e REFRIGERATION SYSTEM	PERIODIC OVERHAUL	1	-	X	-
	N_2 REFRIGERATION SYSTEM	PERIODIC OVERHAUL	1	-	X	-
	PIPING, CONNECTIONS	INSPECTION	144	-	X	X
	VALVES, CONTROL	INSPECTION	24	X	-	X
	HEAT EXCHANGER	(INCLUDED WITH SHIELD COOLING)				
	PUMPS AND DRIVES (WATER)	(INCLUDED WITH SHIELD COOLING)				
22.03.04	POWER SUPPLY COOLING					
	H_e REFRIGERATION SYSTEM	(WITH SUPPLEMENTAL HEAT, COOLING)				
	N_2 REFRIGERATION SYSTEM	(WITH SUPPLEMENTAL HEAT, COOLING)				
	PIPING, CONNECTIONS	NONE	27	-	X	X
	VALVES	INSPECTION	15	-	X	X
22.04	RADIOACTIVE WATER TREATMENT	(NOT INCLUDED)				

TABLE 4–4
IMS TOKAMAK MAINTENANCE MODES (CONT.)

COST ACCOUNT NUMBER	MAINTENANCE COMPONENT (SUBASSEMBLY)	SCHEDULED MAINTENANCE ACTION	NUMBER OF UNITS (TOTAL)	MAINTENANCE MODE		
				SCHEDULED OUTAGE	WHILE OPERATING	FORCED OUTAGE
22.05	FUEL HANDLING AND STORAGE					
22.05.01	FUEL PURIFICATION SYSTEM	REPLACE PURIFIER		X	-	X
22.05.02	LIQUIDATION	NONE		X	-	X
22.05.03	FUEL PREPARATION	INSPECTION	NOT	X	-	X
22.05.04	FUEL INJECTION	PERIODIC OVERHAUL	DEFINED	X	-	X
22.05.05	FUEL STORAGE/PIPING	INSPECTION		-	X	X
22.05.06	TRITIUM RECOVERY	REPLACE ABSORBERS		-	X	-
22.05.07	EMERGENCY AIR DETRITIATION	(NOT INCLUDED)				
22.06	OTHER REACTOR EQUIPMENT					
22.06.01	MAINTENANCE EQUIPMENT					
	CRANES	ADJUST/LUBE		X	-	X
	OVERHEAD MANIPULATOR	ADJUST/LUBE		X	-	X
	FLOOR MTD. MANIPULATOR	ADJUST/LUBE	SEE	-	X	X
	HEAVY FLOOR MTS. HOIST/MANIP.	ADJUST/LUBE	DETAILED	-	X	X
	SHIELD DOOR RETRACTION SYS.	ADJUST/LUBE	LIST	X	-	X
	COOLANT LINE RETRACTORS	NONE		X	-	X
	TUGS AND DOLLIES	PERIODIC REPLACEMENT		-	X	X
	ENTRANCE AND EGRESS LOCKS	ADJUST/LUBE		-	X	X
22.06.02	SPECIAL HEATING SYSTEMS	(NOT INCLUDED)				
22.06.03	COOLANT STORAGE AND MAKEUP	(NOT INCLUDED)				
22.06.04	GAS SYSTEMS	(NOT INCLUDED)				
22.06.05	BUILDING VENTILATION SYSTEM					
	FANS	LUBRICATION	NOT	-	X	-
	FILTERS AND SCRUBBERS	PERIODIC CLEANING	DEFINED	-	X	-
22.07	INSTRUMENTATION AND CONTROL					
22.07.01	REACTOR I&C EQUIPMENT					
	PROBES (PERFORMANCE MONITORING SYS)	PERIODIC REPLACEMENT		X	X	-
	INTEGRAL INSTRUMENTS (REACTOR STATUS SYS)	REPLACEMENT W/UNIT	NOT DEFINED	X	X	-
	EXTERNAL INSTRUMENTS (PLASMA CONTROL SYSTEM)	PERIODIC OVERHAUL		X	X	-
	CONTROL ROOM EQUIPMENT	CALIBRATION		-	X	-
	COMPUTERS	NONE		-	X	-
22.07.02	RADIATION MONITORING SYSTEM	NONE		X	X	-
22.07.03	ISOLATED GAUGES	(NOT INCLUDED)				

Therefore, when estimating the impact on relative forced outage frequency, as discussed in Sections 4.2.5 and 4.3.5, these differences are considered.

The numerical designation of each subsystem included in Tables 4-2 through 4-4 is taken from Reference 1 which breaks down all reactor systems to a standard set of cost accounts. By this means the breakdown of subsystems is assured to be a reasonably complete listing. All numbers through the third level of detail are included for completeness, even though some subsystems are not applicable to the reactor being defined. Where a more detailed breakout is needed to define major components that will be replaced or repaired or where the replaceable component breakdown disagrees with the cost account list, unnumbered listings are used.

The allocation of components and subsystems to a cost center is straightforward for the tokamak reactor. However, because the TMR consists of many different components with similar functions it was necessary to separate it into two lists, one list for the central cell, and one for the end plug and direct converter region. This procedure permits identification of such systems as the different neutral beam injectors and the different first walls and cooling systems by separate cost center identification. Even with this technique some confusion may arise in interpreting which subsystem applies to a particular maintenance action because of the similarity in nomenclature.

Further definition of some of the TMR central cell components listed in Table 4-2 is given in the following notes. The numbers refer to the cost account numbers listed in the table:

- 22.01.01 - Any wall modifier coating is assumed to be recoated by an internal system without a complete shutdown.
- 22.01.04 - No supplemental heating system is required for the central cell region. However, two neutral beam injectors are included in this region under 22.05.04, one at each end of the central cell, since they are used for tritium fueling. The vacuum and cooling systems for supplemental heating refer to these neutral beam injectors.
- 22.01.05 - Primary structure and supports are assumed to be good for the life of the reactor and should require no maintenance.
- Piping connections include only those on either side of a replaceable unit such as a valve or heat exchanger.

- o Control valves and some isolation valves are assumed to be inside of the reactor enclosure. Wherever possible, valves (and piping connections) are placed outside of the reactor enclosure and, if redundant, can be maintained while the reactor is operating.
- o 22.01.06.01 - The cryopumps for the plasma chamber and for the direct converter (22.01.06.04) are all located in the direct converter chamber discussed as a part of the end plug region. No cryopumps are used in the central cell region.
- o 22.01.07 - Diesel generators are assumed for emergency power to shutdown the plant in the event of a power outage. Estimates of the total electrical cable lengths are only for the cabling located in the reactor room. No data is available to indicate the true dimensions of this cabling.
- o 22.01.06.05 - Two reactor vacuum systems are assumed. The one for the enclosure between the central cell shield and the trench walls is included with the central cell. The other is located in the direct converter chamber and included with the end plug definition.
- o 22.01.08 - No separate impurity control system is required for the TMR.
- o 22.02.01.07 - The tritium extraction system is assumed to be a part of the tritium recovery system. These systems are undefined.
- o 22.02.02 - The intermediate cooling system is located outside of the reactor room and uses a redundant loop to permit maintenance during reactor operation.
- o 22.03.02 - The shield cooling system is assumed to be a part of the primary cooling loop.
- o 22.03.04 - Separate cooling of power supplies is not considered. Such a system would be external to the reactor room and maintenance during reactor operation is assumed feasible. Therefore neither scheduled nor forced outages are affected.
- o 22.04 - Radioactive waste treatment is considered beyond the scope of this study.
- o 22.05.03 - Fuel liquification and preparation beyond recovery and storage are assumed unnecessary because of the gaseous injection system. Any such preparation is included with the recovery system.
- o 22.05.07 - Emergency air detritiation is not defined.
- o 22.06.01 - The maintenance equipment quantities are a variable in the study and are discussed in Section 4.2.4.

- o 22.06.02 through 22.06.05 - These systems are considered outside of the reactor room for the most part and should have little influence on maintainability. Therefore, they have not been defined.
- o 22.07.01 - The reactor instrumentation and control system has not been defined. The maintenance of a typical external instrument is discussed under the specific scenarios and is assumed similar for both TMR and tokamak.

For Table 4-3, which defines the TMR end plug and direct converter systems, many of the foregoing comments are applicable. Some additional considerations are:

- o 22.01.01 - The plug wall, structure and shielding (22.01.02) are considered combined in a series of modules which are all included in this item.
- o 22.01.03 - End plug magnets are considered life of plant items and scheduled maintenance is considered unnecessary.
- o 22.03.01 - The magnet refrigeration system for the central cell magnets is assumed to service the end plug magnets also.
- o 22.03.03 - The cooling systems for supplemental heating are the cooling systems for cryopumps and shielding located in the end plug neutral beam injector.
- o 22.03.05 - Direct converter cooling is required to cool the chamber walls and back plates of the direct converter modules.

Table 4-4 defines the IMS tokamak system. Since there is little duplication of system types in a tokamak only one listing is used. The general comments for the TMR regarding such components as piping and valves apply to the tokamak reactor also. Some additional clarifying notes applicable to the tokamak listing are:

- o 22.01.01 - First wall coating maintenance is assumed to be conducted in a manner similar to recoating the central cell wall of the TMR. The internal system does not require a complete reactor shutdown.
- o 22.01.02 - The number of shield units assumes one primary (inner) shield unit on each removable sector and one secondary (outer) shield unit at each sector door. Shielding integral with the structure is assumed a permanent part of the structure. This permanent shielding is a life of plant item and is assumed to require no maintenance.
- o 22.02.01.07 - The tritium extraction system is assumed to be the same as that required by the TMR and is located outside of the reactor

room. This system is assumed to be redundant and maintained during reactor operation.

- o 22.05 - The fueling system for tokamaks is not defined and, therefore, this system has been omitted from the maintainability analysis.
- o 22.06 - Maintenance equipment maintenance is considered separately as for the TMR. This is discussed in Section 4.3.2.
- o 22.07 - Only the external instrumentation included in the TMR analysis is considered for the tokamak analysis. The remainder of the system is not defined except to assume that redundancy is sufficient to obviate forced outages.

Examination of the component lists for the TMR and tokamak resulted in the selection of critical subsystems for detailed maintenance analysis. The criterion used in selecting subsystems and subsequent maintenance actions applicable to two reactors as different in concept as the TMR and the tokamak is that the selected maintenance actions must define a basis for an objective maintainability comparison. Table 4-5 lists the major considerations leading to the determination of this criterion. As a result, the subsystems to be considered include all of the major reactor subsystems as listed in Table 4-6 for both the TMR and the tokamak reactor systems. It is readily seen that the preponderance of systems for the TMR are in the end plug region while the tokamak systems all are directly associated with the plasma chamber.

When considering the selected subsystems, the maintenance actions deemed most significant for the TMR are those listed in Table 4-7. These are examined in detail in this study.

TABLE 4–5
CONSIDERATIONS IN SELECTING SUBSYSTEMS FOR ANALYSIS

SIGNIFICANT CONSIDERATIONS:

- o SUBSYSTEMS FOR TMR AND TOKAMAK DIFFER SIGNIFICANTLY IN CONCEPT AND TYPE
- o ACCESS TO SYSTEMS FOR MAINTENANCE ALSO DIFFERS SIGNIFICANTLY
- o MAINTENANCE SCHEDULE CRITICAL PATH IS EXPECTED TO INVOLVE MORE THAN ONE SUBSYSTEM
- o TMR HAS MORE SUBSYSTEMS TO BE EVALUATED THAN TOKAMAK

CONCLUSION:

- o A VALID COMPARISON OF MAINTENANCE IMPACTS REQUIRES EVALUATION OF ALL SUBSYSTEMS

TABLE 4–6
PRINCIPAL CANDIDATE SUBSYSTEMS FOR MAINTAINABILITY ANALYSIS

o MAINTAINABILITY ASSESSMENT IS REQUIRED FOR:

TMR SUBSYSTEMS	TOKAMAK
CENTRAL CELL FIRST WALL/BLANKET	FIRST WALL/BLANKET
END PLUG WALL/SHIELD	DIVERTOR PLATES
END PLUG NEUTRAL BEAM INJECTORS	NEUTRAL BEAM INJECTORS
DIRECT CONVERTER GRIDS	CRYOPUMPS
DIRECT CONVERTER CRYOPUMPS	TOROIDAL FIELD MAGNETS
END PLUG MAGNETS	

o ALSO SELECTED COMPONENTS ARE ASSESSED FOR SIGNIFICANT VARIATIONS BETWEEN REACTORS

TABLE 4–7
TMR SELECTED MAINTENANCE ACTIONS

- o CENTRAL CELL FIRST WALL/BLANKET REPLACEMENT
- o NEUTRAL BEAM ION SOURCE REPLACEMENT
- o NEUTRAL BEAM INJECTOR CRYOPUMP REPLACEMENT
- o END PLUG WALL REPLACEMENT
- o DIRECT CONVERTER GRID REPLACEMENT
- o DIRECT CONVERTER CRYOPUMP REPLACEMENT
- o DIRECT CONVERTER CHAMBER WALL COOLING PANEL REPLACEMENT
- o YIN-YANG COIL SET REPLACEMENT

The scenarios defined for each maintenance action include a definition of the procedure used to a third level of detail, or lower if necessary, to establish a basis for a time estimate. The time required to perform each function is then estimated. For consistency, these times are based as much as possible on estimated times required for similar functions in the previous study phases. The major assumptions are listed and the maintenance equipment required is defined. The number of personnel required for direct labor is also estimated.

The detailed scenarios for the TMR and the tokamak are described further in Sections 4.2.1 and 4.3.1, respectively.

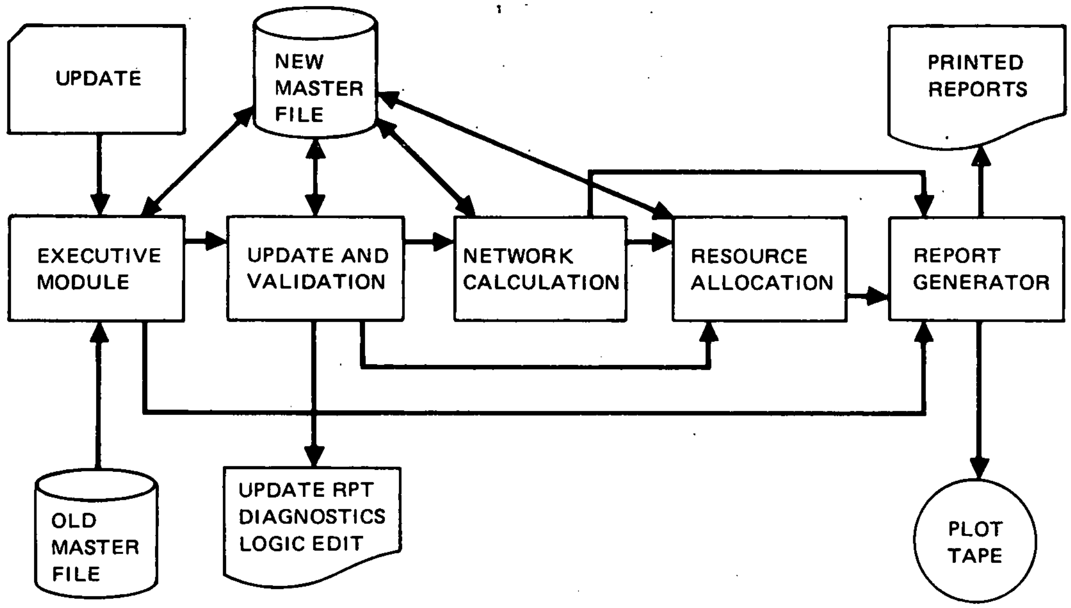
4.1.2 Scheduled Maintenance Plan Development - The individual maintenance action scenarios performed during a nominal scheduled shutdown are combined to determine the total scheduled shutdown time required. These scheduled shutdown periods are examined to determine their relative impacts on the cost of electricity. To do this a fixed maintenance downtime allowance is assumed for forced outages and for balance of plant scheduled maintenance requirements. Subsequent to determining the cost of electricity goals to be used, this fixed allowance is varied as discussed in the next section.

The determination of a scheduled shutdown time requires consideration of both the time needed to conduct the maintenance procedures and requires matching the resources available with those needed by any given maintenance procedure. The minimum downtime is determined by the longest period required by any sequence of maintenance actions that are dependent upon each other. This is the "critical path" and can be quickly and reasonably approximated when resources are unlimited. These critical paths provide a relative basis for comparison of the TMR and the tokamak reactors but the absolute impact of maintenance on the cost of electricity requires consideration of the influence of resources.

To demonstrate the influence of resource limitations on the scheduled outage time, which influences both availability and the cost of electricity, an activity network code was used. This code is titled the "Management Schedule and Control System" (MSCS) and was developed by McDonnell Douglas Automation Company. The MSCS code is similar to the IBM Project Management System IV code used for scheduling maintenance actions in some industries, including utilities. The MSCS code includes a resource allocation module as indicated in the basic flow diagram shown in Figure 4-1. This module reworks the network calculations to schedule activities only when resources are available for them in resource "pools". In the use of the MSCS code, maintenance resources limiting the schedule can be major items of maintenance equipment, personnel, floor space and facility capabilities such as entry and egress ports. In addition to investigating scheduled outage time, this resource analysis can determine specific and optimized requirements for facilities and equipment based on the total cost of electricity. Such an extensive analysis, however, is beyond the scope of this present study.

The cost of electricity for the TMR and tokamak reactors was defined by using the TOCOMO and MICOMO codes, respectively, for each reactor. These codes are system analysis and costing codes developed during earlier studies specifically for the reactor concepts being examined (References 8 and 9).

MSCS BASIC FLOW



13–3175 FROM REFERENCE 7

FIGURE 4–1

4.1.3 Allocation of Forced Outage Goals - COE and/or availability goals are selected in the same manner as during the previous study phase. The sensitivity of both the COE and availability to the days allowed for forced outages is determined when using an optimum scheduled outage scenario. This technique was used for several tokamak reactors during the earlier phase of the study as illustrated by Figure 4-2. In this figure the variation in allowable downtime for forced outages is apparent when a constant COE or availability is selected. A similar plot for the TMR and IMS tokamak is discussed in Section 5.5.

The selected COE goal is determined as one that is as low as possible yet encompasses both reactors, i.e., it allows for a positive value of forced outage time in both reactors. Similarly, the availability goal is selected as one that is acceptable in accordance with today's power plant availability standards, or higher. This has generally been assumed as at least 72%.

Figure 4-2 also indicates that the cost of electricity is highly sensitive to the system availability. In the cases illustrated, a decrease in availability from approximately 76.5% to 72% causes the cost of electricity to increase from 52 mills/kWh to approximately 55.3 mills/kWh for the Culham concept. The Culham concept produces 962 MWe and the cost increase results from the loss in production of 380 GWh/calendar year. To regain this availability a capital cost increase of \$131 $\overline{M}$ could be justified. Because of this sensitivity of COE to a loss in availability and the resultant justification for an increase in capital costs if availability can be

ALLOWABLE UNSCHEDULED DOWN TIME IS DEPENDENT UPON GOALS

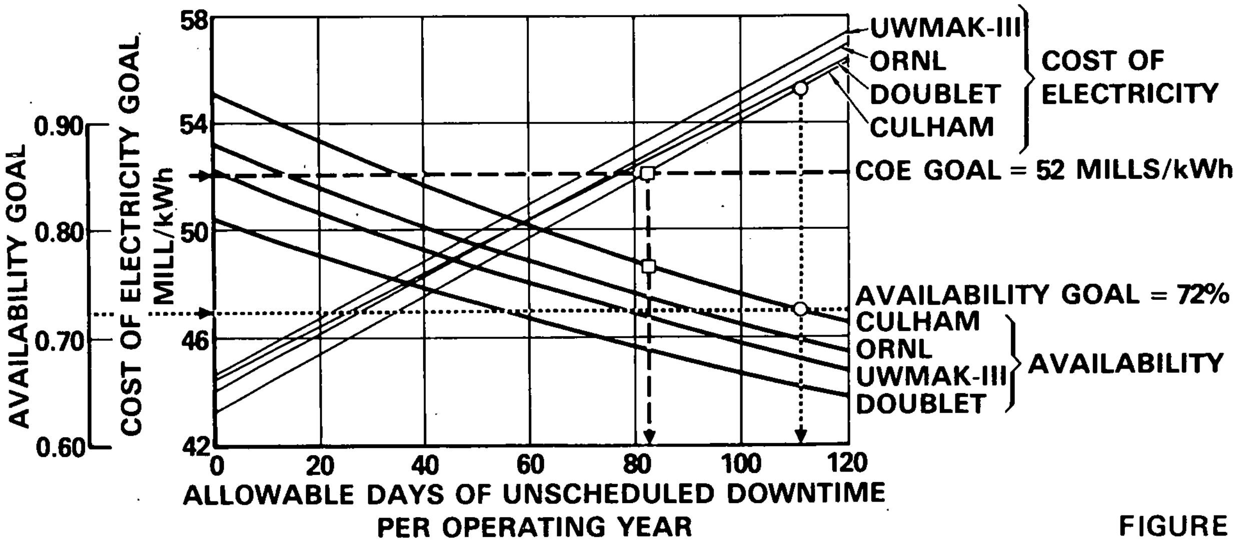


FIGURE 4–2

increased, the use of redundant systems and increased quantity or capability of maintenance equipment has been assumed insofar as possible. Through these means the scheduled maintenance downtime is made as short as possible thereby allowing the maximum time for forced outages by either the TMR or the tokamak reactors.

The relative unavailability allowable for those components which require a forced outage upon failure, as defined in Tables 4-2, 4-3 and 4-4, is determined by assuming failure rates and using these rates to calculate the total forced outage downtime per operating year for each component. This calculation accounts for the downtime per maintenance action, the number of components and an approximate factor for the redundancy defined for the component. In general, redundant systems are only maintained during scheduled outages since the redundancy is assumed to be sufficient to keep the system operating between scheduled outages. However, some exceptions are made where the component redundancy is limited by design. The lack of failure data for newly designed components limits this analysis. Therefore, its use for relative estimates is the most that can be accomplished. Through this process, the total reactor forced outage downtime allowable per operating year can be allocated based on the percentage of forced outage unavailability contributed by each component. The sensitivity of allowable forced outage downtime allocations to both the quantity and the required downtime estimated for each component became evident as a result of making allocations in this manner. Also, the components in the design that may contribute significantly to forced outages became evident and approximate requirements for downtime and failure frequency can be circumvented by emphasis on the maintainability of these components. The details of this approach are discussed for the TMR and the tokamak reactors in Sections 4.2.5 and 4.3.5, respectively.

4.2 TMR MAINTENANCE PLAN - The maintenance plan development discussed in the following sections is for the TMR baseline design concept described in Section 3.2. The details of this maintenance plan must be considered in view of the fact that the baseline design concept is the first relatively complete and coherent design concept defined for the TMR. Revisions in the concept are constantly being made and a revised complete design concept is currently being studied (Reference 6). Several of the maintenance actions for this revised concept have also been examined to serve as a basis for defining trends in TMR maintainability.

4.2.1 Selected Maintenance Action Scenarios - The maintenance actions listed previously in Table 4-7 are defined to the detail considered essential to understand the procedure used. In many cases greater detail was used to determine both the maintenance functions necessary and the time required for each function before summing the time as presented here.

In all scheduled maintenance action scenarios, reactor shutdown and startup is included in the total time. However, in a combined scenario for a scheduled outage these functions would only be accomplished once. The shutdown and startup requirements for the TMR are similar to those for the tokamak in many respects. A brief examination of the time controlling function for shutdown of the tokamak, i.e., removal of afterheat in the first wall/blanket, indicates that this function would also control the shutdown time for the TMR in the absence of more detailed calculations. A similar examination of the startup requirements indicates that the vacuum pumpdown of the TMR would probably be the time controlling function. This is expected to be longer than for the tokamak because of both the larger volume pumped and the reduced conductance through the end plug plasma ports. Therefore, this startup time was increased for the TMR to a total of 36 hours in comparison to the 28 hours defined in the previous study phase for the tokamak reactor.

All time estimates given in this section assume continuous effort is conducted by all personnel engaged in the maintenance action and no allowances have been made for various time dilution factors such as productivity factors or suiting and cleanup delays.

4.2.1.1 Central Cell Sector Replacement - The replacement schedule for a single central cell sector is given in Table 4-8.

TABLE 4–8

SINGLE CENTRAL CELL SECTOR REPLACEMENT
TANDEM MIRROR BASELINE REACTOR (REMOTE OPERATIONS)

LEVEL 1 TASK	LEVEL 2 TASK	DURATION (HRS:MIN)
SHUTDOWN	REACTOR SHUTDOWN	17:00
ACCESS	REMOVE TRENCH COVER	7:00
	CONNECT MAGNET COOLING MODULE	5:55
	DISCONNECT ELECTRICAL AND COOLANT LINES	8:10
	REMOVE INTER-SECTOR SHIELD SEGMENTS	15:30*
REMOVAL	REMOVE CENTRAL CELL SECTOR	4:00
REPLACEMENT	EMPLACE CENTRAL CELL SECTOR	4:30
REASSEMBLY	INSTALL INTER-SECTOR SHIELD SEGMENTS	24:20*
	CONNECT ELECTRICAL AND COOLANT LINES	8:30
	REMOVE MAGNET COOLING MODULE	4:25
	TEST INSTALLATION	2:20
	INSTALL VACUUM TRENCH COVER	7:45
STARTUP	START REACTOR	36:00
	TOTAL:	145:25
	TIME REQUIRED FOR EACH ADDITIONAL SECTOR	54:30

*TIME ESTIMATE IS FOR SECTOR SHIELD SEGMENTS ON BOTH SIDES OF SECTOR. SUCCEEDING SECTORS ONLY REQUIRE REMOVAL OF THE SHIELD SEGMENTS ON ONE SIDE OF THE SECTOR.

The procedure first requires removal of the vacuum trench cover. The trench cover is positioned by location pins and attached to the basic structure of the trench by a latching mechanism that attaches to floor mounted lugs outside of the trench cover seals. This type of mechanism can be disengaged very quickly. An Overhead Manipulator (OHMAN) is used to operate these latches. This OHMAN is installed above the trench by a Central Overhead Crane (COC), as shown in Figure 4-3. The trench cover weight is approximately twice as much as a central cell sector and two Heavy Central Overhead Cranes (HCOC) are provided to remove it. Trench covers can be stacked or placed on the floor beside the trench as shown in Figure 4-4. Figure 4-4 also illustrates a seal welding device that may be used, if required,

OVERHEAD MANIPULATOR

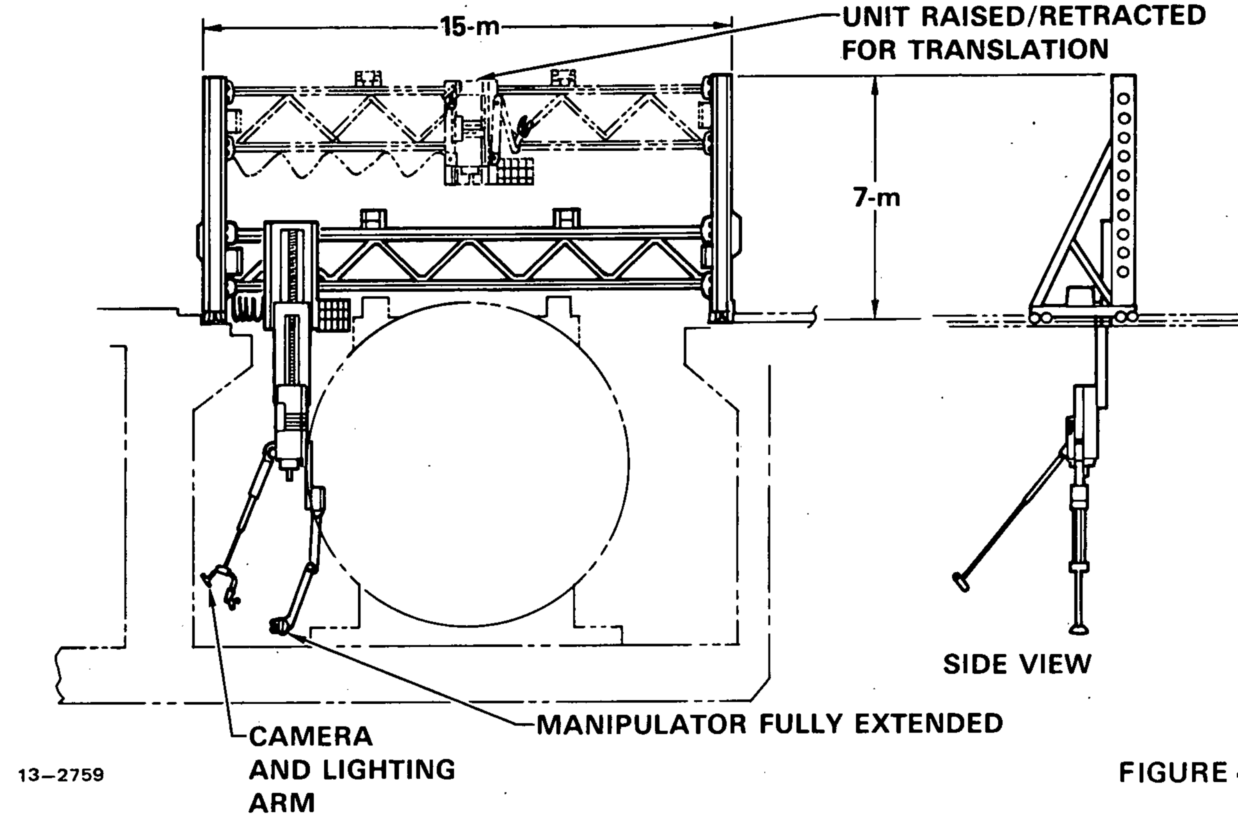


FIGURE 4–3

CENTRAL CELL TRENCH DOOR OPERATIONS

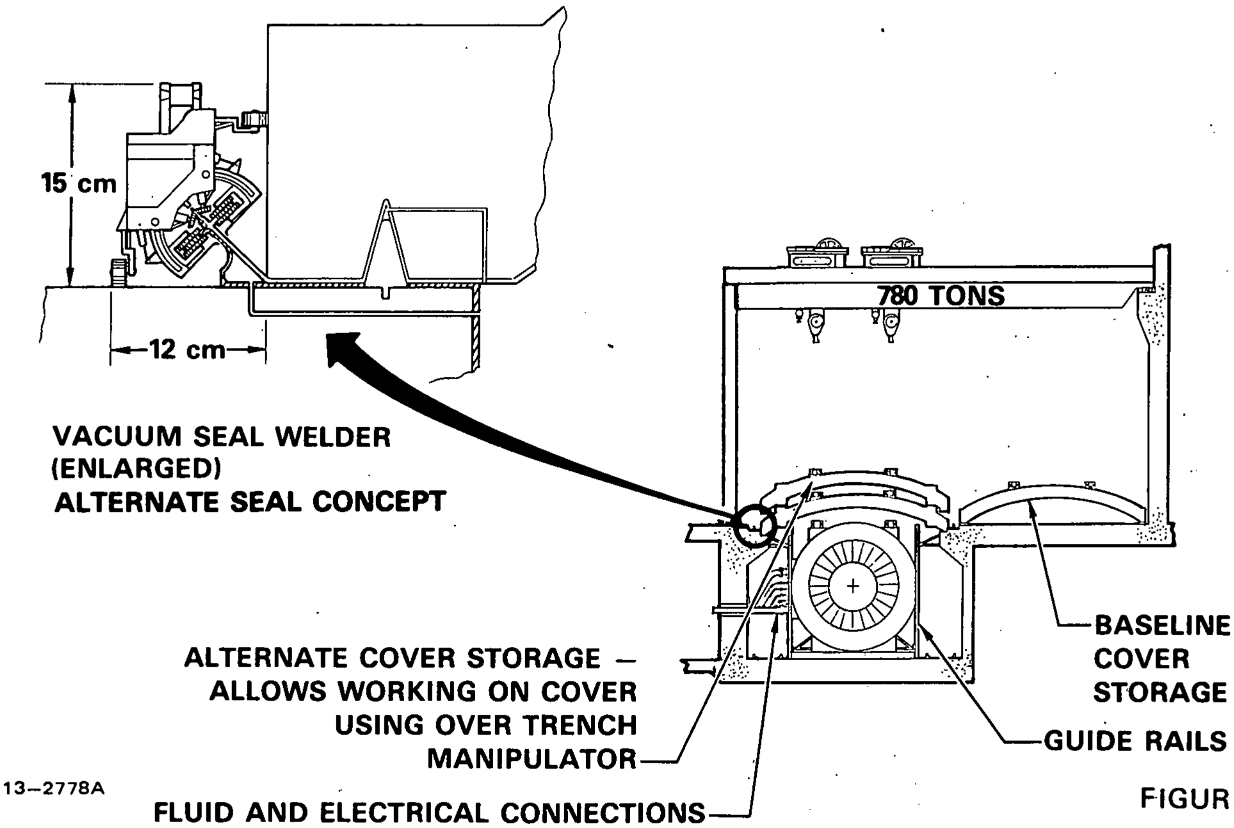


FIGURE 4–4

instead of the mechanical seals. This device is also used for welded seals on the direct converter chamber and neutral beam injectors.

The central cell magnets are integrated with the central cell sectors so that one magnet is removed together with each sector as a single unit. Estimates of the warmup time required by these magnets vary from 14 to 120 days. Therefore, for the purpose of the maintenance plan estimates, it is assumed that the warmup of the magnets must be controlled at a slower rate than is feasible if the residual cryogens in the magnet are merely allowed to boil off. This controlled warmup rate is achieved by installing a magnet cryogenic cooling module on the central cell sector before any cryogen lines are disconnected. In addition to controlling warmup of the magnet, this magnet cooling module is designed to keep the magnet cold indefinitely in the event that the central cell sector is only removed from the reactor for a short time. Also, the magnet cooling module allows the magnet to be chilled before the central cell sector is moved into position, thereby eliminating any cooldown time after the central cell sector is installed in the reactor. The installation of this module is conducted using the OHMAN assisted by the overhead crane. The module then moves with the sector during replacement.

The electrical, vacuum and coolant lines are brought through the side wall of the trench and are disconnected between the trench wall and the central cell sector by the OHMAN.

The shield segments between central cell sectors are removed in the sequence depicted in Figure 4-5. These shield segments are assumed to act as spacers between sectors and are latched in place. The top sector latches are unlatched and then it is removed by the overhead crane. A Trench Robot (TROB) machine is installed on each side of the sector in the trench and the lower sectors are lowered and forced outward by a detachable link. The TROB controls this movement. The overhead crane is attached and the TROB guides the sector as it is lifted from the trench. The removal and installation of these sectors is the longest operation in the central cell sector exchange sequence detachable link. The TROB controls this movement. The overhead crane is attached and the TROB guides the sector as it is lifted from the trench. The removal and installation of these sectors is the longest operation in the central cell sector exchange sequence defined in Table 4-8. Other shield block and spacer designs that are capable of reducing the time required to detach the central cell sectors are discussed in Sections 4.2.6 and 5.9.

Once the shield segments are removed, one HCOC is used to hoist the entire central cell sector clear of the trench, as shown in Figure 4-6, and to place it in

CENTRAL CELL SHIELD SEGMENT REMOVAL

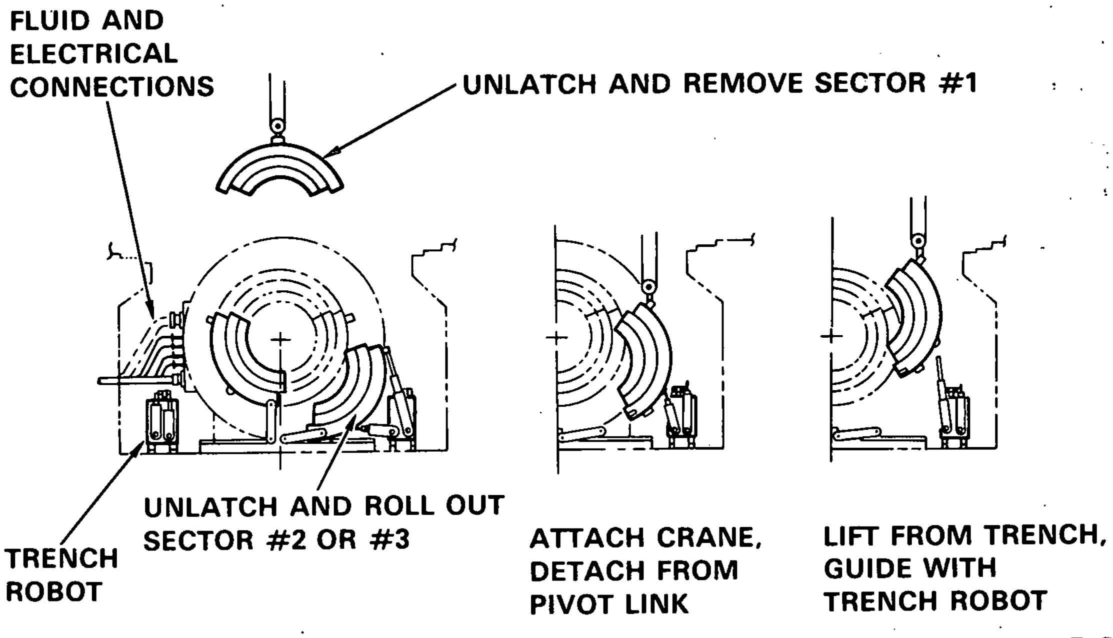


FIGURE 4–5

CENTRAL CELL SECTOR REPLACEMENT

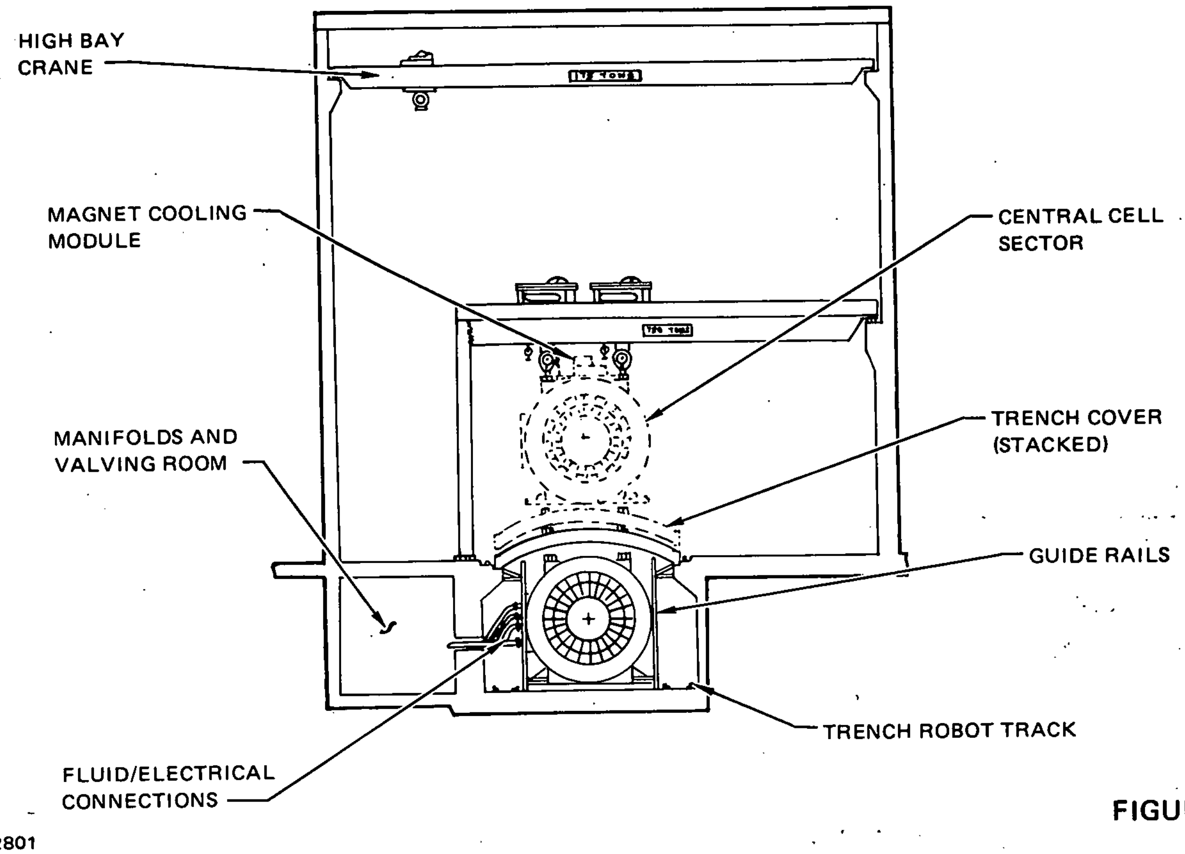


FIGURE 4–6

the central region of the reactor room. The guide rails indicated in Figure 4-6 are assumed to be permanently in place. A detailed study is required to establish the need for these guide rails. The procedure defined in Table 4-8 assumes that all first wall/blanket module replacement in a sector is conducted outside of the reactor room in a hot cell and that a spare sector is available.

4.2.1.2 Neutral Beam Ion Source Replacement - The replacement schedule for the neutral beam ion source in the 1.2 MeV end plug neutral beam injector (NBI) is defined in Table 4-9. This NBI is described in Section 3.2.5.

TABLE 4–9
1.2 MeV NEUTRAL BEAM INJECTOR ION SOURCE REPLACEMENT
TANDEM MIRROR BASELINE REACTOR (REMOTE OPERATIONS)

LEVEL 1 TASK	LEVEL 2 TASK	DURATION (HRS:MIN)
SHUTDOWN	REACTOR SHUTDOWN	17:00*
ACCESS	UNSEAL NBI ACCESS DOOR	6:40
	DISCONNECT ACCESS DOOR SERVICES	2:40
	REMOVE ACCESS DOOR	10:20
	INSTALL NBI MANIPULATOR	3:00
	DISCONNECT ION SOURCE SERVICES	10:40
REMOVAL	REMOVE ION SOURCE MODULE	8:00
REPLACEMENT	EMPLACE ION SOURCE MODULE	6:30
REASSEMBLY	CONNECT ION SOURCE SERVICES	18:20
	REMOVE NBI MANIPULATOR	3:30
	INSTALL NBI ACCESS DOOR	13:40
	SEAL ACCESS DOOR	6:40
	TEST ACCESS DOOR SEAL	6:30
	CONNECT ACCESS DOOR SERVICES	4:00
	TEST NBI INSTALLATION	8:00
STARTUP	REACTOR STARTUP	36:00*
	TOTAL:	161:30

*DELETE FOR SCHEDULED MAINTENANCE. ASSUME COMPLETED FOR CENTRAL CELL MAINTENANCE.

The approach to gaining access to the ion source assumes that the ion source and the high voltage grids which surround it are replaced as a single module. The cesium plasma stripping cell and its associated high voltage grids make up another module which can be replaced. Access to these modules is achieved by removing the entire side panel of the NBI housing, including the shielding and one half of the vacuum cryopump panels. This exposes the ion source module and all other internal equipment of the NBI system, as shown in Figure 4-7. By removing the side panel, both the vertical and horizontal NBI systems can be serviced in the same manner and with the same equipment.

NEUTRAL BEAM INJECTORS—GENERAL ARRANGEMENT

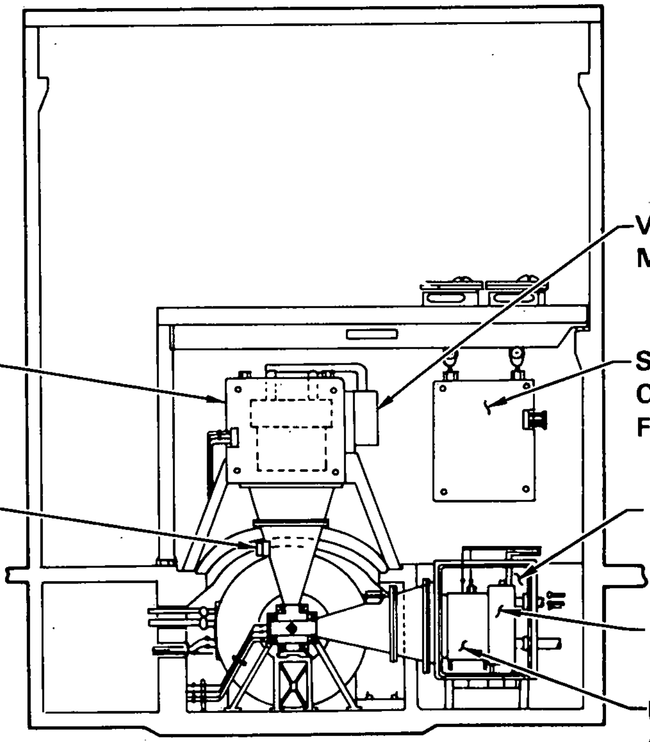


FIGURE 4–7

The NBI side panel is removed by cutting the welded seal and disconnecting all services to the attached cryopumps. A Heavy Central Overhead Crane (HCOC) is attached to the side panel and the fasteners are disconnected by an overhead manipulator (OHMAN). The panel is moved laterally to clear the cryopump panels and then vertically to give access. A dolly or other fixture can be used for temporary storage to clear the crane for other duties.

The ion source removal operations are conducted by an NBI Manipulator (NBIMAN) which is attached to the NBI housing frame by a Light Central Overhead Crane (LCOC) and an OHMAN as shown in Figure 4-8. This manipulator provides support for the ion source module during the removal operations and disconnects all services to the module. The module is withdrawn laterally from the NBI housing to a point where the crane can be attached. The module is then lifted clear of the NBI housing.

NEUTRAL BEAM INJECTOR ION SOURCE REPLACEMENT
Vertical NBI

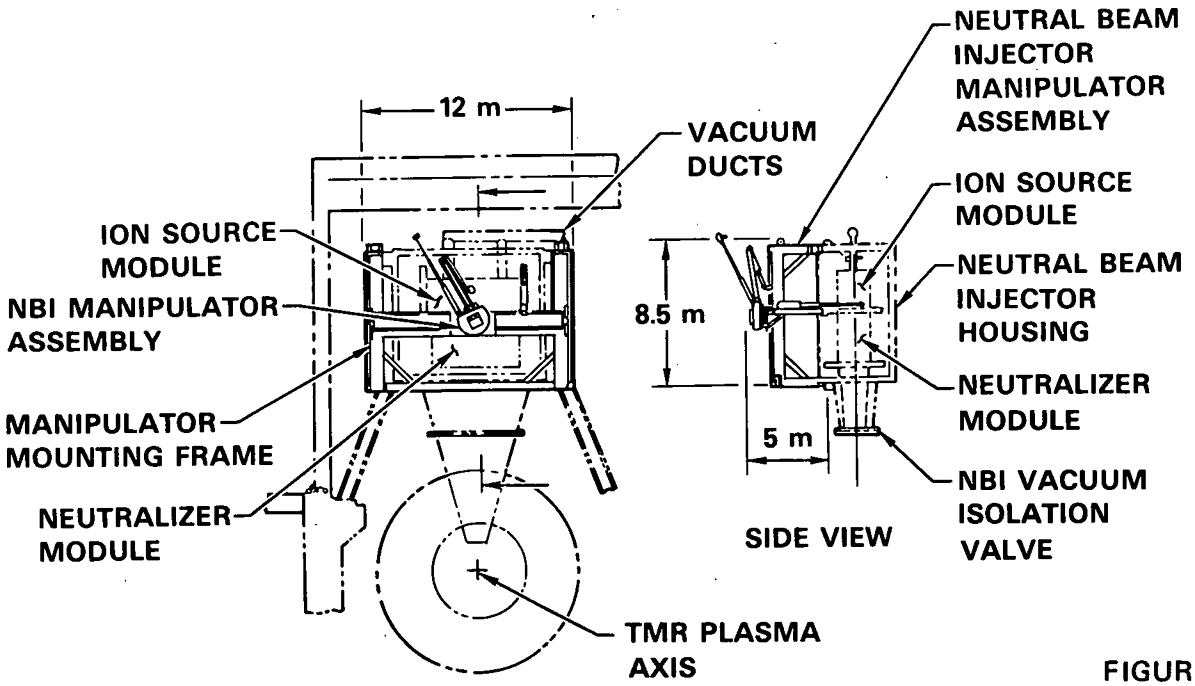


FIGURE 4–8

13–2798

Installation of the replacement module is essentially the reverse of the foregoing procedure except for additional testing to assure that all connections are satisfactory and that a valid vacuum seal exists.

4.2.1.3 Neutral Beam Injector Cryopump Replacement - The replacement of the NBI cryopumps is conducted in the same manner as the first and last part of the NBI ion source replacement procedure defined in Table 4-9. This procedure includes removal and installation of the NBI side panel which requires a total of 58.5 hours, not including reactor shutdown or startup.

Both side panels of the NBI housing are removable and one half of the cryopump panels are attached to each side. Therefore, the side panels and associated cryopump panels are removed and reinstalled as a unit. Since only one half of the cryopump panels are removed and reinstalled during ion source replacement, the other NBI side panel must be removed to replace the other half of the cryopump panels. It is assumed that a set of complete side panels, including shielding, is included as spares for replacement of the cryopump panels. An alternate procedure could replace only the cryopump panels by removing them from the door while in the reactor room, if the downtime allowed and equipment is available, thus reducing the need for spare side panels.

4.2.1.4 End Plug First Wall/Shield Replacement - The replacement schedule for the first wall/shield modules in the end plug region is summarized in Table 4-10. This schedule applies to the first wall/shield module configuration described in

Section 3.2.4. Table 4-10 indicates the sequence required to remove all modules in series but several variations in this sequence are possible, depending upon the modules to be removed and the equipment available. The module numbers refer to the numbering defined in Figure 3-5.

TABLE 4–10
END PLUG FIRST WALL/SHIELD REPLACEMENT
TANDEM MIRROR BASELINE REACTOR (REMOTE OPERATIONS)

LEVEL 1 TASK	LEVEL 2 TASK	DURATION (HRS:MIN)
SHUTDOWN	REACTOR SHUTDOWN	17:00*
ACCESS	REMOVE VACUUM TRENCH COVER	7:00*
	REMOVE SHIELD SEGMENTS BETWEEN MODULES #1 AND #2	10:30
	SEPARATE MODULES #2, #3 AND #4 FROM #5	3:45
REMOVAL	REMOVE MODULE #5	4:40
	REMOVE MODULES #6 AND #7	9:20
	REMOVE YIN-YANG MODULE #8	7:10
	REMOVE MODULES #4, #3 AND #2	13:20
	REMOVE MODULE #1	7:10
	REMOVE END VACUUM TRENCH COVER	7:45
	REMOVE SHIELD SEGMENTS BETWEEN MODULES #11 AND #12	10:30
	REMOVE MODULE #12	1:20
	REMOVE MODULES #11 AND #10	9:20
	REMOVE YIN-YANG MODULE #9	7:10
REPLACEMENT	REPLACE YIN-YANG MODULE #9	11:50
	REPLACE MODULES #10 AND #11	12:40
	REPLACE MODULE #12	18:00
	REPLACE END VACUUM TRENCH COVER	13:15
	REPLACE YIN-YANG MODULE #8	11:50
	REPLACE SHIELD MODULES #7, #6 AND #5	19:00
	REPLACE SHIELD MODULE #1	16:00
	REPLACE SHIELD MODULES #2, #3 AND #4	19:00
REASSEMBLE	REPLACE INTER MODULE SHIELD SEGMENTS	16:00
	INSTALL VACUUM TRENCH COVER	12:00*
STARTUP	REACTOR STARTUP	36:00*
	TOTAL:	301:35

* DELETE FOR SCHEDULED MAINTENANCE.
ASSUME COMPLETED FOR CENTRAL CELL MAINTENANCE.

The general approach to disassembly and removal of the modules is to work from both sides of the end plug solenoid coils, first opening up a sufficient gap to move the modules laterally. This is accomplished by removing a shield ring from between modules number 1 and 2 and from between modules number 11 and 12. The shield rings are similar to the central cell shield segments shown in Figure 4-5. The lateral movement of the modules disengages the nested joint between all other modules. Once the joint is disengaged at those modules which can be raised directly by the HCOC (numbers 5 and 12) they are removed. Space is thereby provided to move all other modules laterally until they are accessible to the HCOC. Lateral movement of the modules is accomplished with the aid of gas bearings.

The lateral movement of the modules is accomplished by using a pair of Shielding Manipulators (SHMAN), one located on a track on each side of the first wall/shield modules. Figure 4-9 illustrates the concept of the manipulator and its operating locations with respect to the first wall/shield modules. These manipulators are anchored to the side tracks and use extendable actuators to move the modules laterally. The power and the compressed air necessary for this operation are provided through the mounting pedestals from outside sources.

Because the first wall neutron and thermal loading in the plug region and in the region between the plug and the central cell is expected to be greater than the loading the in the region toward the direct converter chamber, the time to replace

END PLUG WALL/SHIELD REPLACEMENT

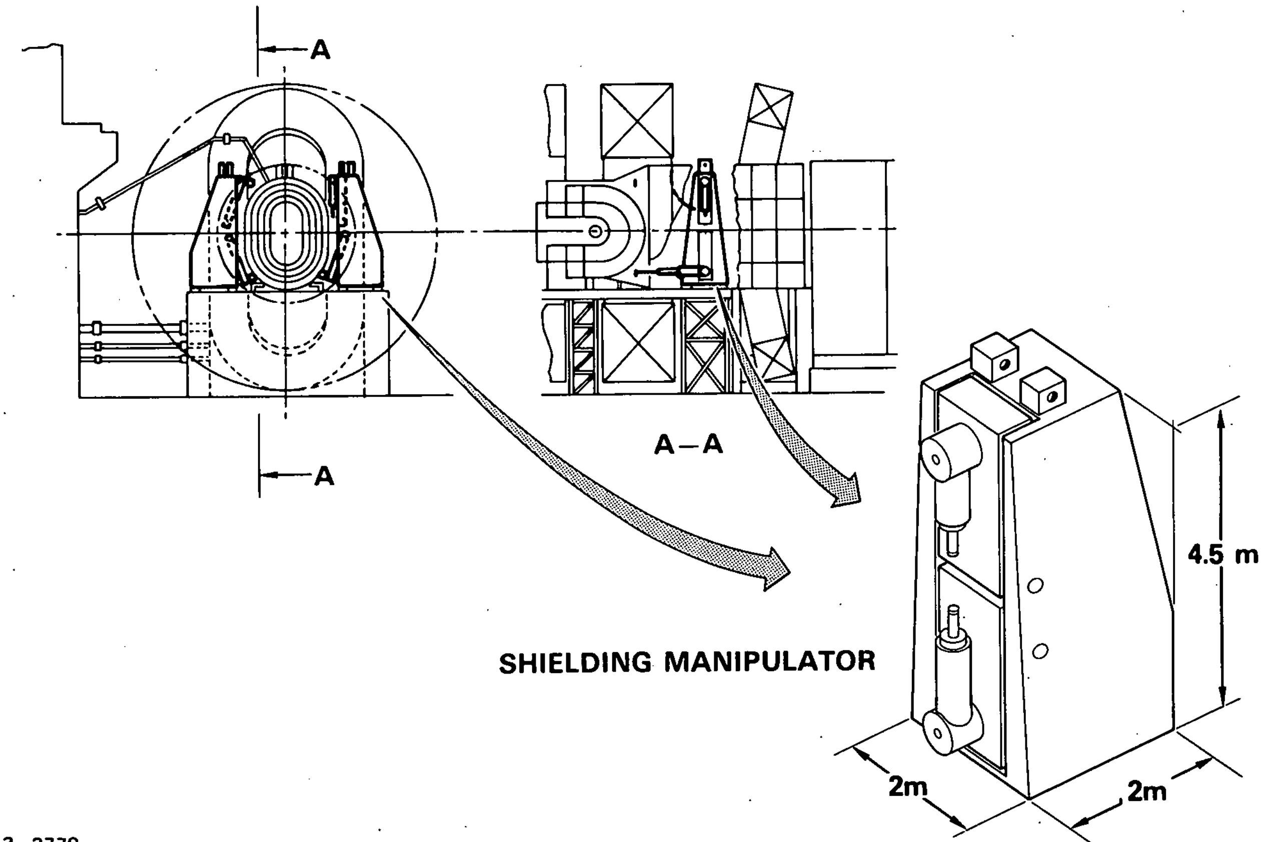


FIGURE 4–9

only the first wall/shield modules in the Yin-Yang coil set and the time to replace only the modules between the Yin-Yang and the central cell are of interest. These times are derived from Table 4-10 and are 193:50 hours and 144:45 hours, respectively. The time for replacement of the Yin-Yang modules (modules number 8 and 9) includes removal and replacement of the trench covers but does not include reactor shutdown and startup. The same conditions apply to the time for replacement of all modules between the Yin-Yang coils and the central cell (modules number 1 through 8).

4.2.1.5 Direct Converter Grid Replacement - The replacement schedule for the direct converter grid modules is defined in Table 4-11. The module configuration is

TABLE 4–11
DIRECT CONVERTER GRID REPLACEMENT
TANDEM MIRROR BASELINE REACTOR (REMOTE OPERATIONS)

LEVEL 1 TASK	LEVEL 2 TASK	DURATION (HRS:MIN)
SHUTDOWN	REACTOR SHUTDOWN	17:00
ACCESS	EMPLACE OVERHEAD MANIPULATOR	1:30
	REMOVE CENTER ACCESS COVER	17:00
	(REMOVE SIDE ACCESS COVER)	16:00*
	DISCONNECT GRID MODULE SERVICES	3:50
REMOVAL	REMOVE GRID MODULE TO STORAGE RACK	2:30
	(REMOVE GRID MODULE UNDER DOOR BEAM TO RACK)	3:30*
REPLACEMENT	EMPLACE GRID MODULE IN DIRECT CONVERTER	3:30
	(EMPLACE UNDER DOOR BEAM GRID MODULE)	4:30*
REASSEMBLE	CONNECT GRID MODULE SERVICES	5:10
	LEAK CHECK COOLANT LINES	2:00
	INSTALL CENTER ACCESS COVER	27:05
	(INSTALL SIDE ACCESS COVER)	24:35*
	LEAK CHECK VACUUM SEALS (ONE COVER)	8:00
	REMOVE OVERHEAD MANIPULATOR	3:00
STARTUP	STARTUP REACTOR	36:00
	TOTAL TIME FOR ONE MODULE	126:35
	TIME FOR EACH ADDITIONAL MODULE	17:00
	TOTAL TIME FOR ALL MODULES	446:45**

*NOT INCLUDED IN TOTAL.
USED WHERE APPROPRIATE WHEN REPLACING MODULES UNDER SIDE COVERS AND UNDER SUPPORT BEAMS.

**ASSUMES ALL MODULES REPLACED IN SERIES. PARALLEL OPERATIONS CAN BE CONDUCTED. EMPLACEMENT AND REMOVAL OF THE OVERHEAD MANIPULATOR IS CONDUCTED ONLY ONCE.

described in Section 3.2.5. Each module supports 40 sets of collector vanes and associated grid wires which then requires a total of 17 modules for the entire direct converter. The number of modules is based on an estimated size that provides convenient handling and requires only a nominal number of spares.

Figure 4-10 illustrates the general arrangement of the three access doors and the location of the grid module repair station. The overhead manipulator (OHMAN) used for this maintenance action is of the same design as shown in Figure 4-3. The door seal welds are cut and rewelded using the general approach for cutting and welding shown for the trench doors in Figure 4-4. Welded seals are assumed since only one vacuum barrier exists in this region. The light cranes are of the same capacity as the LCOC and are capable of lifting the access doors.

DIRECT CONVERTER GRID REPLACEMENT

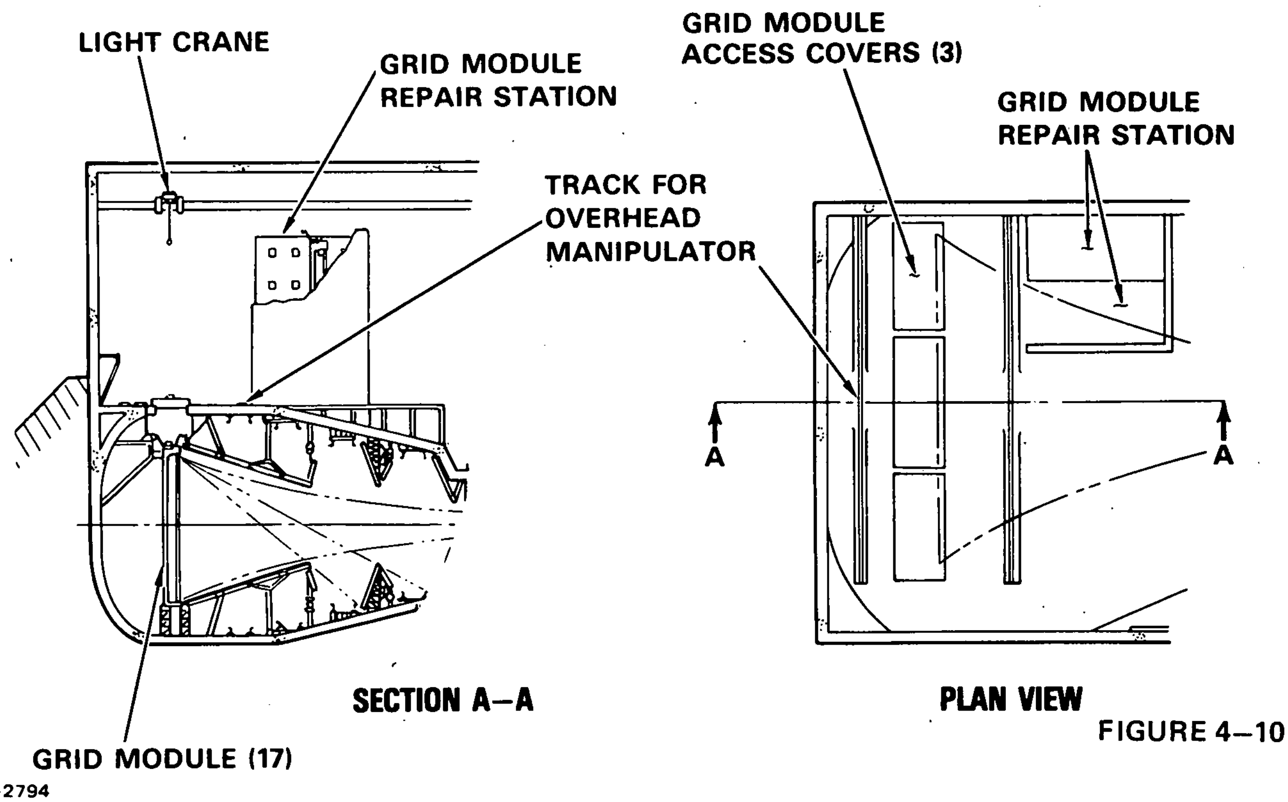


FIGURE 4–10

All module service connections for coolant and power are located at the top of each module and are accessible from the opening in the chamber when the appropriate door is removed. All structural attachment bolts are also accessible from this opening at the top of the module. The module is located at the base by locator pins but no service attachments are required at the base. The modules are assumed to be activated by neutron streaming and, therefore, all operations subsequent to removal of the access doors are fully remote.

The replacement of more than one module involves several additional considerations as indicated in Table 4-11. Those modules located under the access cover cross support beams can only be replaced while an adjacent module in the center section is removed. This operation also requires an additional 2:00 hours per module because of the more complex movements required. The total time given for replacement of all modules allows for time to install and remove the OHMAN located on the tracks above the direct converter only once and assumes that all modules are removed in series. This time can be reduced by the use of parallel operations and additional maintenance equipment without increasing the facilities required. The minimum replacement time will approach the time required for replacement of the seven modules in the central grid zone which is 179:35 hours.

4.2.1.6 Direct Converter Cryopump Replacement - The replacement schedule for the direct converter cryopump panels is delineated in Table 4-12. The cryopumps are made up of 50 panels in each direct converter chamber and are located as discussed in Section 3.2.7. Each panel is 2 m x 4 m for a total of 400 m^2 in each direct converter chamber.

Figure 4-11 shows the access door to the direct converter compartment. This door is located in a trench at the side of the main reactor trench and is a vacuum barrier between reactor room pressure and the direct converter chamber. All equipment and all cryopump panels are lowered to this level by the LCOC.

Figure 4-12 illustrates the arrangement of both the cooling panels for the direct converter chamber wall and the cryopump panels. The maintenance equipment used is also illustrated. To gain access to the panels the chamber door seal is cut and the door removed by use of the HCOC and stowed along the trench wall. The door seal is welded because this is the only vacuum seal between the reactor room atmosphere and the direct converter chamber. A horizontal door in the reactor room floor may be used to obviate the problem of passing the tracks for a vehicle through the vertical door opening.

The replacement procedure is initiated by installing the Direct Converter Transporter (DCTRAN) on the access tracks with a Direct Converter Manipulator (DCMAN) and a piece of elliptical track mounted on it. The transporter is moved into the chamber to the circumferential track on which the DCMAN is to be installed. The elliptical track segment is latched in position with the DCMAN installed on it. The DCMAN can then move to any panel position around the periphery of the direct

TABLE 4–12
DIRECT CONVERTER CRYOPUMP REPLACEMENT
TANDEM MIRROR BASELINE REACTOR (REMOTE OPERATIONS)

LEVEL 1 TASK	LEVEL 2 TASK	DURATION (HRS:MIN)
SHUTDOWN	REACTOR SHUTDOWN	17:00
ACCESS	INSTALL OVERHEAD MANIPULATOR OVER ACCESS DOOR	1:30
	UNSEAL ACCESS DOOR	7:50
	DETACH AND STOW ACCESS DOOR	9:10
	INSTALL DIRECT CONVERTER TRANSPORTER ON TRACKS	2:00
	INSTALL DIRECT CONVERTER MANIPULATOR IN CHAMBER	3:15
	(INSTALL ADDITIONAL DC MANIPULATOR IN CHAMBER)	5:15*
REMOVE	DETACH CRYOPUMP PANEL	6:40
	TRANSFER PANEL TO TRANSPORTER	2:30
	MOVE PANEL TO DOLLY	2:30
REPLACE	EMPLACE REPLACEMENT PANEL ON TRANSPORTER	2:30
	MOVE REPLACEMENT PANEL INTO POSITION	4:30
	INSTALL REPLACEMENT PANEL	12:20
REASSEMBLE	REMOVE DC MANIPULATOR FROM CHAMBER	4:00
	(STOW ADDITIONAL DC MANIPULATOR ON DOLLY)	6:30*
	STOW DC TRANSPORTER ON DOLLY	2:30
	CLOSE AND FASTEN ACCESS DOOR	13:50
	SEAL ACCESS DOOR	13:35
	LEAK CHECK DOOR SEAL	8:00
	REMOVE OVERHEAD MANIPULATOR	3:00
STARTUP	STARTUP REACTOR	36:00
	TOTAL FOR ONE PUMP PANEL:	152:40
	TOTAL FOR EACH ADDITIONAL PUMP PANEL IN SAME RING:	31:00**

*NOT INCLUDED IN TOTAL. REQUIRED WHEN REMOVING PANELS IN BOTH RINGS.

**FOR MULTIPLE PANELS ASSUME TRANSPORTER CARRIES ONE PANEL PER DC MANIPULATOR INSTALLED. TIME PER PANEL = 31:00 HOURS PLUS 4.5 HOURS PER DC MANIPULATOR STAGGERED IN SEQUENCE FOR PANEL PICKUP AND DELIVERY.

converter chamber within reach of that track. Panel replacement does not require removal of the DCMAN since the new and old panels are transported in and out of the chamber on a fixture attached to the DCTRAN. Movement of equipment and panels in and out of the trench is by means of the LCOC.

DIRECT CONVERTER CHAMBER ACCESS

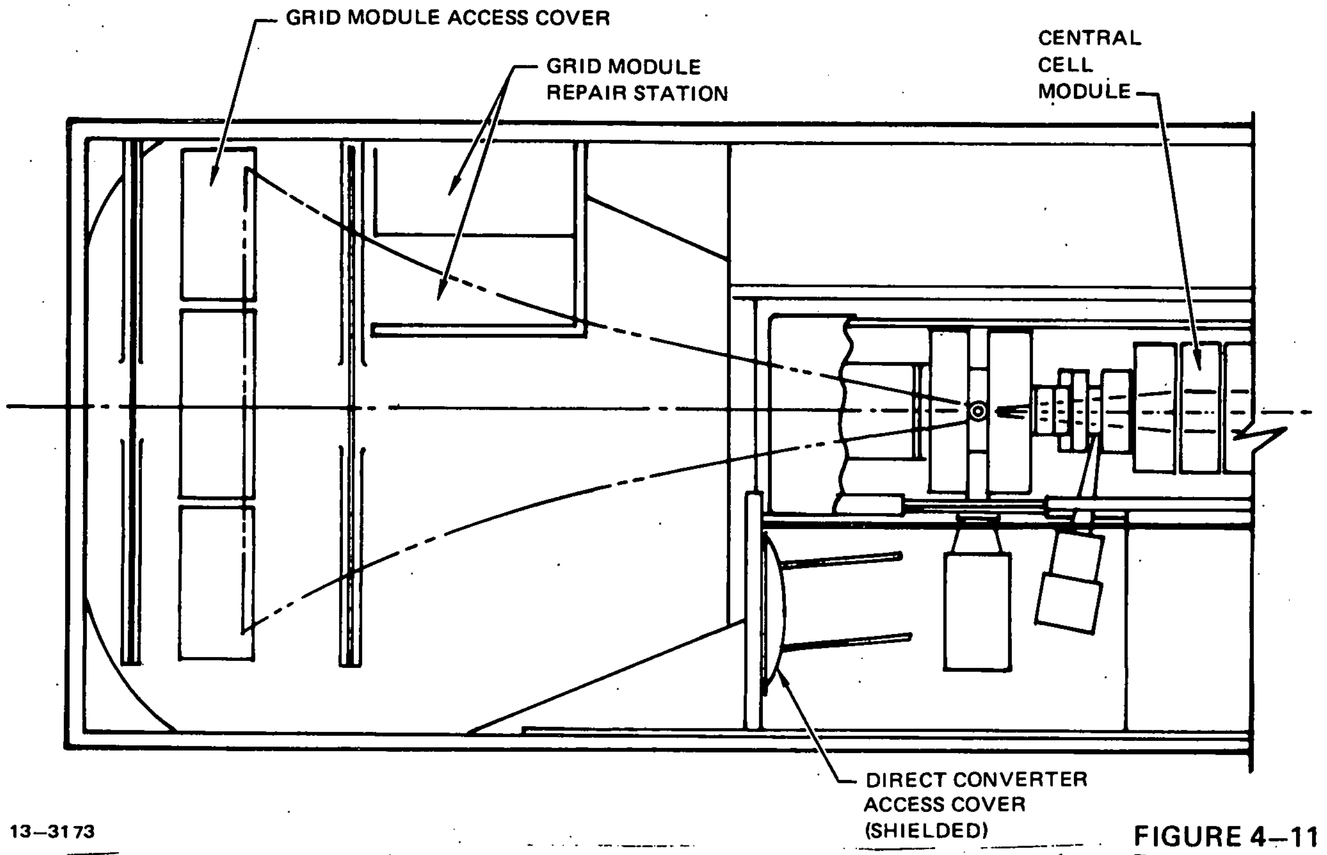
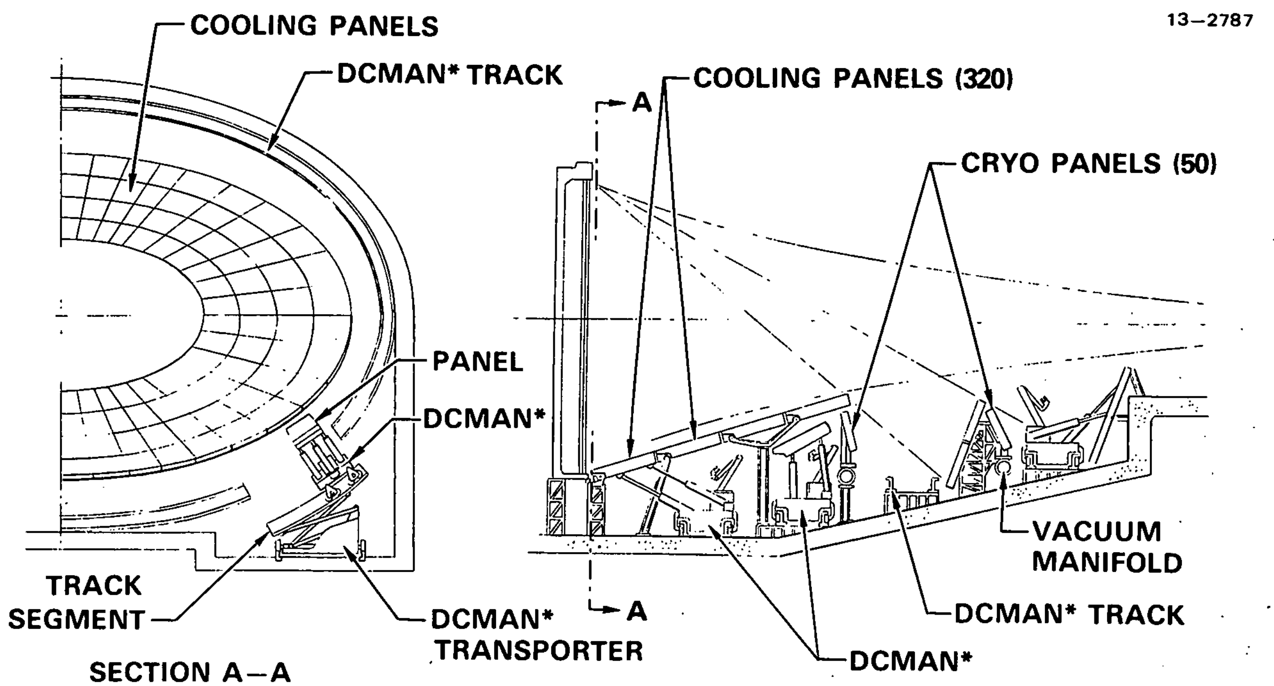


FIGURE 4–11

DIRECT CONVERTER CRYOPUMP AND COOLING PANEL REPLACEMENT



*DIRECT CONVERTER MANIPULATOR (DCMAN)

COOLING PANELS 2 m x 4 m
CRYOPUMP PANELS 2 m x 4 m

FIGURE 4–12

For replacement of multiple panels, additional DCMAN's are installed on the required tracks. It is anticipated that two can be installed on each elliptical track if required by the number of panels to be replaced. The optimum number depends upon the capability of the transporter to service these manipulator vehicles. The replacement time required for all 50 cryopump panels in one direct converter chamber using just one DCMAN is estimated at 1623 hours. This time is for a series operation and indicates the need for multiple pieces of maintenance equipment to conduct as many parallel operations as possible. This time also indicates the requirement for better access to such panels and the need to avoid installing systems such that they must be removed from within a constrained access space.

4.2.1.7 Direct Converter Chamber Wall Cooling Panel Replacement - The replacement of cooling panels which protect the direct converter chamber wall is conducted by use of similar procedures and the same equipment provided for replacement of the cryopump panels, see Figure 4-12. However, the time required to replace a panel differs, primarily because only the water coolant lines and structural fasteners must be disconnected instead of cryogen lines, the vacuum regeneration duct and shutter control circuits. Access to the chamber and the installation of equipment require the same time unless more DCMAN's are required to access the panels being replaced. To reach all wall cooling panels, four tracks are required instead of the two required to service the cryopump panels. The replacement schedule for the cooling panels is defined in Table 4-13.

4.2.1.8 Yin-Yang Coil Set Replacement - The removal and replacement of the Yin-Yang coil set is defined to provide a comparison with the replacement of a toroidal field coil in the tokamak reactor. The Yin-Yang magnets were chosen because their replacement is assumed to be the most time consuming. Also, access to the Yin-Yang coils appears to be more difficult than access to the other coils in the end plug region even though their weight is much less than the weight of the solenoid coils. It is assumed that the weight of the Yin-Yang coil set is within the 700 tonne capacity of the HCOC. The replacement schedule is defined in Table 4-14.

The procedure used for this maintenance action requires gaining access to the Yin-Yang coil set from both sides and within the bore of the solenoid coils. Removal of the end plug first wall/shield modules number 5 through 12 is accomplished as described in Section 4.2.1.4 and Table 4-10. The cryogen cooling lines, power leads, instrumentation and structural attachments are then accessible. The Yin-Yang coil set is assumed to be supported by the same structural base as the end plug

TABLE 4-13

DIRECT CONVERTER COOLING PANEL REPLACEMENT
TANDEM MIRROR BASELINE REACTOR (REMOTE OPERATIONS)

LEVEL 1 TASK	LEVEL 2 TASK	DURATION (HRS:MIN)
SHUTDOWN	REACTOR SHUTDOWN	17:00
ACCESS	OPEN CHAMBER, INSTALL EQUIPMENT (SEE TABLE 4-12)	23:45
REMOVE	DETACH COOLING PANEL	5:00
	TRANSFER COOLING PANEL TO DOLLY	5:00
REPLACE	MOVE REPLACEMENT PANEL INTO POSITION	7:00
	INSTALL REPLACEMENT PANEL	7:50
REASSEMBLE	REMOVE EQUIPMENT, CLOSE CHAMBER AND TEST (SEE TABLE 4-12)	44:55
STARTUP	STARTUP REACTOR	36:00
	TOTAL FOR ONE COOLING PANEL	146:30
	TOTAL FOR EACH ADDITIONAL PANEL IN SAME RING	24:50

first wall/shield modules. Both coils are handled as a unit until clear of the reactor room. Therefore, when the structural attachments are released, the gas bearings are activated and the shielding manipulators that are used to move the end plug first wall shield modules are also used to move the Yin-Yang coil set to the direct converter side of the solenoid coils. At this point there is sufficient space made available by the removal of the first wall/shield module number 12 to lift the coils from the reactor using the HCOC.

While only one set of equipment was used for the end plug first wall/shield replacement procedure defined in Section 4.2.1.4 two overhead manipulators are utilized with the Yin-Yang coil replacement procedure. The first wall/shield modules are still removed and replaced in series because only one crane is considered available. However, both overhead manipulators are used to disconnect the Yin-Yang coils.

4.2.1.9 End Plug Solenoid Coil Replacement - The end plug solenoid coils are estimated to weigh 1700 tonnes, including integrated supporting structure. The handling and installation requirements for these coils were briefly examined. The coil mass is such that is impractical to size the overhead cranes for this load alone. Therefore, the assumed method for replacement is to dismantle a section of

TABLE 4–14

YIN YANG COIL SET REPLACEMENT
TANDEM MIRROR BASELINE REACTOR (REMOTE OPERATIONS)

LEVEL 1 TASK	LEVEL 2 TASK	DURATION (HRS:MIN)
SHUTDOWN	SHUTDOWN REACTOR	17:00
ACCESS	REMOVE VACUUM TRENCH COVERS*	14:45
	REMOVE WALL/SHIELD MODULES #5 THROUGH #12 (SEE TABLE 4-10)	63:45
REMOVE	REMOVE YIN-YANG COIL SET	19:10
REPLACEMENT	REPLACE YIN-YANG COIL SET	24:20
REASSEMBLY	INSTALL WALL/SHIELD MODULES #5 THROUGH #12 (SEE TABLE 4-10)	89:20
	REPLACE VACUUM TRENCH COVERS*	25:15
STARTUP	STARTUP REACTOR	36:00
	TOTAL:	289:35

* TWO TRENCH COVERS ARE REMOVED INITIALLY AND TWO OVERHEAD MANIPULATORS USED WHEN MINIMUM TIME IS REQUIRED. (SEE TABLE 4-10)

the side wall and remove each coil by first translating it axially to clear the Yin-Yang coils and then laterally through the gap in the side wall. Gas bearings are provided in the coil support to aid in moving the coil.

Removal from the trench, however, only solves the problem of removal from the reactor. Substitution of a replacement coil or rewinding of the coil requires additional space in the building beside the trench to install a magnet winding and case buildup facility. Rewinding the magnet to be repaired or to assembling a replacement magnet would be accomplished on site. Transportation of 1700 tonne structure to a location elsewhere in the plant or to a separate assembly plant would require a highly specialized and expensive capability.

An alternate approach would be to make up each solenoid magnet as three sandwich magnets, installed side by side in a common dewar but structurally independent. The feasibility of such a design to provide the required field strength must be investigated. The advantage of this type of alternate design is that each element of the sandwich can be disconnected and removed by lifting vertically from the trench using the 700 tonne capacity overhead crane. Reworking the magnet could then be accomplished either elsewhere in the power plant facility or in a separate plant if transportation is available. Movement of structures of this size is more readily accomplished than movement of the 1700 tonne single solenoid.

4.2.2 Maintenance Equipment Outage Scenarios - Several unique items of equipment which have been delineated in the preceding section are required to conduct the maintenance actions. The most important of these maintenance equipment items are listed in Table 4-15. The principal maintenance actions for which they are designed are also indicated. These equipment items have been selected to determine the impact of their failure during a maintenance action on the total scheduled downtime. Only equipment working directly on the major reactor components is likely to impart a significant effect on the total downtime. Therefore, the equipment examined is restricted to these items. A more complete list of equipment is found in Section 4.2.4.

The maintenance scenarios included in this section all define the potential impact of a maintenance equipment failure during a maintenance action in which it is involved. These maintenance actions can be either scheduled or forced outage events and the scenarios define the additional time required to recover from the maintenance equipment outage. This failure recovery time is the delay experienced in conducting the particular maintenance action which the maintenance equipment is supporting when it fails. Another time of importance is the failure reaction time. This is the time during which additional maintenance effort is required because of the failure. It includes the time required to replace or repair the failed equipment or to move additional equipment to or from the scene, if necessary. In most cases this time has not been estimated. For these scenarios, the time required to isolate the fault in each scenario is undetermined. The allowance for this type of operation is limited to the time deemed necessary to assure that the equipment is safe to detach and move to some location where the detailed fault can be determined and repaired. All time estimates in this section assume operation without interruption and are not diluted by external productivity or similar factors.

In selecting the conditions existing at the time of the failure and the type of failure for each maintenance equipment item, an attempt was made to always select the most difficult and most time consuming situation. These worst case situations then indicate a maximum impact and also whether any impractical recovery scenarios are likely to exist.

4.2.2.1 Heavy Central Overhead Crane - For this scenario the HCOC is lifting a central cell sector when one of the trolleys stops lifting. The central cell

TABLE 4–15

PRINCIPAL SPECIALIZED MAINTENANCE EQUIPMENT UNITS FOR TANDEM MIRROR BASELINE REACTOR

EQUIPMENT TITLE	CODE	APPLICABLE MAINTENANCE ACTION(S)
HEAVY CENTRAL OVERHEAD CRANE	HCOC	CENTRAL CELL REPLACEMENT TRENCH COVER REPLACEMENT DIRECT CONVERTER CHAMBER DOOR END PLUG WALL/SHIELD MODULES NBI SIDE PANEL/SHIELD
OVERHEAD MANIPULATOR	OHMAN	CENTRAL CELL REPLACEMENT TRENCH COVER REPLACEMENT END PLUG WALL/SHIELD MODULES YIN-YANG COIL REPLACEMENT NBI SIDE PANEL/SHIELD DIRECT CONVERTER CHAMBER DOOR DIRECT CONVERTER GRIDS
TRENCH ROBOT	TROB	CENTRAL CELL REPLACEMENT END PLUG WALL/SHIELD MODULES
NEUTRAL BEAM INJECTOR MANIPULATOR	NBIMAN	NBI ION SOURCE REPLACEMENT
SHIELDING MANIPULATOR	SHMAN	END PLUG WALL/SHIELD MODULES YIN-YANG COIL REPLACEMENT
DIRECT CONVERTER TRANSPORTER	DCTRAN	DIRECT CONVERTER CRYOPUMP PANELS DIRECT CONVERTER WALL COOLING PANELS
DIRECT CONVERTER MANIPULATOR	DCMAN	DIRECT CONVERTER CRYOPUMP PANELS DIRECT CONVERTER WALL COOLING PANELS
LIGHT CENTRAL OVERHEAD CRANE	LCOC	NBI ION SOURCE REPLACEMENT DIRECT CONVERTER GRID REPLACEMENT DIRECT CONVERTER CRYOPUMP PANELS DIRECT CONVERTER WALL COOLING PANELS
MAGNET COOLING MODULE	MCM	CENTRAL CELL REPLACEMENT
TUG	-	ALL
VACUUM SEAL WELDER	VSW	NBI SIDE PANEL/SHIELD SEAL DIRECT CONVERTER GRID ACCESS COVER DIRECT CONVERTER CHAMBER DOOR
SHIELDED PERSONNEL CAPSULE	SPEC	GENERAL MAINTENANCE

sector has cleared its supporting and aligning structure but is not yet clear of the adjacent central cell sectors. The procedure for recovery from this situation together with the estimated time required is defined in Table 4-16.

To recover from this type of failure, all reactor components that require lift points will have a secondary lift point for an additional hook. In addition, the assumption is made that the crane bridge drives can be disconnected if necessary and the crane pushed to a shielded mezzaine where repair work can be conducted. Time for this operation is not included in this scenario because the failure is assumed to be in the trolley mechanism and not in the bridge drive or power supply.

TABLE 4–16

HEAVY CENTER OVERHEAD CRANE FAILURE RECOVERY TANDEM MIRROR BASELINE REACTOR (REMOTE OPERATIONS)

LEVEL 1 TASK	LEVEL 2 TASK	DURATION (HRS:MIN)
FAULT EXAMINATION	EXAMINE FAILED TROLLEY AND CENTRAL CELL SECTOR	4:30
	ATTEMPT ALTERNATE CONTROL	1:00
FAULT RECOVERY	MOVE SPREADER BEAM UNDER HCOC BRIDGE	1:30
	LIFT BEAM WITH TWO LCOC	1:00
	ATTACH BEAM TO CENTRAL CELL SECONDARY HOIST LUG. TRANSFER LOAD	3:30
	DETACH HCOC FAULTY TROLLEY. LOWER CENTRAL CELL TO MOUNT	5:00
	REMOVE SPREADER BEAM	3:30
	REMOVE FAULTY HCOC	3:00
	CONNECT SECOND HCOC TO CENTRAL CELL SECTOR	1:30
	TOTAL:	24:30

4.2.2.2 Overhead Manipulator - The overhead manipulator is employed in many maintenance actions but most functions are associated with disconnecting or connecting service lines or structural attachments. Suitable tools are provided for these functions. For this scenario the assumption is that the overhead manipulator is disconnecting coolant lines to a central cell sector and the manipulator operation freezes in one position with the manipulator attached to a coolant line.

The procedure for recovery from this fault is defined in Table 4-17. The recovery time for this type of fault is relatively short if the manipulator operation allows access by rescue equipment for all of the functions examined. However, the failure reaction time, i.e., the delay time required to continue operations as scheduled, is much longer than the recovery time unless a spare overhead manipulator is available. As an alternate, the installation of a spare unit from some other location in the reactor room will require less time but may be an acceptable compromise between the need for a ready spare and the need to repair the equipment before continuing the maintenance action. The design of the manipulator is such that drives can be disconnected mechanically to allow "free wheeling" to retract or move mechanisms out of the way of other interference which will restrict the ability to move the equipment. The capability to operate the manipulator mechanically for limited functions by means of other equipment is used in this scenario.

TABLE 4-17

OVERHEAD MANIPULATOR FAILURE RECOVERY
TANDEM MIRROR BASELINE REACTOR (REMOTE OPERATIONS)

LEVEL 1 TASK	LEVEL 2 TASK	DURATION (HRS:MIN)
FAULT EXAMINATION	INSPECT FAULT USING ANOTHER OVERHEAD MANIPULATOR	1:30
	ATTEMPT LOCAL CONTROL	1:30
FAULT RECOVERY	MECHANICALLY RELEASE OVERHEAD MANIPULATOR FROM FLUID LINE	2:00
	MECHANICALLY RETRACT MANIPULATOR FROM TRENCH	3:00
	REMOVE MANIPULATOR FROM TRACK. LOAD ON DOLLY	2:00
	TOTAL:	10:00

4.2.2.3 Trench Robot - The scenario postulated for failure of the trench robot occurs during the removal of the lower shield segments between the central cell sectors. The trench robot has been attached to a shield segment and the segment structural fasteners have been released, placing the entire load of the segment on the trench robot. The segment has been moved out of position and all motion of the robot fails. The extendible robot arms are power driven and designed to lock in position in the event of a drive failure. However, these drives can be operated locally by mechanical means, if necessary.

The procedure for recovery from this failure mode is defined in Table 4-18. Spare trench robots are assumed to be unavailable. However, the TROB from the other side of the trench is used and the shield segment is removed during the recovery action. Therefore, in this case the failure recovery time and the failure reaction time are equal. The operational TROB disconnects the faulty robot drives and moves it out of position. For this recovery an additional sling and jack are required. These types of equipment are not included in the overall equipment list and may have to be developed on the spot if the failure mode is unforeseen. Such development will extend the estimated maximum recovery time significantly.

4.2.2.4 Neutral Beam Injector Manipulator - The assumed failure of the neutral beam injector manipulator occurs during removal of the ion source from the neutral beam housing. The manipulator rails have been extended into the neutral beam injector housing, the ion source has been disconnected and is partially withdrawn, being supported by the manipulator rails. The failure causes all motion to stop at this point.

TABLE 4-18
TRENCH ROBOT FAILURE RECOVERY
TANDEM MIRROR BASELINE REACTOR (REMOTE OPERATIONS)

LEVEL 1 TASK	LEVEL 2 TASK	DURATION (HRS:MIN)
FAULT EXAMINATION	EXAMINE ION SOURCE AND MANIPULATOR USING OVERHEAD MANIPULATOR	3:00
	ATTEMPT LOCAL CONTROL	1:30
FAULT RECOVERY	MECHANICALLY OPERATE RETRACTION MECHANISM TO REMOVE ION SOURCE, ATTACH LCOC	7:00
	MECHANICALLY DISCONNECT ION SOURCE FROM MANIPULATOR RETRACTION MECHANISM, REMOVE ION SOURCE	5:30
	REMOVE FAILED NEUTRAL BEAM INJECTOR MANIPULATOR	6:30
	INSTALL SECOND NEUTRAL BEAM INJECTOR MANIPULATOR	4:00
	TOTAL FAILURE REACTION TIME	27:30
	ESTIMATED ION SOURCE REMOVAL TIME	6:30
	TOTAL FAILURE RECOVERY TIME	21:00

The procedure to recover from this situation is outlined in Table 4-19. This position is a particularly difficult one to observe and the time estimate for fault examination reflects the difficulty even though access is feasible by use of the overhead manipulator. In this failure mode the mechanical operation of the drives is relied upon to minimize the fault recovery time. The time shown in Table 4-19 includes both the fault recovery time and the fault reaction time since the maintenance action is actually completed while recovering from the equipment breakdown.

4.2.2.5 Shielding Manipulator - The shielding manipulators that are used for replacement of the end plug first wall/shield modules operate in the reactor trench and are always accessible from directly above. The recovery procedure is the same for all conditions of operation. The fault for this analysis is assumed to occur with both the right and left manipulators attached to a wall/shield module and with all module cooling and structural connections detached. The gas bearing in the module has been activated and movement into position for hoisting has started when one of the manipulators ceases operation. Table 4-20 defines the procedure and indicates the estimated time required to recover from this fault.

TABLE 4–19

NEUTRAL BEAM INJECTOR MANIPULATOR FAILURE RECOVERY
TANDEM MIRROR BASELINE REACTOR (REMOTE OPERATIONS)

LEVEL 1 TASK	LEVEL 2 TASK	DURATION (HRS:MIN)
FAULT EXAMINATION	INSPECT FAULT, ATTEMPT LOCAL CONTROL	3:00
FAULT RECOVERY	INSTALL SECOND TRENCH ROBOT BESIDE FAILED UNIT	3:00
	SUPPORT SHIELD SEGMENT BY HCOC	1:30
	INSTALL JACK UNDER SHIELD SEGMENT USING OVERHEAD MANIPULATOR	1:30
	MECHANICALLY DISENGAGE ROBOT FROM SHIELD SEGMENT	3:00
	MOVE FAULTY ROBOT OUT OF POSITION	1:00
	REMOVE SHIELD SEGMENT WITH OPERATIONAL ROBOT AND HCOC	4:00
	REMOVE FAULTY ROBOT FROM TRENCH	3:00
	TOTAL:	20:00

TABLE 4–20

SHIELDING MANIPULATOR FAILURE RECOVERY
TANDEM MIRROR BASELINE REACTOR (REMOTE OPERATIONS)

LEVEL 1 TASK	LEVEL 2 TASK	DURATION (HRS:MIN)
FAULT EXAMINATION	EXAMINE SHIELDING MANIPULATOR USING INSTALLED LIGHTS AND CAMERAS	1:30
	MANUALLY ATTEMPT DIRECT CONTROL USING THE OVERHEAD MANIPULATOR	1:30
FAULT RECOVERY	MECHANICALLY DISCONNECT SHIELDING MANIPULATOR, RETRACT ARMS	3:30
	REMOVE FAILED SHIELDING MANIPULATOR WITH LCOC	3:00
	INSTALL SPARE SHIELDING MANIPULATOR	2:00
	TOTAL:	11:30

The shielding manipulator, as with the other equipment used with the TMR, is equipped with mechanical overrides for releasing tools and moving reactor arms. Therefore, release from the module is a relatively simple operation. Access to these attachment points is gained from above the trench using an overhead manipulator which is already in position. It is also assumed that the direct converter manipulators are designed to provide uniform withdrawal motion so that if one stops, or if the module becomes jammed on one side, the other manipulator will stop before the module becomes cocked too far with respect to the gas bearing bed plate. Since these operations occur with the first wall/shield modules moved apart to expose the activated inner wall, they must be conducted by remotely operated equipment.

4.2.2.6 Direct Converter Manipulator - The direct converter manipulator is used to remove components within the direct converter chamber, particularly the cryopump panels and the wall cooling panels. Access to this device when in its operating position must be accomplished by remotely controlled equipment because the interior of the direct converter chamber is exposed to radiation. Access is also difficult by any means other than another direct converter manipulator.

The scenario chosen for examination assumes that a direct converter manipulator is operating on one of the elliptical tracks around the periphery of the chamber and has detached a direct converter cooling panel but has not yet lowered it clear of obstructions. The manipulator arms fail to operate. Movement of the manipulator on the track is not possible because of interference between the panel and adjacent panels and manifolding. Table 4-21 outlines the procedure for recovery from this fault.

The basic approach is to place two additonal direct converter manipulators on the same elliptical track. Both additional manipulator machines can be emplaced at one time. These are moved to either side of the failed manipulator. The cooling panel is supported by these two machines and released from the failed manipulator. The cooling panel is then temporarily bolted in place. The additional manipulators release the drive on the failed manipulator and move it to the rail segment. From this point, one of the spare manipulators and the failed manipulator are removed while the second spare continues with the task of replacing panels.

The time given in Table 4-21 is the failure reaction time. The failure recovery time is longer because, while the spare manipulator continues with the work as soon as the faulty machine is installed on the removable rail section, it requires 4:40 hours to return to the point in the procedure where the failure occurred. The total failure recovery time is then 28:25 hours.

4.2.2.7 Shielded Personnel Capsule - A shielded personnel capsule has been devised to serve as a general purpose light duty maintenance device for those maintenance actions where better viewing and access is desired than is available with the set of equipment considered up to this point. The space available in such confined areas as the trench is sufficient to use such a capsule.

TABLE 4-21

DIRECT CONVERTER MANIPULATOR FAILURE RECOVERY
TANDEM MIRROR BASELINE REACTOR (REMOTE OPERATIONS)

LEVEL 1 TASK	LEVEL 2 TASK	DURATION (HRS:MIN)
FAULT EXAMINATION	INSTALL 2 ADDITIONAL DIRECT CONVERTER MANIPULATORS ON SAME TRACK AS FAULTY MANIPULATOR	8:45
	MOVE THE ADDITIONAL MANIPULATORS INTO POSITION	1:00
	EXAMINE FAULTY MANIPULATOR FOR PHYSICAL DAMAGE	2:00
FAULT RECOVERY	DISCONNECT PANEL FROM FAULTY MANIPULATOR	4:30
	INSTALL THE PANEL IN ORIGINAL POSITION	3:30
	MECHANICALLY RETRACT FAULTY MANIPULATOR RAM ARMS	1:00
	MOVE FAULTY MANIPULATOR TO TRANSPORTER	3:00
	REMOVE FROM DIRECT CONVERTER CHAMBER	3:30
	TOTAL:	27:15

Figure 4-13 illustrates the personnel capsule concept. This capsule is approximately a cube 2.5 meters on a side. Sufficient shielding is provided to protect the operator from the anticipated activated reactor areas but not from active neutrons. Therefore, its use is limited to the reactor hall outside of the reactor when the reactor is operating or to close proximity to the reactor only when the reactor is shut down. The optical windows are intended to provide wide visibility. The dual master-slave manipulators are operated from within the capsule as with some present manipulator designs. The capsule will be capable of operating other maintenance equipment by remote control, instead of using a control room operator. Any of the cranes in the reactor room have sufficient capacity to suspend the 80 tonne capsule. A self-contained life support system is also provided. The entry hatch is useable as a rescue hatch and it is anticipated that a minimum of two capsules will be in the reactor room at all times. Entry to the capsules would be through access ports in the reactor room wall in order to provide quick access and operation without moving any equipment into the reactor room.

The most severe failure mode for such a capsule is one that will not allow it to be immediately removed from the reactor. The inability to release a component on which it is working presents such a case. The failure for which a recovery sequence is defined assumes that neither manipulator will operate, thus indicating a fault in the power supply for the augmented power arms.

SHIELDED PERSONNEL CAPSULE

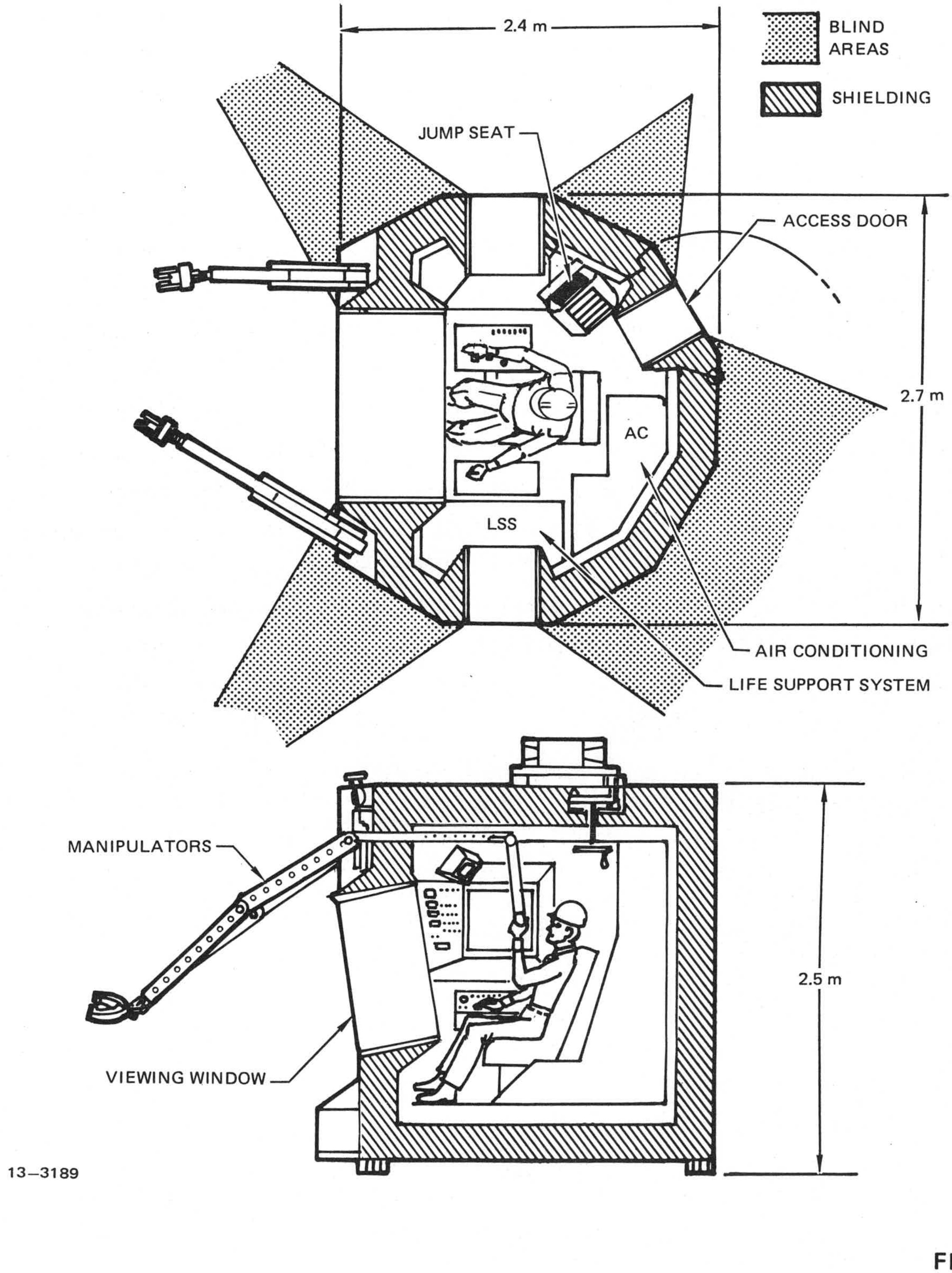


FIGURE 4–13

Table 4-22 defines the failure recovery sequence. In this case the fault occurs with the capsule in the trench. Thus the overhead manipulator (OHMAN) is conveniently located for the recovery operation. A second capsule could perform the operation just as well if the OHMAN is not available. It is further assumed that a spare capsule is available and is brought into the reactor room on a transporation dolly so that two capsules will be in the reactor room at all times, even when the faulty capsule has been removed. Six hours is available for this operation.

4.2.3 Total Scheduled Outage Plan - In the previous study (References 3 and 10) the total scheduled outage plans for tokamak reactors assumed that one maintenance action, namely the first wall/blanket replacement, constituted the critical path for scheduled maintenance. This assumption is sufficiently valid that the scheduled maintenance plans based on it serve as a comparative base for evaluation. However, when comparing maintainability for a TMR and a tokamak reactor the scheduled outage plan must be as representative as possible of a total scheduled outage in order to compare both reactors. Therefore, in developing the scheduled outage downtime for the TMR, the critical path for a scheduled outage has been selected based on a consideration of all subsystem maintenance that may be conducted during a nominal scheduled outage.

In addition to the scheduled outage scenarios that include the maintenance actions described in Section 4.2.1, additional scheduled outage requirements are derived from the components and subsystems listed in Tables 4-2 and 4-3. The

TABLE 4–22

SHIELDED PERSONNEL CAPSULE FAILURE RECOVERY TANDEM MIRROR BASELINE REACTOR (REMOTE OPERATIONS)

LEVEL 1 TASK	LEVEL 2 TASK	DURATION (HRS:MIN)
FAULT EXAMINATION	INTEGRAL WITH CAPSULE	0
FAULT RECOVERY	POSITION OVERHEAD MANIPULATOR	1:30
	MECHANICALLY DISCONNECT CAPSULE MANIPULATOR	2:00
FAULT RECOVERY	DOCK CAPSULE AT ENTRY PORT - OPERATOR GETS OUT	1:30
	MOVE CAPSULE TO TRANSPORTER	1:30
	MOVE REPLACEMENT CAPSULE TO ENTRY PORT - OPERATOR ENTERS	1:30
	MOVE REPLACEMENT CAPSULE TO WORK AND RESTART	2:00
	TOTAL:	10:00

downtime estimates for these subsystems are based on the previously defined estimates and on estimates made in detail for the IMS tokamak reactor as included later in Section 4.3.1. The maintenance activities defined for the tokamak concept which apply to similar subsystems in both reactors are:

- o Coolant valve replacement
- o Electrical power cable replacement
- o Shield door seal replacement
- o Charge exchange analyzer replacement

Based on these detailed analyses, downtimes for the similar scheduled maintenance actions in Tables 4-2 and 4-3 are estimated at the top level. These maintenance actions are also combined into common groups, such as control valves and instrumentation. They are then summed into a total plan after defining the replacement fraction for each component. This replacement fraction is determined by considering the life, or overhaul period, allocated to the component and the scheduled outage interval of the reactor.

Table 4-23 lists the downtime required for each maintenance action included in the maintenance plan, which includes both those estimated in detail and those estimated that are similar to others which have been defined in detail. For these estimates a productivity factor of 0.625 is included to make the downtime estimate representative of a total expected time for each maintenance action. The scheduled downtimes assume that reactor shutdown and startup occur in addition to the times given.

The maintenance actions selected for a typical scheduled outage at two values of replacement fraction are listed in Table 4-24. The replacement fraction of 0.25 requires a scheduled outage approximately every 2 operating years while the replacement fraction of 0.5 requires a scheduled outage every 4 operating years. These times are based on an estimated central cell first wall/blanket life of approximately 7.8 years. The life of some components is expected to be shorter and these are assumed to be replaced completely at every annual outage. It is assumed that all flow control valves will be inspected annually. Other items, such as the neutral beam ion sources, are indicated as a 100% replacement in Table 4-24. The life of the direct converter cryopumps is assumed to be approximately the same as that of the first wall/blanket and, therefore, has the same replacement fraction as the central cell sectors. The trench cover seal replacement remains constant because only four covers need be removed for either replacement fraction. Other components are assumed to be maintained partially at every annual shutdown and, therefore,

TABLE 4–23

TMR SCHEDULED MAINTENANCE ACTION DOWNTIMES

MAINTENANCE ACTION	DOWNTIME (1) PER UNIT, DAYS
BASED ON DETAILED ESTIMATES	
CENTRAL CELL SECTOR REPLACEMENT	
FIRST SECTOR	6.2
ADDITIONAL SECTORS	3.6
NEUTRAL BEAM ION SOURCE REPLACEMENT	7.2
NEUTRAL BEAM INJECTOR CRYOPUMP REPLACEMENT	
HALF OF EACH CRYOPUMP ASSEMBLY	3.9
END PLUG WALL REPLACEMENT	
PLUG TO CENTRAL CELL WALL	9.2 (2)
ENTIRE PLUG WALL	16.6 (2)
DIRECT CONVERTER GRID REPLACEMENT	
FIRST GRID MODULE	4.9 (3)
EACH ADDITIONAL GRID MODULE	1.1
DIRECT CONVERTER CRYOPUMP PANEL REPLACEMENT	
FIRST PANEL	6.6
EACH ADDITIONAL PANEL	2.1
DIRECT CONVERTER CHAMBER COOLING PANEL REPLACEMENT	
FIRST PANEL	6.2
EACH ADDITIONAL PANEL	1.6
YIN YANG COIL SET REPLACEMENT	15.8 (4)
ADDITIONAL COMPONENT ESTIMATES BASED ON SIMILARITY	
FUEL INJECTOR CRYOPUMP REPLACEMENT (HALF OF TOTAL/NBI)	3.9
CENTRAL CELL TRENCH COVER SEAL REPLACEMENT	1.9
CENTRAL CELL CONTROL VALVE INSPECTION	1.5
CENTRAL CELL COOLANT VALVE REPLACEMENT	1.9
FUEL INJECTOR ION SOURCE REPLACEMENT	1.5
DIRECT CONVERTER DOOR SEAL REPLACEMENT	.9
END PLUG AND DIRECT CONVERTER CONTROL VALVE INSPECTION	1.5
END PLUG AND DIRECT CONVERTER COOLANT VALVE REPLACEMENT	1.9
INSTRUMENTATION REPLACEMENT	.5
PLASMA CONTROL SENSOR ASSEMBLY REPLACEMENT	2.2

(1) 24 HOUR, 3 SHIFT DAYS, SHUTDOWN AND STARTUP EXCLUDED, PRODUCTIVITY OF .625 INCLUDED

(2) WITHOUT TRENCH COVER REMOVAL BETWEEN PLUG AND CENTRAL CELL

(3) TIME DIFFERS FROM MODULES UNDER SIDE COVERS

(4) NOT INCLUDED IN TOTAL OUTAGE, FORCED OUTAGE ONLY

their replacement fraction remains constant. These include the direct converter chamber cooling panels, the coolant valves and the instrumentation and plasma control sensors. All except the cooling panels are redundant systems. The Yin-Yang magnet sets are not considered for scheduled maintenance because of their expected long life.

Critical Path Selection - The list of maintenance actons in Table 4-24 has been examined to determine the probable critical path when conducting as many

TABLE 4–24

MAINTENANCE ACTIONS INCLUDED IN TMR SCHEDULED OUTAGE

MAINTENANCE ACTION	NUMBER OF UNITS WORKED		PERCENT OF TOTAL	
	RF = .25	RF = .5	RF = .25	RF = .5
DOWNTIME BASED ON DETAILED ESTIMATES				
REPLACE CENTRAL CELL SECTORS	9	18	25	50
REPLACE NEUTRAL BEAM ION SOURCES	4	4	100	100
REPLACE NEUTRAL BEAM CRYOPUMPS	4	4	100	100
REPLACE END PLUG WALLS	2	2	100	100
REPLACE DIRECT CONVERTER CRYOPUMP PANELS	25	50	25	50
REPLACE DIRECT CONVERTER CHAMBER COOLING PANELS	6	6	1	1
ADDITIONAL COMPONENTS IN SCHEDULED OUTAGE				
REPLACE FUEL INJECTOR CRYOPUMPS	4	4	100	100
REPLACE CENTRAL CELL TRENCH DOOR SEALS	4	4	67	67
INSPECT CENTRAL CELL CONTROL VALVES	59	59	100	100
REPLACE CENTRAL CELL COOLANT VALVES	10	10	10	10
REPLACE FUEL INJECTOR ION SOURCES	8	8	100	100
REPLACE DIRECT CONVERTER DOOR SEALS	6	6	100	100
INSPECT PLUG AND DC CONTROL VALVES	27	27	100	100
REPLACE PLUG AND DC COOLANT VALVES	20	20	10	10
REPLACE INSTRUMENTATION	40	40	20	20
REPLACE PLASMA CONTROL SENSOR ASSEMBLIES	3	3	10	10
TOTAL MAINTENANCE ACTIONS	231	265		

RF = REPLACEMENT FRACTION

maintenance actions in parallel as deemed possible. Three potential combinations of events are selected as candidates for critical path operations. These are delineated in Table 4-25, 4-26 and 4-27 which show the buildup for the critical path in all three cases. Based on extensions of these critical path estimates to a replacement fraction of 1.0, the maximum scheduled downtime for the TMR could be 40 days for replacement of 50 cryopump panels in a direct converter.

From observation of these critical path estimates it is apparent that a significant variation in the replacement fraction used for the central cell sectors relative to the replacement fraction used for the direct converter cryopump panels will affect the total downtime. Also, while the replacement of the end plug wall/shield requires a long time in the examples chosen, replacement of these wall/shield

TABLE 4–25

TMR SCHEDULED MAINTENANCE CRITICAL PATH DEVELOPMENT
PATH #1 – CENTRAL CELL SECTOR REPLACEMENT

MAINTENANCE ACTION	Δ TIME HRS.	SUMMATION (.625 PRODUCTIVITY)
REPLACE: 9 CENTRAL CELL SECTORS, 1 TRENCH COVER SEAL		
REACTOR SHUTDOWN	17.00*	17.00
REPLACE FIRST SECTOR	85.67	137.07
REPLACE SECOND SECTOR (PARALLEL OFFSET FOR LINE CONNECTIONS AND TEST)	31.50	50.40
REPLACE 3RD THROUGH 9TH SECTORS	220.50	352.80
REPLACE TRENCH COVER SEAL	20.00	32.00
REACTOR STARTUP	36.00*	36.00
	410.67	625.27 26.1 DAYS
REPLACE: 18 CENTRAL CELL SECTORS, 2 TRENCH COVER SEALS		
REPLACE 9 SECTORS (SEE ABOVE)	410.67	625.27
REPLACE SECTORS 10 THROUGH 18 (PARALLEL WITH SECTORS 1 THROUGH 9)		
OPEN/CLOSE ONE TRENCH COVER (TOTAL PARALLEL OFFSET)	7.75	12.40
TOTAL:	288.42	637.67 26.6 DAYS

*PRODUCTIVITY NOT APPLIED TO SHUTDOWN AND STARTUP TIMES.

TABLE 4–26

TMR SCHEDULED MAINTENANCE CRITICAL PATH DEVELOPMENT
PATH #2 – DIRECT CONVERTER CRYOPUMP REPLACEMENT

MAINTENANCE ACTION	Δ TIME HRS.	SUMMATION (.625 PRODUCTIVITY)
REPLACE: 12 DIR. CONVERTER CRYOPUMP PANELS/CONVERTER		
6 DIR. CONVERTER CRYOPUMP PANELS/CONVERTER		
REACTOR SHUTDOWN	17.00*	17.00
REPLACE FIRST PUMP PANEL	99.67	159.47
ADD DIRECT CONVERTER MANIPULATOR	11.75	18.80
TRANSPORTER PARALLEL OFFSET	4.50	7.20
REPLACE EACH ADD'L PAIR OF PANELS (12/2)-1 = 5 ADD'L PAIR @ 31.00 PR.	155.00	248.00
ADD FOR 2 ADD'L DIRECT CONVERTER MANIPULATORS	23.00	37.60
ADD TRANSPORT PARALLEL OFFSET	9.00	14.40
REPLACE 6 COOLING PANELS (PARALLEL)	0.00	
REPLACE DIRECT CONVERTER CHAMBER DOOR SEAL	13.50	21.60
STARTUP REACTOR	36.00*	36.00
TOTAL:	362.92	560.07 23.3 DAYS
REPLACE: 25 DIR. CONVERTER CRYOPUMP PANELS/CONVERTER		
6 DIR. CONVERTER COOLING PANELS/CONVERTER		
REPLACE 11 CRYOPUMP PANELS (SEE ABOVE)	369.92	560.07
ADD FOR 13 DIRECT CONVERTER CRYOPUMP PANELS 13/2 = 7 ADD'L PAIR @ 31:00 PR.	217.00	347.20
TOTAL:	586.92	907.27 37.8 DAYS

*PRODUCTIVITY NOT APPLIED TO SHUTDOWN AND STARTUP TIMES.

modules will not extend the time if only a portion of the modules are replaced. It is apparent that, if either more cooling panels or cryopump panels are to be replaced, this operation becomes significantly longer than the other critical paths and more equipment is difficult to provide in the current configuration.

The equipment, cranes, floorspace and manpower required to conduct these scheduled maintenance operations are resources which can limit the capability to conduct all other operations in parallel with these critical paths. Other resources such as facilities and spares can also be limiting but are not considered further in this study. The examination of the resource requirements is defined in the following section.

4.2.4 <u>Resources Required for TMR Scheduled Outages</u> - The amount of resources required for scheduled outages is far greater than for forced outages. Therefore,

TABLE 4–27

TMR SCHEDULED MAINTENANCE CRITICAL PATH DEVELOPMENT
PATH #3 – END PLUG FIRST WALL/SHIELD REPLACEMENT

MAINTENANCE PLAN	Δ TIME HRS.	SUMMATION (.625 PRODUCTIVITY)
REPLACE: END PLUG WALL/SHIELD IN ONE END PLUG VERTICAL NBI CRYOPUMP PANELS VERTICAL NBI ION SOURCE		
REACTOR SHUTDOWN	17.00*	17.00
REMOVE PLUG WALL/SHIELD (COMPLETE)	99.00	158.40
REPLACE PLUG WALL/SHIELD (COMPLETE)	149.00	238.40
REPLACE TRENCH DOOR SEALS (2 x 20.0)	40.00	64.00
REPLACE VERTICAL NBI ION SOURCE	108.50	173.60
REPLACE VERTICAL NBI OPPOSITE CRYOPUMP PANEL	58.50	93.60
REPLACE NBI DOOR SEALS (2 x 13.50)	27.00	43.20
REACTOR STARUP	36.00*	36.00
TOTAL:	535.00	824.2 34.3 DAYS
REPLACE: END PLUG WALL/SHIELD BETWEEN PLUG AND CENTRAL CELL VERTICAL NBI CRYOPUMP PANELS VERTICAL NBI ION SOURCE		
REACTOR SHUTDOWN	17.00*	17.00
REMOVE PLUG WALL/SHIELD (PARTIAL)	62.92	100.67
REPLACE PLUG WALL/SHIELD (PARTIAL)	93.83	150.13
REPLACE TRENCH DOOR SEALS (1 x 20.0)	20.00	32.00
REPLACE NBI ION SOURCE	108.50	173.60
REPLACE NBI CRYOPUMP PANEL	58.50	93.60
REPLACE NBI DOOR SEALS	27.00	43.20
REACTOR STARTUP	36.00*	36.00
TOTAL:	423.75	646.2 26.9 DAYS

*PRODUCTIVITY NOT APPLIED TO SHUTDOWN AND STARTUP TIMES.

the resources required for scheduled outages are defined. These resources include maintenance equipment and direct operating personnel.

4.2.4.1 Maintenance Equipment Requirements - The maintenance equipment required for the TMR is listed in Table 4-28. This list includes the number of each maintenance item required for each replacement fraction. The quantities included in this list can, at best, be only approximate because they are dependent upon the relative replacement fractions of the different components being maintained.

TABLE 4–28
EQUIPMENT SUMMARY LIST FOR TMR MAINTENANCE OPERATIONS

ITEM DESIGNATION	LIFTING CAPABILITY	SIZE L x W x H	WEIGHT/UNIT	QUANTITY/REPLACEMENT FRACTION SPARES	1/10-1/9	1/6-1/5	1/4-1/3	1/2	1
o HEAVY CENTER OVERHEAD CRANE (HCOC)	700 TONNES	30 m x 8 m x 6 m	620 TONNES	0	2	2	2	4	4
o LIGHT CENTER OVERHEAD CRANE (LCOC)	200/20 TONNES	40 m x 5 m x 5 m	280 TONNES	0	2	2	2	4	4
o LIGHT END PLUG OVERHEAD CRANE (LPOC)	200/20 TONNES	40 m x 5 m x 5 m	280 TONNES	0	2	2	2	2	2
o HIGH BAY OVERHEAD CRANE (HIBOC)	200/20 TONNES	40 m x 5 m x 5 m	280 TONNES	0	2	2	2	2	2
o OVERHEAD MANIPULATOR (OHMAN)	1 TONNE	15 m x 3 m x 7 m	26.5 TONNES	2	4	5	6	10	16
o TRENCH ROBOT (TROB)	1.5 TONNES	1.5 m x 1.5 m x 2.5 m	3 TONNES	2	4	4	6	8	16
o MAGNET COOLING MODULE (MCM)	N/A	3 m x 2 m x 2 m	5 TONNES	2	4	6	9	18	18
o TUG	N/A	9.5 m x 6 m x 4 m	8 TONNES	1	2	4	6	10	10
o AUTOMATIC PIPE WELDER AND WORKHEADS (APW)	N/A	15 m x 3 m x 5 m	25 TONNES	1	1	2	2	4	8
o IMPACT WRENCH	N/A	70 m x 24 cm x 33 cm	2 TONNES	3	8	9	12	18	24
o OVERHEAD MANIPULATOR DOLLY	SUPPORTS 26.5 TONNES	15 m x 4 m x 1 m	8 TONNES	2	4	5	6	10	16
o TRENCH ROBOT DOLLY	SUPPORTS 3 TONNES	4 m x 3 m x 1 m	1 TONNE	1	2	2	3	4	8
o MAGNET COOLING MODULE DOLLY	SUPPORTS 10 TONNES	3 m x 4 m x 1 m	3 TONNES	1	2	3	5	9	9
o AUTOMATIC PIPE WELDER DOLLY	SUPPORTS 25 TONNES	15 m x 3 m x 1 m	7 TONNES	1	1	2	2	4	8
o SHIELD SEGMENT DOLLY	SUPPORTS 20 TONNES	7 m x 3 m x 3.5 m	6 TONNES	2	5	7	10	19	19
o CENTRAL CELL SECTOR DOLLY	SUPPORTS 620 TONNES	9 m x 5 m x 2 m	120 TONNES	1	2	2	2	4	4
o BLANKET MODULE WORKHEAD	1.5 TONNES	5 m x 3 m x 9 m	15 TONNES	1	1	1	1	1	1
o BLANKET MODULE WORKHEAD DOLLY	SUPPORTS 17 TONNES	5 m x 3 m x 1 m	5 TONNES	1	1	1	1	1	1
o LEAK TEST WORKHEAD	N/A	.5 m x .3 m x .3 m	.3 TONNE	2	4	5	6	10	16
o INSPECTION WORKHEAD	N/A	.5 m x .3 m x .3 m	.3 TONNE	2	4	5	6	10	16
o NEUTRAL BEAM INJECTOR MANIPULATOR (NBIMAN)	7.5 TONNES	12 m x 5 m x 8.5 m	21 TONNES	1	1	1	1	2	4
o VACUUM SEAL WELDER/CUTTER	N/A	.7 m x 1.5 m x 1.5 m	2.2 TONNES	1	4	4	6	8	8
o NEUTRAL BEAM INJECTOR MANIPULATOR DOLLY	SUPPORTS 21 TONNES	12 m x 5 m x 1 m	6 TONNES	1	1	1	1	2	4
o ION SOURCE MODULE DOLLY	SUPPORTS	5 m x 3 m x 1 m	2 TONNES	1	1	1	1	2	4
o NEUTRAL BEAM INJECTOR CRYOPUMP AND SHIELD DOLLY	SUPPORTS 200 TONNES	12 m x 4 m x 1 m	60 TONNES	1	1	1	2	4	8
o SHIELDING MANIPULATORS	100 TONNES	2 m x 2 m x 4.5 m	11 TONNES EA.	2	2	2	2	4	8
o AIR COMPRESSOR UNIT	N/A	3 m x 2 m x 3 m	7 TONNES	1	1	1	1	2	4
o SHIELDING MANIPULATOR DOLLY	SUPPORTS 22 TONNES	4 m x 2 m x 1 m	7 TONNES	1	1	1	1	2	4
o GRID MODULE STORAGE RACKS	N/A	2 m x 2 m x 17 m	10 TONNES	1	3	5	9	11	20
o GRID MODULE DOLLY	SUPPORTS 7 TONNES	17 m x 2 m x 1 m	2 TONNES	1	1	1	1	2	2
o DIRECT CONVERTER MANIPULATOR (DCMAN)	4 TONNES	2.5 m x 4 m x 3 m	20 TONNES	2	4	8	8	18	18
o DIRECT CONVERTER MANIPULATOR TRANSPORTER	24 TONNES	6 m x 6 m x 6 m	40 TONNES	1	2	2	2	4	4
o DIRECT CONVERTOR MANIPULATOR TRANSPORTER DOLLY	SUPPORTS 64 TONNES	6 m x 6 m x 1 m	19 TONNES	1	2	2	2	4	4
o CRYOPUMP PANEL DOLLY (COOLING PANEL DOLLY)	SUPPORTS 8 TONNES	4 m x 2 m x 1 m	2 TONNES	3	4	6	8	14	26
o FUELING NBI CRYOPUMP AND SHIELD DOLLY	SUPPORTS 100 TONNES	5 m x 2 m x 1 m	30 TONNES	1	1	1	1	2	2
o TRENCH DOOR SEAL WORKHEAD	N/A	UNDEFINED	UNDEFINED	1	-	1	2	3	4
o TRENCH DOOR SEAL DOLLY	N/A	UNDEFINED	UNDEFINED	1	-	1	2	3	6
o GENERAL PURPOSE VALVE DOLLY	SUPPORTS 1 TONNE MAX	1 m x 1 m x 1 m	.3 TONNES	1	10	10	10	10	10
o GENERAL PURPOSE CABLE DOLLY	SUPPORTS 1-5 TONNES	4 m x 4 m x 1 m	1 TONNE	1	1	1	2	2	2
o GENERAL PURPOSE INSTRUMENT DOLLY	SUPPORTS 1-5 TONNES	4 m x 4 m x 1 m	1 TONNE	1	1	1	2	2	2
o SHIELDED PERSONNEL MAINTENANCE CAPSULE	1 TONNE	2.7 m x 2.4 m x 2.5 m	80 TONNES	1	2	2	2	2	2
o CRYOGEN LINE MAINTENANCE UNITS	N/A	-	2 TONNES	1	2	2	2	2	2
o LINE CUTTING/WELDING TOOLS	N/A	-	1 TONNE	1	2	2	2	2	2
o MISCELLANEOUS TOOLS	N/A	-	5 TONNES/SET	1	2	2	2	2	2
		TOTAL WT:	1964.6 TONNES	652.7	3863.2	4137.2	4344.8	7202.6	8065.2
ONE TOTAL EQUIPMENT SET= 1964.6 + 652.7 = 2617.3 TONNES			NO. OF EQUIVALENT SETS:		1.725	1.828	1.909	3.001	3.331

These replacement fractions are, in turn, dependent on the relative life or overhaul period of the components.

The list in Table 4-28 is a composite list of the quantity of each item of maintenance equipment required for all major component maintenance actions and for the different replacement fractions possible with each component. This table is based on the listings in Table 4-29 which defines the equipment items required for each maintenance action. The quantities defined for each equipment item assume that as many parallel operations as feasible are conducted for each maintenance action under consideration. The major equipment requirements for the additional maintenance actions defined in Table 4-24 are also included in the listing in Table 4-29 as "Miscellaneous" equipment, if not defined for other maintenance actions.

The total individual equipment quantities included in Table 4-28 are determined by summing the equipment quantities required for all maintenance actions where each major equipment item is used. The quantities shown for each replacement fraction include the quantities required for the same replacement fraction for all maintenance actions. This implies that a common replacement fraction for all maintenance actions is used during a scheduled outage. While the actual situation will differ, it is believed that the composite nature of the listing provides a reasonable definition of the trend for maintenance equipment requirements as the equivalent replacement fraction varies. The summation of maintenance equipment requirements in this manner is varied to limit the number of individual items when it is apparent that a strict total would require more units than could possibly be used at one time. Even here, there is some question whether the maximum number indicated can be used, but the quantities specified indicate a maximum trend in order to encompass the largest possible range of requirements.

The equipment assumed available for the replacement fractions used when determining the scheduled downtimes discussed in Section 4.2.3 is that indicated in the replacement fraction columns in Table 4-28 for 1/4 and 1/2 of the total units. These quantities of equipment are required when conducting the maintenance operations listed in Table 4-24. For costing purposes a set of maintenance equipment consists of one unit of each equipment item plus one spares set. The number of equivalent sets of maintenance equipment is then calculated as:

$$\text{Number of equivalent sets} = \frac{\text{weight of equipment for replacement fraction} + \text{weight of spares set}}{\text{weight of one unit set of equipment} + \text{weight of spares set}}$$

TABLE 4–29

TMR MAINTENANCE EQUIPMENT REQUIREMENTS BY MAINTENANCE ACTION

MAINTENANCE ACTION	ITEM DESIGNATION	MAJOR FUNCTION	QUANTITY/REPLACEMENT FRACTION					
			SPARES	1/10-1/9	1/6-1/5	1/4-1/3	1/2	1
CENTRAL CELL SECTOR REPLACEMENT	o HEAVY CENTER OVERHEAD CRANE (HCOC)	REMOVE/EMPLACE TRENCH COVERS, CENTRAL CELL SECTORS AND HEAVY EQUIPMENT	0	2	2	2	4	4
	o OVERHEAD MANIPULATOR (OHMAN)	DETACH/ATTACH TRENCH COVERS FLUID AND POWER LINES AND SHIELD SEGMENTS AT CENTRAL CELL SECTORS	1	2	2	3	4	8
	o TRENCH ROBOT (TROB)	REMOVE/EMPLACE SHIELD SEGMENTS, SPACERS, ETC., BELOW CENTRAL CELL SECTORS	2	4	4	6	8	16
	o LIGHT CENTER OVERHEAD CRANE (LCOC)	REMOVE/EMPLACE LIGHT EQUIPMENT, SHIELD SEGMENTS, ETC. IN TRENCH AND REACTOR ROOM	0	2	2	2	4	4
	o MAGNET COOLING MODULE (MCM)	MAINTAINS CENTRAL CELL MAGNETS AT SUPERCONDUCTING TEMPERATURES DURING SECTOR TRANSFER	2	4	6	9	18	18
	o TUG	MOVE COMPONENTS AND EQUIPMENT IN/OUT REACTOR ROOM	1	2	4	6	10	10
	o AUTOMATIC PIPE WELDER AND WORKHEADS (APW)	ALIGNS AND WELDS/CUTS PIPE CONNECTORS OF VARYING SIZE WITH SIZED WORKHEADS	1	1	2	2	4	8
	o IMPACT WRENCH	AUTOMATED DEVICE TO DISCONNECT/CONNECT FASTENERS. USE WITH OHMAN AND TROB	1	2	2	3	4	8
	o OVERHEAD MANIPULATOR DOLLY	TRANSPORT OHMAN TO/FROM REACTOR ROOM	1	2	2	3	4	4
	o TRENCH ROBOT DOLLY	TRANSPORT TROB TO/FROM REACTOR ROOM	1	1	1	2	2	4
	o MAGNET COOLING MODULE DOLLY	TRANSPORT MCM TO/FROM REACTOR ROOM	1	2	2	3	4	8
	o AUTOMATIC PIPE WELDER DOLLY	TRANSPORT APW TO/FROM REACTOR ROOM	1	1	1	1	2	4
	o SHIELD SEGMENT DOLLY	TRANSPORT AND TEMPORARILY STORE SHIELD SEGMENTS FROM ONE JOINT	2	4	6	9	18	18
	o CENTRAL CELL SECTOR DOLLY	MOVE CENTRAL CELL SECTORS BETWEEN CENTRAL CELL AND HOT CELL. MOVE THROUGH TRANSFER LOCKS	1	2	2	2	4	4
	o BLANKET MODULE WORKHEAD	EXTRACT/INSERT INDIVIDUAL MODULES FROM REMOVED OR EXPOSED SECTOR	1	1	2	4	6	10
	o BLANKET MODULE WORKHEAD DOLLY	TRANSFER BLANKET MODULE WORKHEAD AND OTHER WORKHEADS TO/FROM REACTOR ROOM	1	1	2	4	6	10
	o LEAK TEST WORKHEAD	TEST VACUUM COVER AND FLUID LINE INSTALLATIONS FOR LEAKS. USE WITH OHMAN	1	1	2	4	6	10
	o INSPECTION WORKHEAD	INSPECT EXPOSED BLANKET MODULE AND FLUID LINES FOR DAMAGE	1	1	2	4	6	10
NEUTRAL BEAM INJECTOR ION SOURCE REPLACEMENT	o LIGHT END PLUG OVERHEAD CRANE (LPOC)	REMOVE/EMPLACE NBI SIDE PANELS, ION SOURCES, EQUIPMENT	0	2	-	2	2	2
	o OVERHEAD MANIPULATOR (OHMAN)	DETACH/ATTACH NBI SIDE PANELS, FLUID LINES, ETC.	1	1	-	1	2	4
	o NEUTRAL BEAM INJECTOR MANIPULATOR (NBIMAN)	DETACH/ATTACH AND EXTRACT/EMPLACE NBI MODULES TO/FROM AND IN/OUT OF NBI HOUSING	1	1	-	1	2	4
	o VACUUM SEAL WELDER/CUTTER	WELD/CUT VACUUM SEALS ON NBI SIDE PANELS	1	1	-	1	2	2
	o IMPACT WRENCH	AUTOMATED DEVICE TO DISCONNECT/CONNECT NBI SIDE PANEL AND OTHER FASTENERS	1	1	-	1	4	4
	o TUG	MOVE COMPONENTS AND EQUIPMENT IN/OUT REACTOR ROOM	1	1	-	1	1	2
	o OVERHEAD MANIPULATOR DOLLY	TRANSPORT OHMAN TO/FROM REACTOR ROOM	1	1	-	1	2	4
	o NEUTRAL BEAM INJECTOR MANIPULATOR DOLLY	TRANSPORT NBIMAN TO/FROM REACTOR ROOM	1	1	-	1	2	4
	o INSPECTION WORKHEAD	INSPECT SEAL WELDS	1	1	-	1	2	4
	o LEAK TEST WORKHEAD	TEST FOR VACUUM AND FLUID LEAKS	1	1	-	1	2	4
	o ION SOURCE MODULE DOLLY	TRANSPORT ION SOURCE MODULES TO/FROM REACTOR ROOM	1	1	-	1	2	4
NEUTRAL BEAM INJECTOR CRYOPANEL REPLACEMENT (1)	o OVERHEAD MANIPULATOR (OHMAN)	DETACH/ATTACH NBI SIDE PANELS ON SIDE OPPOSITE ION SOURCE REMOVAL	-	-	-	1	2	4
	o VACUUM SEAL WELDER/CUTTER	WELD/CUT VACUUM SEALS ON ADD'L SIDE PANELS	-	-	-	1	2	2
	o IMPACT WRENCH	FOR ADDITIONAL OHMAN	-	-	-	1	2	4
	o INSPECTION WORKHEAD	INSPECT SEALS ON ADD'L SIDE PANELS	-	-	-	1	2	4
	o LEAK TEST WORKHEAD	TEST CONNECTIONS ON ADD'L SIDE PANELS	-	-	-	1	2	4
	o NEUTRAL BEAM INJECTOR CRYOPANEL (SIDE PANEL) AND SHIELD DOLLY	TRANSPORT NBI CRYOPANELS TO/FROM REACTOR ROOM	1	1	-	2	4	8

(1) CONDUCTED IN CONJUNCTION WITH OR AS A PART OF NBI ION SOURCE REPLACEMENT MAINTENANCE ACTION. EQUIPMENT SHOWN IS ADDITIONAL EQUIPMENT ONLY.

TABLE 4–29

TMR MAINTENANCE EQUIPMENT REQUIREMENTS BY MAINTENANCE ACTION (CONT.)

MAINTENANCE ACTION	ITEM DESIGNATION	MAJOR FUNCTION	QUANTITY/REPLACEMENT FRACTION					
			SPARES	1/10-1/9	1/6-1/5	1/4-1/3	1/2	1
END PLUG WALL REPLACEMENT	o HEAVY CENTER OVERHEAD CRANE (HCOC)	REMOVE/EMPLACE TRENCH DOORS AND LARGE WALL SEGMENT	0	2	-	2	2	2
	o LIGHT END PLUG OVERHEAD CRANE (LPOC)	REMOVE/EMPLACE PLUG WALL MODULES, SHIELD SECTORS AND EQUIPMENT	0	2	-	2	2	2
	o OVERHEAD MANIPULATOR (OHMAN)	DETACH/ATTACH TRENCH DOORS, FLUID LINES, SHIELD SEGMENTS, AND EQUIPMENT	1	1	-	1	2	4
	o TRENCH ROBOT (TROB)	REMOVE/EMPLACE SHIELD SEGMENTS BELOW PLUG WALL MODULES	1	2	-	2	4	8
	o SHIELDING MANIPULATORS (SHMAN) (SETS OF 2)	MOVE PLUG WALL MODULES BETWEEN OR INSIDE OF PLUG MAGNET BORES. EMPLACE FOR CRANE PICKUP OR REASSEMBLY.	1	1	-	1	2	4
	o IMPACT WRENCH	AUTOMATED DEVICE TO DISCONNECT/ CONNECT FASTENERS. USE WITH OHMAN OR TROB	1	1	-	1	2	4
	o AIR COMPRESSOR UNIT	PROVIDE AIR PRESSURE FOR MODULE AIR BEARINGS	1	1	-	1	2	4
	o TUG	MOVE COMPONENTS/EQUIPMENT IN/OUT OF REACTOR ROOM	1	1	-	1	1	2
	o OVERHEAD MANIPULATOR DOLLY	TRANSPORT OHMAN TO/FROM REACTOR ROOM	1	1	-	1	2	4
	o TRENCH ROBOT DOLLY	TRANSPORT TROB TO/FROM REACTOR ROOM	1	2	-	2	4	8
	o SHIELDING MANIPULATOR DOLLY	TRANSPORT SHIELDING MANIPULATOR TO/FROM REACTOR ROOM	1	1	-	1	2	4
	o LEAK TEST WORKHEAD	TEST TRENCH COVER AND FLUID LINE INSTALLATIONS FOR LEAKS. USE WITH OHMAN	-	-	-	1	2	4
DIRECT CONVERTER (DC) GRID MODULE REPLACEMENT	o HIGH BAY OVERHEAD CRANE (INTERCHANGEABLE WITH LPOC)	REMOVE/EMPLACE DIRECT CONVERTER DOORS, GRID MODULES AND EQUIPMENT	0	2	2	2	2	2
	o OVERHEAD MANIPULATOR (OHMAN)	DETACH/ATTACH DIRECT CONVERTER DOORS, FLUID LINES AND POWER CABLES	1	1	2	2	4	4
	o VACUUM SEAL WELDER/CUTTER	WELD/CUT VACUUM SEALS ON DIRECT CONVERTER GRID DOORS. USE WITH OHMAN	1	1	2	2	4	4
	o IMPACT WRENCH	AUTOMATED DEVICE TO DISCONNECT/ CONNECT DIRECT CONVERTER GRID DOORS. USE WITH OHMAN	1	1	2	2	4	4
	o TUG	MOVE EQUIPMENT AND SPARE GRIDS TO/FROM REACTOR ROOM	1	1	1	1	1	1
	o GRID MODULE STORAGE RACKS	SUPPORT GRID MODULES IN REPAIR STATION IN REACTOR ROOM.	1	3	5	9	11	20
	o OVERHEAD MANIPULATOR DOLLY	TRANSPORT OHMAN TO/FROM REACTOR ROOM	1	1	2	2	4	4
	o GRID MODULE DOLLY	TRANSPORT GRID MODULES TO/FROM REACTOR ROOM	1	1	1	1	2	2
	o INSPECTION WORKHEAD	INSPECT SEAL WELDS ON DIRECT CONVERTER DOORS. USE WITH OHMAN	-	1	2	2	4	4
	o LEAK TEST WORKHEAD	TEST DIRECT CONVERTER DOORS FOR LEAKS. USE WITH OHMAN	-	1	2	2	4	4
DIRECT CONVERTER (DC) CRYOPUMP REPLACEMENT	o HEAVY CENTER OVERHEAD CRANE (HCOC)	HOIST DC DOORS TO OPEN POSITION	0	2	2	2	2	2
	o LIGHT END PLUG OVERHEAD CRANE (LPOC)	HOIST CRYOPUMP PANELS AND EQUIPMENT TO/FROM DC ACCESS TRENCH	0	2	2	2	2	2
	o DIRECT CONVERTER MANIPULATOR (DCMAN)	REMOVE/INSTALL DC CRYOPUMP PANELS IN DC CHAMBER	1	2	4	4	8	8
	o DIRECT CONVERTER MANIPULATOR TRANSPORTER (DCTRAN)	MOVE DCMAN AND CRYOPUMP PANELS IN/OUT OF DC CHAMBER	1	2	2	2	4	4
	o OVERHEAD MANIPULATOR (OHMAN)	DETACH/ATTACH DC CHAMBER DOORS	1	2	2	2	2	2
	o VACUUM SEAL WELDER/ CUTTER	WELD/CUT VACUUM SEALS ON DC CHAMBER DOORS. USE WITH OHMAN	1	2	2	2	2	2
	o IMPACT WRENCH	AUTOMATED DEVICE TO DISCONNECT/ CONNECT FASTENERS ON DC CHAMBER DOORS	1	2	2	2	2	2
	o DIRECT CONVERTER MANIPULATOR TRANSPORT DOLLY	TRANSPORT DCTRAN AND/OR DCMAN TO/FROM REACTOR ROOM	1	2	2	2	4	4
	o OVERHEAD MANIPULATOR DOLLY	TRANSPORT OHMAN TO/FROM REACTOR ROOM	1	2	2	2	2	2
	o TUG	MOVE EQUIPMENT AND CRYOPUMP PANELS TO/FROM REACTOR ROOM	1	2	2	2	4	4
	o CRYOPUMP PANEL DOLLY	TRANSPORT CRYOPUMP PANELS TO/FROM REACTOR ROOM	3	2	4	6	12	24
	o INSPECTION WORKHEAD	INSPECT SEAL WELDS ON DC CHAMBER DOORS. USE WITH OHMAN	-	1	2	2	2	2
	o LEAK TEST WORKHEAD	TEST DC CHAMBER DOORS FOR LEAKS. USE WITH OHMAN	-	1	2	2	2	2

TABLE 4–29
TMR MAINTENANCE EQUIPMENT REQUIREMENTS BY MAINTENANCE ACTION (CONT.)

MAINTENANCE ACTION	ITEM DESIGNATION	MAJOR FUNCTION	QUANTITY/REPLACEMENT FRACTION					
			SPARES	1/10-1/9	1/6-1/5	1/4-1/3	1/2	1
DIRECT CONVERTER (DC) COOLING PANEL REPLACEMENT(2) (3) (NOT LIFE LIMITED COMPONENT)	o DIRECT CONVERTER MANIPULATOR (DCMAN)	REMOVE/INSTALL DC COOLING PANELS IN DC CHAMBER	-	2	4	4	8	8
	o DC MANIPULATOR TRANSPORT DOLLY	TRANSPORT DCMAN TO/FROM REACTOR ROOM	-	2	2	2	4	4
	o COOLING PANEL DOLLY (SAME AS CRYO-PANEL DOLLY)	TRANSPORT COOLING PANELS TO/FROM REACTOR ROOM	-	2	2	2	2	2
	o TUG	MOVE EQUIPMENT AND COOLING PANELS TO/FROM REACTOR ROOM	-	1	1	1	1	1
MISCELLANEOUS(3) (NO LIFE LIMITED COMPONENTS)	o OVERHEAD MANIPULATOR (OHMAN)	DISCONNECT/CONNECT FUELING NBI CRYOPUMPS, ION SOURCES, ETC.	1	1	1	1	2	2
	o FUELING NBI CRYOPUMP DOLLY	TRANSPORT CRYOPUMPS TO/FROM REACTOR ROOM	1	1	1	1	2	2
	o VACUUM SEAL WELDER/CUTTER	WELD/CUT FUELING NBI VACUUM SEALS	1	1	1	1	2	2
	o TRENCH DOOR SEAL WORKHEAD	REMOVE/INSTALL TRENCH DOOR SEALS	1	-	1	2	3	4
	o TRENCH DOOR SEAL DOLLY	TRANSPORT TRENCH DOOR SEALS TO/FROM REACTOR ROOM	1	-	1	2	3	6
	o IMPACT WRENCH	REMOVE/INSTALL LINE/CABLE FASTENERS	1	2	2	2	2	2
	o LEAK TEST WORKHEAD	TEST FOR LEAKS AT VALVES IN LINES	1	2	2	2	2	2
	o GENERAL PURPOSE VALVE DOLLY	TRANSPORT VALVES TO/FROM REACTOR (VALVES ARE FREQUENT MAINTENANCE ITEM)	1	10	10	10	10	10
	o GENERAL PURPOSE CABLE DOLLY	TRANSPORT CABLES TO/FROM REACTOR	1	1	1	2	2	2
	o GENERAL PURPOSE INSTRUMENT DOLLY	TRANSPORT LARGE INSTRUMENTS AND ASSOCIATED SHIELDING	1	1	1	1	1	1
	o SHIELDED PERSONNEL CAPSULE	PROVIDE PERSONNEL ACCESS TO UNIQUE MAINTENANCE ACTION LOCATIONS AND CAPABILITY FOR LIGHT OPERATIONS	1	1	1	1	1	1
	o TUG	MOVE MATERIAL, ETC. IN/OUT OF RR	1	1	1	1	1	1
	o CRYOGEN LINE UNITS	PREPARE LINES FOR MAINT. AND OPERATIONS	1	2	2	2	2	2
	o LINE CUTTING/WELDING TOOLS	REPAIR SMALL FLUID LINES	1	2	2	2	2	2
	o MISCELLANEOUS TOOLS	PERFORM SPECIALIZED FUNCTIONS	-	-	-	-	-	-

(2) CONDUCTED IN CONJUNCTION WITH DIRECT CONVERTER CRYOPUMP REPLACEMENT MAINTENANCE ACTION. EQUIPMENT SHOWN IS ADDITIONAL EQUIPMENT ONLY.

(3) THESE MAINTENANCE ACTIONS ARE NOT USUALLY A FUNCTION OF REPLACEMENT FRACTION BUT THEIR FREQUENCY DEPENDS ON RELIABILITY OF THE COMPONENTS OR ON REPLACEMENT OF OTHER COMPONENTS WHICH ARE LIFE LIMITED.

This data is used in the MICOMO code to determine capital cost of maintenance equipment.

4.2.4.2 Direct Operating Personnel Requirements - The direct operating personnel required to conduct the remote maintenance actions listed in Table 4-24 are defined in Table 4-30. This number allows one operator for each primary equipment unit and assumes that this operator will also work the tools used by the machine. Two operators are assigned to each tug to aid in guiding the dollys through the floor traffic and to control associated equipment. The number of personnel are assumed to be those required for each shift. Therefore, the total work force is three times the number per shift plus normal personnel allowances for vacations, absence, and similar factors.

TABLE 4-30

TMR DIRECT OPERATING PERSONNEL REQUIRED

	REPLACEMENT FRACTION				
	1/9	1/6	1/4	1/2	1
NO. OF CENTRAL CELL SECTORS REPLACED	4	6	9	18	36
NO. OF PERSONNEL REQUIRED, (ASSUME 2 CONTROL, 1 OPERATOR/EQUIPMENT, 2/TUG)					
EQUIPMENT ITEMS					
HCOC	2	2	2	4	4
LCLC	6	6	6	8	8
OHMAN	4	5	6	10	16
TROB	4	4	6	8	16
TUG (2)	4	8	12	20	20
LEAK TEST AND INSPECTION	4	5	6	10	16
NBIMAN	1	1	1	2	4
SHMAN	2	2	2	4	8
DCMAN	4	8	8	18	18
DCTRAN	2	2	2	4	4
TLOCKS	1	1	2	2	2
APW	1	2	2	4	8
CONTROL ROOM OPERATORS	2	2	2	2	2
TOTAL NUMBER OF PERSONNEL REQUIRED	37	48	57	96	126

It is recognized that all equipment will not be operating at any given time and, therefore, the estimate appears excessive. However, additional equipment operating requirements are to be expected as the maintenance plans become more detailed, requiring more personnel. Therefore, this estimate allows for some growth in the requirement.

Additional personnel are expected to be available to support these operations. These personnel are the normal plant maintenance force and are included in the nominal operating cost generated by the MICOMO TMR system and cost code used for the cost analysis.

4.2.5 Total Forced Outage Plan Composition - Forced outages resulting from individual component failures have been examined to define those component failures that will most likely have an important influence on the total forced outage downtime for the TMR. The component lists generated for the TMR and shown in Tables

4-2 and 4-3 are further defined in Tables 4-31 and 4-32. These lists have been examined to determine which component failures will result in forced outages, assuming the redundancy indicated. The downtime to recover from such an outage and the relative frequency of the outages for the various components have been estimated. The relative total forced outage downtime per operating year is then estimated for each component. When making these estimates it is assumed that the fault isolation to a component or replaceable assembly level is conducted remotely during shutdown and no additional time allowance has been assessed for this function. While these estimates are quite preliminary they indicate which components are likely to be the drivers in determining forced outage requirements.

Tables 4-31 and 4-32 define the forced outage components, the number of identical components required for system operation, the additional redundant components, and the percentage of the allowable forced outage downtime that is expected to be used by each component. Several types of redundancy are considered. In some cases, such as the primary coolant loops, a complete redundant loop is assumed. This loop is interconnected to allow its use in place of any other loop in the event of a component failure in one of the operating loops. This type of redundancy allows correction of the failure without shutting down the reactor unless a double point failure occurs. While a failure of one of the loop isolation valves would require a reactor shutdown these valves are non-operating unless another failure occurs. This would then constitute a double point failure. The probability of failure of these valves by a leak outside of the system is considered but is found to result in only a minor percentage of the total forced outage downtime.

Another type of redundancy is active redundancy such as that used with the cryopump panels. Since excess area is available, the loss of several panels through failure to complete the regeneration cycle can be accepted and the system will continue to operate until a scheduled shutdown occurs or until too many panels are inoperative. Instrumentation is assumed to have this type of redundancy also in addition to the doubly redundant voting system which allows the automatic determination of a failure in one sensor. In addition, standby on-line redundancy is assumed for such components as control valves where a spare valve is installed in series but is inoperative, i.e., normally open, unless the operating valve fails to control.

The components having the most significant forced outage downtimes in Tables 4-31 and 4-32 are given in order of influence in Table 4-33. Components rise to a point of significance in the list for different reasons. Both the replacement time

TABLE 4–31

TMR CENTRAL CELL FORCED OUTAGE MAINTENANCE OPERATIONS

COST ACCOUNT NUMBER	MAINTENANCE COMPONENT (SUBASSEMBLY)	PROBABLE DOMINANT FAILURE MODE	UNSCHEDULED FAILURE IMPACT** (SEE CODE)	NO. OF UNITS REQUIRED	NO. OF UNITS REDUNDANT	ESTIMATED DOWNTIME PER MAINTENANCE ACTION, DAYS*	PERCENT OF FORCED OUTAGE DOWNTIME
22	REACTOR PLANT EQUIPMENT						
22.01	REACTOR EQUIPMENT						
22.01.01	BLANKET AND FIRST WALL						
	FIRST WALL AND STRUCTURE	FIRST WALL MODULE LEAK	1,2	864	0	8.4	3.5
	ATTENUATORS	(NOT APPLICABLE)					
	WALL MODIFIERS (COATINGS)	BURN OFF	1,3	-	-	-	-
22.01.02	PRIMARY SHIELD	COOLANT CONNETION LEAK	1	864	0	8.4	.9
22.01.03	FIELD MAGNETS	DEWAR LEAK	1,2	36	0	8.4	.1
	POWER LEADS	BURNED OUT LEAD	1	72	0	8.4	.4
22.01.04	SUPPLEMENTAL HEATING	(NOT APPLICABLE)					
22.01.05	STRUCTURE AND SUPPORT	(NOT INCLUDED)					
22.01.06	VACUUM SYSTEMS						
22.01.06.01	PLASMA CHAMBER VACUUM	(SEE END PLUGS)					
22.01.06.02	MAGNET DEWAR VACUUM						
	PUMPS/COMPRESSORS	BEARING FAILURE	3	1	1	-	-
	PIPING, CONNECTIONS	CONNECTOR LEAK	3	152	0	4.3	-
	EXTERNAL VALVES	VALVE SEAL LEAK	3	76	0	5.1	-
22.01.06.03	SUPPLEMENTAL HEATING VACUUM	(FOR FUEL INJECTION BEAMS)					
	CRYOPUMPS	VALVE ACTUATORS	1,2	4	4	6.1	.9
	MECHANICAL PUMPS	(USE DIRECT CONVERTER PUMPS)					
	CRYOGEN PIPING, CONNECT.	CONNECTOR LEAK	1,3	144	0	4.3	1.1
	CRYOGEN VALVES, CONTROL	FAIL OPEN OR CLOSED	1,2	8	8	-	nil
	VACUUM PIPING, CONNECTIONS	CONNECTOR LEAK	1,3	4	0	4.3	nil
	VACUUM VALVES, REGEN.	VALVE SEAL LEAK	1,3	2	0	5.1	nil
	CRYOGEN VALVES, ISO	VALVE SEAL LEAK	3	54	0	5.1	-
22.01.06.04	DIRECT CONVERTER VACUUM	(SEE END PLUGS)					
22.01.06.05	REACTOR VACUUM SYSTEM	(FOR REACTOR ROOM)					
	PUMPS/COMPRESSORS	BEARING FAILURES	3	4 SETS	2 SETS	-	-
	PIPING, CONNECTIONS	CONNECTOR LEAK	3	24	0	4.3	-
	EXTERNAL VALVES	VALVE SEAL LEAK	3	12	0	5.1	-
22.01.06.06	REACTOR VACUUM WALL PENETRATIONS	SEAL LEAK	1,2	1 SET	0	4.1	4.9
22.01.07	POWER SUPPLY, ENERGY STORAGE						
	DIESEL GENERATORS	FAIL TO START	3	2	1	-	-
	CABLES, METERS	CONNECTOR INTERRUPT	1,2,3	5000	1000 (NOT CONNECTED)	1.8	.2
	POWER CONDITIONING						
	POWER SUPPLIES, MAGNET	POWER DISRUPTION	3	12	6	-	-
	CONTROLLERS	RELAY FAILURES	3	36	6	-	-
	SWITCHES/CIRCUIT BREAKER	CIRCUIT BREAKER FAILURE	3	36	6	-	-
	DIAGNOSTIC POWER CONDITIONING	POWER DISRUPTION	3	1 SET	1 SET	-	-
	FUEL INJECTION POWER	POWER DISRUPTION (EACH BEAM)	3	2	1	-	-
22.01.08	IMMUNITY CONTROL	(NOT APPLICABLE)					
22.01.09	DIRECT ENERGY CONVERTER	(SEE END PLUGS)					
22.02	MAIN HEAT TRANSPORT SYSTEMS						
22.02.01	PRIMARY COOLANT SYSTEM						
22.02.01.01	PUMPS AND DRIVES	SEAL LEAK	3	6	1	-	-
22.02.01.02	PIPING, CONNECTIONS	CONNECTOR LEAK	1,3	444	74	4.3	1.9
	ISOLATION VALVES	VALVE SEAL LEAK	1,3	6 SETS	1 SET	4.1	.6
	CONTROL VALVES	ACTUATOR FAILURE	1,2	36	36	4.1	.8
22.02.01.03	HEAT EXCHANGER	TUBE LEAK	3	12	2	-	-
22.02.01.04	TANKS	CONNECTOR LEAK	3	6	1	-	-
22.02.01.05	CLEAN-UP SYSTEM	CONTROL FAILURE	3	6	1	-	-
22.02.01.06	THERMAL INSULATION	(SEE PIPING, ABOVE)					
22.02.01.07	TRITIUM EXTRACTION	(SEE TRITIUM RECOVERY)					

TABLE 4–31
TMR CENTRAL CELL FORCED OUTAGE MAINTENANCE OPERATIONS (CONT.)

COST ACCOUNT NUMBER	MAINTENANCE COMPONENT (SUBASSEMBLY)	PROBABLE DOMINANT FAILURE MODE	UNSCHEDULED FAILURE IMPACT** (SEE CODE)	NO. OF UNITS		ESTIMATED DOWNTIME PER MAINTENANCE ACTION, DAYS*	PERCENT OF FORCED OUTAGE DOWNTIME
				REQUIRED	REDUNDANT		
22.02.02	INTERMEDIATE COOLANT SYSTEM						
22.02.02.01	PUMPS AND DRIVES	SEAL LEAK	3	6	1	-	-
22.02.02.02	PIPING, CONNECTIONS	CONNECTOR LEAK	1,3	84	14	4.3	nil
	ISOLATION VALVES	VALVE SEAL LEAK	1,3	12	2	4.1	nil
	CONTOL VALVES	ACTUATOR FAILURE	1,2	12	2	4.1	.5
22.02.02.03	STEAM GENERATOR	TUBE LEAK	3	6	1	-	-
22.02.02.04	TANKS	CONNECTOR LEAK	3	6	1	-	-
22.02.02.05	CLEAN-UP SYSTEM	CONTROL FAILURE	3	6	1	-	-
22.03	AUXILIARY COOLING SYSTEMS						
22.03.01	MAGNET COOLING						
	He REFRIGERATION SYSTEM	VALVE SEAL	3	144	0	-	-
	N_2 REFRIGERATION SYSTEM	VALVE SEAL	3	144	0	-	-
	PIPING CONNECTORS	CONNECTOR LEAK	1,3	566	0	4.3	4.4
	TANKS/CONTAINERS	CONNECTOR LEAK	3	74	0	-	-
22.03.02	SHIELD COOLING	(SEE PRIMARY COOLANT)					
22.03.03	SUPPLEMENTAL HEATING COOLING	(FOR FUEL INJECTION BEAMS)					
	He REFRIGERATION SYSTEM	VALVE SEAL	3	4	0	-	-
	N_2 REFRIGERATION SYSTEM	VALVE SEAL	3	4	0	-	-
	PUMPS AND DRIVES, WATER	SEAL LEAK	3	1	1	-	-
	PIPING CONNECTORS	CONNECTOR LEAK	1,3	32	0	5.1	.3
	VALVES, CONTROL	VALVE SEAL LEAK	1,2	8	0	5.1	.3
22.03.04	POWER SUPPLY COOLING	(NOT INCLUDED)					
22.04	RADIOACTIVE WATER TREATMENT	(NOT INCLUDED)					
22.05	FUEL HANDLING AND STORAGE						
22.05.01	FUEL PURIFICATION SYSTEM	(SEE END PLUGS)					
22.05.02	LIQUIDATION	(NOT APPLICABLE)					
22.05.03	FUEL PREPARATION	(SEE FUEL INJECTION, BELOW)					
22.05.04	FUEL INJECTION						
	ION SOURCES	FILAMENT BURNOUT	1,2	6	6	3.7	2.7
	ION BEAM DUMP	COOLANT LEAK	1,2	2	0	4.3	nil
	ION DUMP MAGNETS	CONDUCTOR SHORT	1	2	0	4.3	nil
22.05.05	FUEL STORAGE/PIPING	CONNECTOR LEAK	1,3	2	0	4.3	.7
22.05.06	TRITIUM RECOVERY	CONTROL FAILURE	3	-	-	-	-
22.05.07	EMERGENCY AIR DETITRIATION	NOT DEFINED	-	-	-	-	-
22.06	OTHER REACTOR EQUIPMENT						
22.06.01	MAINTENANCE EQUIPMENT						
	CENTER OVERHEAD CRANE	MECHANISM FAILURE	2	SEE DETAILED LIST		-	-
	MAGNET COOLING MODULE	VALVE FAILURE	2,3			-	-
	TRENCH ROBOT	BEARING FAILURES	2,3			-	-
	OVERHEAD MANIPULATOR	BEARING FAILURES	2,3			-	-
	TOOLS (WELDERS)	MECHANISM FAILURE	2,3			-	-
	FIXTURES	STRIPPED FITTING	2,3			-	-
	TUGS AND DOLLIES	BEARING FAILURE	2,3			-	-
	VIEWING SYSTEMS	CAMERA FAILURE	2,3			-	-
	ENTRANCE AND EGRESS LOCKS	MECHANISM FAILURE	2,3			-	-
22.06.02	SPECIAL HEATING SYSTEMS	(NOT INCLUDED)					
22.06.03	COOLANT STORAGE AND MAKEUP	(NOT INCLUDED)					
22.06.04	GAS SYSTEMS	(NOT INCLUDED)					
22.06.05	BUILDING VENTILATION SYSTEM						
	FANS	DRIVE FAILURE	3	NOT DEFINED			
	FILTERS AND SCRUBBERS	CONTROL FAILURE	3				

TABLE 31

TMR CENTRAL CELL FORCED OUTAGE MAINTENANCE OPERATIONS (CONT.)

COST ACCOUNT NUMBER	MAINTENANCE COMPONENT (SUBASSEMBLY)	PROBABLE DOMINANT FAILURE MODE	UNSCHEDULED FAILURE IMPACT** (SEE CODE)	NO. OF UNITS		ESTIMATED DOWNTIME PER MAINTENANCE ACTION, DAYS*	PERCENT OF FORCED OUTAGE DOWNTIME
				REQUIRED	REDUNDANT		
22.07	INSTRUMENTATION AND CONTROL						
22.07.01	REACTOR I&C EQUIPMENT						
	(PERFORMANCE MONITORING SYS)	INSTRUMENT FAILURE	2,3			-	-
	PROBES (REACTOR STATUS SYS)	INSTRUMENT FAILURE	2,3			-	-
	INTEGRAL INSTRUMENTS (PLASMA CONTROL SYS)	INSTRUMENT FAILURE	2,3	NOT DEFINED		-	-
	EXTERNAL INSTRUMENTS (PLASMA CONTROL SYSTEM)	INSTRUMENT FAILURE	3			-	-
	CONTROL ROOM EQUIPMENT	INDICATOR FAILURE	3			-	-
	COMPUTERS	POWER SUPPLY FAILURE	3			-	-
22.07.02	RADIATION MONITORING SYSTEM	SENSOR FAILURE	2,3			-	-
22.07.03	ISOLATED GAUGES	(NOT INCLUDED)					

*REMOTE OPERATION, ADJUSTED FOR .625 PRODUCTIVITY FACTOR

**FAILURE IMPACT CODE:
1 IMMEDIATE SHUTDOWN
2 REPAIR DURING SCHEDULED SHUTDOWN
3 REPAIR DURING OPERATION

TABLE 4–32
TMR END PLUG AND DIRECT CONVERTER FORCED OUTAGE MAINTENANCE OPERATIONS

COST ACCOUNT NUMBER	MAINTENANCE COMPONENT (SUBASSEMBLY)	PROBABLE DOMINANT FAILURE MODE	UNSCHEDULED FAILURE IMPACT** (SEE CODE)	NO. OF UNITS REQUIRED	NO. OF UNITS REDUNDANT	ESTIMATED DOWNTIME PER MAINTENANCE ACTION, DAYS*	PERCENT OF FORCED OUTAGE DOWNTIME
22	REACTOR PLANT EQUIPMENT						
22.01	REACTOR EQUIPMENT						
22.01.01	BLANKET AND FIRST WALL						
	PLUG WALL AND STRUCTURE	COOLANT LEAK	1,2	24	0	9.0	.7
	ATTENUATORS, ETC.	(NOT APPLICABLE)					
	WALL MODIFIERS	(NOT APPLICABLE)					
22.01.02	PRIMARY SHIELD	(WITH PLUG WALL)					
22.01.03	MAGNETS						
	SOLENOID	CONDUCTOR SHORT	1,3	4	0	23.8	nil
	YIN YANG	CONDUCTOR SHORT	1,3	4	0	18.0	nil
	TRANSFER	CONDUCTOR SHORT	1,3	2	0	13.9	nil
	POWER LEADS	BURNED OUT LEAD	1	20	0	8.4	.1
22.01.04	SUPPLEMENTAL HEATING						
22.01.04.01	NEUTRAL BEAM HEATING						
	ION SOURCES	GRID BURNOUT	1,2	4	0	9.4	22.6
	ION BEAM DUMP PLATES	COOLANT LEAK	1	4	0	9.4	.1
	PLASMA STRIPPING CELL	COOLANT LEAK	1	4	0	6.1	14.7
	ION DUMP MAGNETS	CONDUCTOR SHORT	1	4	0	9.4	.2
	D_2 MERCURY PUMPS	HEATER FLOW CONTROL	1	8	0	4.2	1.4
	Na COOLANT SYSTEM	COOLANT LEAK	1,3	2	0	3.3	.8
22.01.05	PRIMARY STRUCTURE AND SUPPORT	(NOT INCLUDED)					
22.01.06	VACUUM SYSTEMS						
22.01.06.01	PLASMA CHAMBER VACUUM	(WITH DIRECT CONVERTER VAC.)					
22.01.06.02	MAGNET DEWAR VACUUM						
	PUMPS/COMPRESSORS	(USE CENTRAL CELL PUMPS)					
	PIPING, CONNECTIONS	CONNECTOR LEAK	3	48	0	3.3	-
	VALVES	VALVE SEAL LEAK	3	24	0	4.1	-
22.01.06.03	SUPPLEMENTAL HEATING VALVE						
	CRYOPUMPS	VALVE ACTUATORS	1,2	20	10	6.1	1.2
	MECHANICAL PUMPS	(USE DIRECT CONVERTER PUMPS)					
	CRYOGEN PIPING, CONNECT.	CONNECTOR LEAK	1,3	240	0	3.3	1.4
	CRYOGEN VALVES, LHe CONTROL	FAIL OPEN	1,2	30	30	5.1	.9
	VACUUM PIPING, CONNECTIONS	CONNECTOR LEAK	1,3	4	0	3.3	nil
	VACUUM VALVES	VALVE SEAL LEAK	1,3	2	0	4.1	nil
	CRYOGEN VALVES	VALVE SEAL LEAK	3	90	0	4.1	-
22.01.06.04	DIRECT CONVERTER VACUUM						
	CRYOPUMPS	VALVE ACTUATORS	1,2	50	50	8.9	1.2
	MECHANICAL PUMPS	SEAL LEAK	3	2 SETS	1 SET	-	-
	CRYOGEN PIPING, CONNECT.	CONNECTOR LEAK	1,3	136	0	3.3	.8
	CYROGEN VALVES, LHe CONTROL	FAIL OPEN OR CLOSED	1,2	100	100	5.1	2.3
	VACUUM PIPING, CONNECT.	CONNECTOR LEAK	1,3	4	0	3.3	nil
	VACUUM VALVES	VALVE SEAL LEAK	1,3	2	0	4.1	nil
	CRYOGEN VALVES	VALVE SEAL LEAK	3	150	0	4.1	-
22.01.06.05	REACTOR VACUUM SYSTEM	(SEE CENTRAL CELL SYSTEM)					
22.01.06.06	VACUUM WALL (PENETRATIONS)						
	DIRECT CONVERTER	SEAL LEAK	1,2	2 SETS	0	4.1	9.9
	PLUG REGION	SEAL LEAK	1,2	2 SETS	0	4.1	
	SUPPLEMENTAL HEATING	SEAL LEAK	1,2	2 SETS	0	4.1	
22.01.07	POWER SUPPLY, ENERGY STORAGE						
	DIESEL GENERATORS	(USE CENTRAL CELL UNITS)					
	CABLES, METERS	CONNECTOR INTERRUPT	1,2,3	4000	750	1.8	.2
	POWER CONDITIONING						
	POWER SUPPLIES, NBI	POWER DISRUPTION	3	60 (4 SETS)	15	-	-
	CONTROLLERS	RELAY FAILURE	3	14	4	-	-
	SWITCHES/CIRCUIT BREAKER	CIRCUIT BREAKER FAILURE	3	14	4	-	-
	DIAGNOSTIC POWER CONDITIONING	POWER DISRUPTION	3	1 SET	1 SET	-	-
	FUEL INJECTION POWER	(SEE CENTRAL CELL)					

TABLE 4–32

TMR END PLUG AND DIRECT CONVERTER FORCED OUTAGE MAINTENANCE OPERATIONS (CONT.)

COST ACCOUNT NUMBER	MAINTENANCE COMPONENT (SUBASSEMBLY)	PROBABLE DOMINANT FAILURE MODE	UNSCHEDULED FAILURE IMPACT** (SEE CODE)	NO. OF UNITS REQUIRED	NO. OF UNITS REDUNDANT	ESTIMATED DOWNTIME PER MAINTENANCE ACTION, DAYS*	PERCENT OF FORCED OUTAGE DOWNTIME
22.01.08	IMPURITY CONTROL	(NOT APPLICABLE)					
22.01.09	DIRECT ENERGY CONVERTER						
22.01.09.01	VACUUM TANK	(SEE VACUUM WALLS)					
22.01.09.02	DIRECT CONVERTER MODULES	VANE DISCONNECT	1,2	34	0	7.1	11.6
22.01.09.03	THERMAL PANELS, WATER	COOLANT LEAK	1,2	640	0	8.4	3.2
22.01.09.04	POWER CONDITIONING EQUIP.	POWER DISRUPTION	3	4	2	-	-
22.02	MAIN HEAT TRANSPORT SYSTEMS						
22.02.01	PRIMARY COOLANT SYSTEM	(SEE CENTRAL CELL)					
22.02.02	INTERMEDIATE COOLANT SYSTEM	(SEE CENTRAL CELL)					
22.03	AUXILIARY COOLING SYSTEMS						
22.03.01	MAGNET COOLING SYSTEM	COOLANT LEAK	1	10	0	3.3	1.0
22.03.02	SHIELD COOLING, WATER						
22.03.02.02	PIPING, CONNECTIONS	CONNECTOR LEAK	1,3	132	0	3.3	.8
	HEAT EXCHANGER	TUBE LEAK	3	2	1	3.3	-
	VALVES, CONTROL	VALVE SEAL LEAK	1,2	24	0	4.1	nil
22.03.02.03	PUMPS AND DRIVES	SEAL LEAK	3	1	1		-
22.03.02.05	CLEAN-UP SYSTEM	(NOT DEFINED)	3	NOT DEFINED			-
22.03.03	SUPPLEMENTAL HEATING COOLING						
	Ha REFRIGERATION SYSTEM	VALVE SEAL	3	4	0	-	-
	N_2 REFRIGERATION SYSTEM	VALVE SEAL	3	4	0	-	-
	PUMPS AND DRIVES, WATER	(USE SHIELD COOLANT PUMPS)					
	PIPING CONNECTIONS	CONNECTOR LEAK	1,3	32	0	3.3	.2
	VALVES, CONTROL	VALVE SEAL LEAK	1,2	8	0	4.1	nil
22.03.04	POWER SUPPLY COOLING	(NOT INCLUDED)					
22.03.05	DIRECT CONVERTER COOLING						
	PUMPS AND DRIVES	SEAL LEAK	3	1	1	-	-
	PIPING CONNECTIONS	CONNECTOR LEAK	1,3	20	0	3.3	.1
	VALVES, CONTROL	VALVE SEAL LEAK	1,2	58	0	4.1	nil
	HEAT EXCHANGER	TUBE LEAK	3	1	1	-	-
	CLEARN-UP SYSTEM	(NOT INCLUDED)					
22.04	RADIOACTIVE WATER TREATMENT	(NOT INCLUDED)					
22.05	FUEL HANDLING AND STORAGE						
22.05.01	FUEL PURIFICATION SYSTEM	CONTROL FAILURE	3	9	0	-	-
22.05.02	LIQUIDATION	(NOT APPLICABLE)					
22.05.03	FUEL PREPARATION	(SEE CENTRAL CELL)					
22.05.04	FUEL INJECTION	(SEE CENTRAL CELL)					
22.05.05	FUEL STORAGE/PIPING	CONNECTOR LEAK	1,3	26	0	3.3	.2
22.05.06	TRITIUM RECOVERY	CONTROL FAILURE	3	6	0	-	-
22.05.07	EMERGENCY AIR DETITRIATION	NOT DEFINED	3	NOT DEFINED		-	-
22.06	OTHER REACTOR EQUIPMENT						
22.06.01	MAINTENANCE EQUIPMENT						
	HIGH BAY CRANE	MECHANISM FAILURE	2	SEE DETAILED LIST		-	-
	SHIELDING MANIPULATOR	BEARING FAILURES	2,3			-	-
	NBI MANIPULATOR	BEARING FAILURES	2,3			-	-
	DIRECT CONVERTER MANIPULATOR.	BEARING FAILURES	2,3			-	-
	TOOLS (WIELDERS)	MECHANISM FAILURE	2,3			-	-
	FIXTURES	STRIPPED FITTING	2,3			-	-
	TUGS AND DOLLIES	BEARING FAILURES	2,3			-	-
	VIEWING SYSTEMS	CAMERA FAILURE	2,3			-	-
	ENTRANCE AND EGRESS LOCKS	MECHANISM FAILURE	2,3			-	-
22.06.02	SPECIAL HEATING SYSTEMS	(NOT INCLUDED)					
22.06.03	COOLANT STORAGE AND MAKEUP	(NOT INCLUDED)					
22.06.04	GAS SYSTEMS	(NOT INCLUDED)					
22.06.05	BUILDING VENTILATION SYSTEM						
	FANS	DRIVE FAILURE	3	NOT DEFINED			
	FILTERS AND SCRUBBERS	CONTROL FAILURE	3				

TABLE 4–32

TMR END PLUG AND DIRECT CONVERTER FORCED OUTAGE MAINTENANCE OPERATIONS (CONT.)

COST ACCOUNT NUMBER	MAINTENANCE COMPONENT (SUBASSEMBLY)	PROBABLE DOMINANT FAILURE MODE	UNSCHEDULED FAILURE IMPACT** (SEE CODE)	NO. OF UNITS REQUIRED	NO. OF UNITS REDUNDANT	ESTIMATED DOWNTIME PER MAINTENANCE ACTION, DAYS*	PERCENT OF FORCED OUTAGE DOWNTIME
22.07	INSTRUMENTATION AND CONTROL						
22.07.01	REACTOR I&C EQUIPMENT						
	PROBES						
	(PERFORMANCE MONITORING SYS)	INSTRUMENT FAILURE	2,3			-	-
	INTEGRAL INSTRUMENTS			NOT DEFINED			
	(REACTOR STATUS SYSTEM)	INSTRUMENT FAILURE	2,3			-	-
	EXTERNAL INSTRUMENTS						
	(PLASMA CONTROL SYSTEM)	INSTRUMENT FAILURE	3			-	-
	CONTROL ROOM EQUIPMENT	INDICATOR FAILURE	3			-	-
	COMPUTERS	POWER SUPPLY FAILURE	3			-	-
22.07.02	RADIATION MONITORING SYSTEM	NOT DEFINED	2,3			-	-
22.07.03	ISOLATED GAUGES	(NOT INCLUDED)					

*REMOTE OPERATION, ADJUSTED FOR .625 PRODUCTIVITY FACTOR

**FAILURE IMPACT CODE:
1 IMMEDIATE SHUTDOWN
2 REPAIR DURING SCHEDULED SHUTDOWN
3 REPAIR DURING OPERATION

(MTTR) and the requirement for state of art advances lead to the prominence of the neutral beam components. The large number of piping connections estimated for the central cell magnet cryogen system is responsible for the high percentage of maintenance time that may be required by this system. However, the preliminary nature of such estimates must be considered and any variation in the assumptions made can significantly alter the results of this listing. A principal benefit of the results shown in Table 4-33 is to indicate the types of systems and components that must be considered in reactor design in order to minimize forced outages.

4.2.6 Advanced TMR Scheduled Outage Scenarios - The advanced TMR configuration being defined by the Lawrence Livermore Laboratory is outlined in Section 3.5. Some elaboration of the design is necessary to provide a basis for evaluating maintainability trends. The elaboration defined for use in this study is also discussed in Section 3.5.

TABLE 4–33
TMR FORCED OUTAGE CONTRIBUTIONS

COMPONENT	UNSCHEDULED DOWNTIME[1] (PERCENT OF TOTAL ALLOWABLE)
END PLUG NEUTRAL BEAM ION SOURCES	22.9
END PLUG NEUTRAL BEAM STRIPPING CELLS	14.8
DIRECT CONVERTER GRID MODULES	11.7
END PLUG AND DIRECT CONVERTER VACUUM WALL SEALS	10.0
CENTRAL CELL VACUUM WALL SEALS	5.0
CENTRAL CELL MAGNET PIPING CONNECTIONS	4.4
CENTRAL CELL FIRST WALL/BLANKET	3.5
DIRECT CONVERTER THERMAL PANELS	3.3
FUEL INJECTION NEUTRAL BEAM ION SOURCES	2.7
DIRECT CONVERTER CRYOPUMP CRYOGEN/CONTROL VALVES	2.3
CENTRAL CELL PRIMARY COOLING PIPING CONNECTIONS	1.9
END PLUG NEUTRAL BEAM CRYOPUMP PIPING CONNECTIONS	1.4
END PLUG ION SOURCE VACUUM PUMP	1.4
END PLUG NEUTRAL BEAM CRYOPUMP SHUTTERS	1.3
DIRECT CONVERTER CRYOPUMP SHUTTERS	1.2
FUEL INJECTION NEUTRAL BEAM VACUUM COOLING PIPING CONNECTIONS	1.1
END PLUG MAGNET COOLANT SYSTEM CONNECTIONS	1.0
OTHER COMPONENTS (< 1 PERCENT EACH)	10.1
	100.0%

[1] VARIATIONS IN PRELIMINARY ESTIMATES CAN ALTER RESULTS SIGNIFICANTLY.

Because of the preliminary status of the design only two maintenance actions have been defined for comparison with the baseline TMR design concept. These are the replacement of the central cell sectors and the replacement of the direct converter chamber cryopump panels. The critical region of the end plugs is insufficiently defined to provide a base for a maintainability analysis. Principal uncertainties are the size, number and location of the neutral beam injectors and the RF waveguides. The arrangement of the end plug magnets, together with the dimensions and location shown is being revised. Therefore, the maintainability of this region may change accordingly. However, it is believed that the impact of the design trends on the selected maintenance actions provide significant insight into the potential effects of the conceptual design advances.

4.2.6.1 Central Cell Sector Replacement - The replacement schedule for the central cell sectors of the advanced TMR is outlined in Table 4-34. The revised

TABLE 4-34
SINGLE CENTRAL CELL SECTOR REPLACEMENT
TANDEM MIRROR ADVANCED CONCEPT (REMOTE OPERATIONS)

LEVEL 1 TASK	LEVEL 2 TASK	DURATION (HRS:MIN)
SHUTDOWN	REACTOR SHUTDOWN	17:00
ACCESS	REMOVE TRENCH COVER	7:00
	CONNECT MAGNET COOLING MODULE	5:55
	DISCONNECT ELECTRICAL AND COOLANT LINES	8:10
	REMOVE INTER-SECTOR SHIELD SEGMENTS	8:35*
REMOVAL	REMOVE CENTRAL CELL SECTOR	4:00
REPLACEMENT	EMPLACE CENTRAL CELL SECTOR	4:30
REASSEMBLY	INSTALL INTER-SECTOR SHIELD SEGMENTS	16:50*
	CONNECT ELECTRICAL AND COOLANT LINES	8:30
	REMOVE MAGNET COOLING MODULE	4:25
	TEST INSTALLATION	2:20
	INSTALL VACUUM TRENCH COVER	7:45
STARTUP	START REACTOR	28:00
	TOTAL:	123:00
	TIME REQUIRED FOR EACH ADDITIONAL SECTOR:	48:55

*TIME ESTIMATE IS FOR SECTOR SHIELD SEGMENTS ON BOTH SIDES OF SECTOR. SUCCEEDING SECTORS ONLY REQUIRE REMOVAL OF THE SHIELD SEGMENTS ON ONE SIDE OF THE SECTOR.

central cell design concept differs significantly from the baseline TMR design, not only in the first wall/blanket configuration, but also in the size of the sector and in the technique used for joining the adjacent sectors together. The procedure used in this evaluation assumes that simplified shield blocks are still required both to augment the joint shielding for magnet protection and to serve as spacers for the sectors. It is this simplification that produces the most significant reduction in time and allows the replacement time per sector to be 123:00 hours compared to 145:25 hours for the larger sector in the baseline TMR configuration. The other significant time reduction is the possible reduction in startup time for bringing the system to the desired vacuum since the volume evacuated is significantly reduced. This time reduction is dependent on any change in the plug bore dimension which could increase the conductance at that point.

Other lesser time reductions are possible for transporting the sector or attaching crane hooks to the lift points because of the smaller sector size and mass. These reductions have not been included. The trench cover removal remains the same as for the baseline design because the latching mechanism operation is unchanged. Two central cell cranes are still required to hoist each of the four covers. A magnet cooling module is considered necessary for the advanced TMR for the same reasons as for the baseline TMR. The sector electrical and coolant line connections have not yet been defined. Smaller lines will reduce the time required for disconnect but line connection access remains to be clarified. Therefore, the estimates for these times are unchanged.

It appears evident from this brief examination that the advanced TMR central cell sector replacement can be accomplished in significantly less time because of the simplified joint design and the smaller size.

4.2.6.2 Direct Converter Cryopump Replacement - The advanced TMR cryopump vacuum system located in the direct converter housing has significantly better access than the system devised for the baseline configuration. Because of the smaller diameter direct converter, approximately 15 meters, the end of the direct converter housing is assumed to be a removable circular pressure door approximately 20 meters in diameter. This door can be withdrawn with the direct converter collector vanes attached to it to expose both the collector vanes and the cryopump panels for direct maintenance access. The cryopump panels need only be shielded from a relatively low temperature collector vane since these vanes are actively cooled. Therefore, the cryopump panels can be made readily accessible and are removed by sliding them toward the open end of the chamber.

Table 4-35 defines the replacement procedure for one cryopanel, including the opening and closing of the end cover of the direct converter chamber. The principal item of maintenance equipment used is the overhead manipulator and a set of extension guide rails with remotely operated disconnect equipment. This guide rail assembly can be moved around the periphery of the entrance to the direct converter chamber to disconnect, withdraw, insert and reconnect the cryopump panels. If necessary, two sets of rails can be used when replacing a significant fraction of the cryopump panels. Another advantage of the advanced TMR configuration is that larger panel assemblies can be used because of the increased space that is available for handling them.

TABLE 4–35
DIRECT CONVERTER CHAMBER CRYOPUMP PANEL REPLACEMENT
TANDEM MIRROR ADVANCED CONCEPT (REMOTE OPERATIONS)

LEVEL 1 TASK	LEVEL 2 TASK	DURATION (HRS:MIN)
SHUTDOWN	SHUTDOWN REACTOR	17:00
ACCESS	OPEN DIRECT CONVERTER CHAMBER DOOR	14:30
	MOVE DOOR CLEAR FOR ACCESS	2:00
	EMPLACE EXTENSION RAIL MACHINE	3:15
	DISCONNECT CRYOPUMP PANEL SERVICES	3:30
REMOVAL	REMOVE CRYOPUMP FROM CHAMBER	1:00
	PLACE ON DOLLY	2:15
REPLACEMENT	PLACE REPLACEMENT PANEL ON EXTENSION RAILS	1:45
	MOVE CRYOPUMP PANEL INTO CHAMBER	1:00
REASSEMBLE	CONNECT CRYOPUMP PANEL SERVICES	5:00
	PRESSURE TEST CONNECTIONS	1:30
	REMOVE EXTENSION RAIL MACHINE	2:00
	CLOSE DIRECT CONVERTER CHAMBER DOOR	3:00
	FASTEN CHAMBER DOOR AND SEAL	25:20
STARTUP	STARTUP REACTOR	28:00
	TOTAL:	111:05
	TIME REQUIRED FOR EACH ADDITIONAL PANEL:	21:15*

*REQUIRES REPOSITIONING EXTENSION RAIL MACHINE

4.3 TOKAMAK MAINTENANCE PLAN - The maintenance scenarios and time estimates developed for the earlier part of the study (Reference 3) are used as the basis for the comparisons conducted in this analysis. However, the IMS tokamak scenarios require some modification from those developed for the Culham Mark IIB which served as a base concept. Therefore, the maintenance action scenarios have been revised to apply to the IMS tokamak and are included in this section. Also, some additional scenarios have been developed to cover the wider range of components that must be considered for a valid comparison with the TMR.

4.3.1 Selected Tokamak Maintenance Action Scenarios - The maintenance actions developed for the tokamak are listed in Table 4-36. The second level breakdown for the procedure used in each scenario is also included in this section. Several of these scenarios are representative of a general class of maintenance action and are used as a basis for estimating similar maintenance actions in the TMR maintenance plan. These include scenarios for replacement of the seals, valves, power leads, and the charge exchange analyzer. The latter item is considered to be a typical external diagnostic system that would be required for any reactor control.

TABLE 4–36
TOKAMAK SELECTED MAINTENANCE ACTIONS

- o FIRST WALL BLANKET REPLACEMENT
- o NEUTRAL BEAM ION SOURCE REPLACEMENT
- o NEUTRAL BEAM ISOLATION VALVE REPLACEMENT
- o DIVERTOR CRYOPUMP REPLACEMENT
- o DIVERTOR PARTICLE BOMBARDMENT PLATE REPLACEMENT
- o SHIELD DOOR SEAL REPLACEMENT
- o COOLANT LOOP VALVE REPLACEMENT
- o ELECTRICAL POWER LEAD REPLACEMENT
- o CHARGE EXCHANGE ANALYZER REPLACEMENT
- o TOROIDAL FIELD MAGNET REPLACEMENT

The scenarios developed for the TMR maintenance actions include the reactor shutdown and startup times. Therefore, the scenarios defined for the tokamak maintenance actions also include comparable times. These time estimates were developed in the earlier study phases and are included in the individual scenarios for completeness. However, when a scheduled shutdown occurs in which many maintenance actions are accomplished, the time for only one reactor shutdown and startup is included.

All time estimates discussed in this section assume that the effort is continuous and no allowances for time dilution factors have been made. When combining these scenarios into a total maintenance plan, a productivity factor of .625 is used. This factor is selected as a reasonable compromise between the optimistic factor of .75 used in earlier study phases and the more severe combination of factors defined in Reference 11.

4.3.1.1 First Wall/Blanket Replacement - The maintenance procedure used to replace one of the sixteen first wall/blanket sectors in the IMS tokamak reactor is outlined in Table 4-37. This schedule is identical to that developed for the IMS in the earlier study.

Since the TMR does not utilize an inspection of adjacent sectors, the inspection function is eliminated from the IMS tokamak maintenance plan when removal of more than one sector is conducted in a scheduled replacement operation. The total time for replacement of a sector without inspection of adjacent sectors is 220:40 hours.

4.3.1.2 Neutral Beam Ion Source Replacement - The neutral beam injector assemblies for the IMS tokamak are assumed to be similar to the Tokamak Fusion Test Reactor neutral beam injectors (Reference 5). However, the installation has been simplified as indicated in Section 3.3.3 to reduce the number of connectors that must be broken and remade. Also, the three ion sources are mounted with an isolation valve between the source and the neutral beam injector housing to allow replacement of the ion sources without bringing the main neutral beam injector housing to atmospheric pressure. This feature may permit replacement of the ion sources while the reactor is operating but, for the purpose of this study, it is assumed that a reactor shutdown is required.

The IMS tokamak configuration is designed to allow servicing of the neutral beam injectors in two positions, namely, with the plasma chamber shield door either closed or open. The neutral beam injector is attached to the door and toroidal field core support panel assembly at each sector. When this door assembly is

TABLE 4–37
FIRST WALL/BLANKET SECTOR REPLACEMENT
IMS TOKAMAK REACTOR (REMOTE OPERATIONS)

LEVEL 1 TASK	LEVEL 2 TASK	DURATION (HRS)
SHUTDOWN	SHUTDOWN REACTOR	17.00
ACCESS	RETRACT POLODIAL MAGNET	5:00
	DISCONNECT NBI REGENERATION DUCT	3:35*
	ROTATE SHIELD DOOR, LSAP AND NBI	12:45
	INSTALL TRACK SEGMENT	4:15
	DISCONNECT MODULE COOLANT MANIFOLD	10:00
REMOVAL	REMOVE REACTOR MODULE	18:30
	REMOVE DIVERTOR CANISTERS (6)	26:15
INSPECTION	INSPECT REMAINING MODULES	76:35
REPLACEMENT	REPLACE DIVERTOR CANISTERS (6)	27:45
	REPLACE REACTOR MODULE	19:20
	CONNECT MODULE COOLANT MANIFOLD	7:50
	PRESSURIZE COOLANT MANIFOLD AND TEST	15:30
	REMOVE TRACK SEGMENT	8:30
REASSEMBLE	ROTATE SHIELD DOOR, LSAP AND NBI	14:00
	CONNECT NBI REGENERATION DUCT AND TEST	7:45*
	REPOSITION POLODIAL MAGNETS	6:00
STARTUP	VALIDATION AND STARTUP	28:00
*PARALLEL EFFORT. NOT INCLUDED IN TOTAL TIME	TOTAL:	297:15
	TIME FOR EACH ADDITIONAL SECTOR:	164:00**

**OMITS SHUTDOWN AND STARUP, INSPECTION OF OTHER MODULES AND MOVEMENT OF POLOIDAL MAGNETS.

closed, access to the neutral beam injector and the attached ion sources is from the main floor level of the reactor room. This is the access applicable to the scenario used in this study. A basic assumption attendant to using this access is that the first wall/blanket at that sector is not being replaced during the scheduled outage considered in the maintenance plan. The alternate arrangement with the door assembly open requires access from below the main reactor floor.

Such access is attained in parallel with first wall/blanket sector replacement operations. However, equipment requirements and replacement procedures, when using this access will differ from those defined in the baseline scenario discussed in this section.

The maintenance schedule used for this scenario is outlined in Table 4-38. The procedure assumes that the isolation valve is closed automatically and that the SF_6 is depressurized and purged prior to disconnecting the services. With the rearranged connections, only one SF_6 line, a pair of water cooling lines, a single set of power leads and the beam duct must be disconnected. All service connections require the removal of only one bolt to disconnect the line. Each line will be purged before the disconnect is made. The support structure requires disconnecting the ion source at only four attachment points.

TABLE 4–38
NEUTRAL BEAM ION SOURCE REPLACEMENT
IMS TOKAMAK REACTOR (REMOTE OPERATIONS)

LEVEL 1 TASK	LEVEL 2 TASK	DURATION (HRS:MIN)
SHUTDOWN	REACTOR SHUTDOWN	17:00
	CLOSE NEUTRAL BEAM ION SOURCE ISOLATION VALVE	:05*
	PURGE ION SOURCE OF SF_6	1:00*
ACCESS	ATTACH GENERAL PURPOSE MACHINE HOIST TO ION SOURCE	2:55
	DISCONNECT ION SOURCE SERVICES	1:35
	DISCONNECT BEAM DUCT AND STRUCTURAL SUPPORT	2:10
REMOVE	MOVE ION SOURCE TO DOLLY	:50
REPLACE	EMPLACE REPLACEMENT ION SOURCE ON NBI HOUSING	1:25
	CONNECT REPLACMENT ION SOURCE TO STRUCTURE	3:20
	RECONNECT ION SOURCE SERVICES	2:15
	REMOVE GENERAL PURPOSE MACHINES	:35
	TEST CONNECTIONS	7:00
STARTUP	OPEN ISOLATION VALVE	:05*
	CHARGE ION SOURCE WITH SF_6	:30*
	REACTOR STARTUP	28:00
*CONDUCTED IN PARALLEL. NOT INCLUDED IN TOTAL.	TOTAL:	67:05
TIME FOR REPLACING THREE ION SOURCES ON ONE NEUTRAL BEAM INJECTOR:		97:15

The time required to replace all three ion sources located in one neutral beam injector is also given in Table 4-38. When replacing all three sources, the time required to attach the hoist is reduced and the connections for the three ion sources are tested at the same time, thus reducing the replacement time for each of the two additional ion sources to 15:05 hours.

The principal equipment required is one general purpose manipulator, a dolly to transport the ion sources, and the necessary tools and workheads for making connections. A relatively low capacity hoist is used to handle the ion sources and move them between the dolly and the back of the neutral beam injector.

This operation is depicted as being fully remote in this schedule. A totally contact operation is also conceivable with a different design arrangement using a shielded isolation valve and a completely shielded ion source. The shielding requirements would either increase the spacing of the beams if the ion sources are separated or require removal of all three sources at one time. The system maintainability must be examined in greater detail to determine whether such design features would produce a significant benefit to maintainability.

4.3.1.3 Neutral Beam Isolation Valve Replacement - Each neutral beam injector assembly is connected to the plasma chamber through the outer shield door assembly by means of a beam duct. This duct includes an isolation valve to protect the neutral beam injector when it is not operating and, if required, to act as a vacuum barrier when the neutral beam injector is disconnected from the reactor. Section 3.3.3 discusses the design arrangement.

This scenario considers the maintenance action required in the event it is necessary to replace this isolation valve. Access takes place with the outer shield door closed and from the main floor level of the reactor room as discussed in the scenario for replacement of the ion sources. Table 4-39 defines the procedure for replacement of the valve on one neutral beam injector. The procedure will be identical for the valve on each additional neutral beam injector.

For this scenario the services to the valve and the surrounding shielding include cooling water to the shielding, pneumatic lines to the valve actuator and instrumentation connections. These lines must all be disconnected and, after the valve is replaced and the connections remade, all connections must be tested for leaks. Connectors are of the same single bolt attachment type used for the ion source. The shielding is in two half cylinder pieces which enclose the valve body and are fastened to the support structure by two fasteners for each half cylinder as shown in Figure 3-16. The valve body is held in place by two ring clamps around the beam duct which can be disconnected. Then the valve assembly is lifted out of position. Metal vacuum seals are required in this radiation environment and clearance will be provided by a short bellows section assembled as a part of the beam duct. This bellows section also allows for correction of slight misalignments on reassembly.

TABLE 4-39
NEUTRAL BEAM ISOLATION VALVE REPLACEMENT
IMS TOKAMAK REACTOR (REMOTE OPERATIONS)

LEVEL 1 TASK	LEVEL 2 TASK	DURATION (HRS:MIN)
SHUTDOWN	REACTOR SHUTDOWN	17:00
ACCESS	POSITION GENERAL PURPOSE MACHINE AT VALVE	1:40
	REMOVE BEAM DUCT SHIELDING	4:30
	DISCONNECT VALVE ACTUATOR AND INSTRUMENTATION	1:00
	ATTACH HOIST ON MACHINE TO VALVE	1:15
	REMOVE TWO RING CLAMPS	1:40
REMOVE	LOWER VALVE TO DOLLY	:50
REPLACE	POSITION REPLACEMENT VALVE	1:25
REASSEMBLE	ASSEMBLE RING CLAMPS ATTACHING VALVE TO BEAM DUCT	2:55
	CONNECT VALVE ACTUATOR AND INSTRUMENTATION	1:30
	TEST FLUID LINES AND VACUUM SEALS	2:15
	INSTALL BEAM DUCT SHIELDING	5:10
	TEST COOLANT LINES FOR LEAKS	1:20
STARTUP	STARTUP REACTOR	28:00
	TOTAL:	70:30

4.3.1.4 Divertor Cryopump Replacement - The plasma chamber cryopumps are cylindrical and installed above the reactor. They are connected to the plasma chamber through an isolation valve and a plenum chamber located above the divertor. Each also is connected to the regeneration and roughing system through a vacuum line and a regeneration isolation valve as discussed in Section 3.3.4.

The procedure for replacement of a cryopump on the IMS tokamak reactor is defined in Table 4-40. This procedure assumes that the reactor is shut down and the pump is warmed up before the exchange is made with a replacement cryopump. However, the location of the isolation valves is such that the replacement of a pump could possibly be conducted while the reactor is operating. Such a replacement procedure requires detailed study of the feasibility of designing equipment, including the connectors, seals and pumps, where the motion can be controlled in strong magnetic fields without disrupting the operation. The procedure uses a manipulator workhead installed on an auxiliary maintenance device mounted on or above the central core of the reactor. This equipment allows other maintenance actions to be conducted on the floor of the reactor room without interference by the replacement of the cryopumps.

TABLE 4–40
PLASMA CHAMBER CRYOPUMP REPLACEMENT
IMS TOKAMAK REACTOR (REMOTE OPERATIONS)

LEVEL 1 TASK	LEVEL 2 TASK	DURATION (HRS:MIN)
SHUTDOWN	SHUTDOWN REACTOR	17:00
	EQUALIZE CRYOPUMP AND REACTOR ROOM PRESSURE	:25*
ACCESS	INSTALL WORKHEAD ON CENTRAL CORE MAINTENANCE DEVICE	3:20
	DISCONNECT SERVICES AND REGENERATION DUCT	3:00
	DISCONNECT FROM PLENUM ISOLATION VALVE	1:40
	DISCONNECT FROM STRUCTURE	2:10
REMOVE	MOVE CRYOPUMP FROM SUPPORT STRUCTURE TO DOLLY	1:35
REPLACE	EMPLACE REPLACEMENT CRYOPUMP	1:35
REASSEMBLE	CONNECT CRYOPUMP TO SUPPORT STRUCTURE	2:00
	CONNECT CRYOPUMP TO PLENUM DUCT	2:10
	CONNECT SERVICES AND REGENERATION DUCT	4:20
	TEST CONNECTIONS FOR LEAKS	6:50
	REMOVE CENTRAL CORE MAINTENANCE DEVICE WORKHEAD	1:20
STARTUP	STARTUP REACTOR	28:00
*PARALLEL OPERATION. NOT INCLUDED IN TOTAL TIME.	TOTAL:	75:00
	TIME FOR ADDITIONAL CYROPUMP:	25:20**

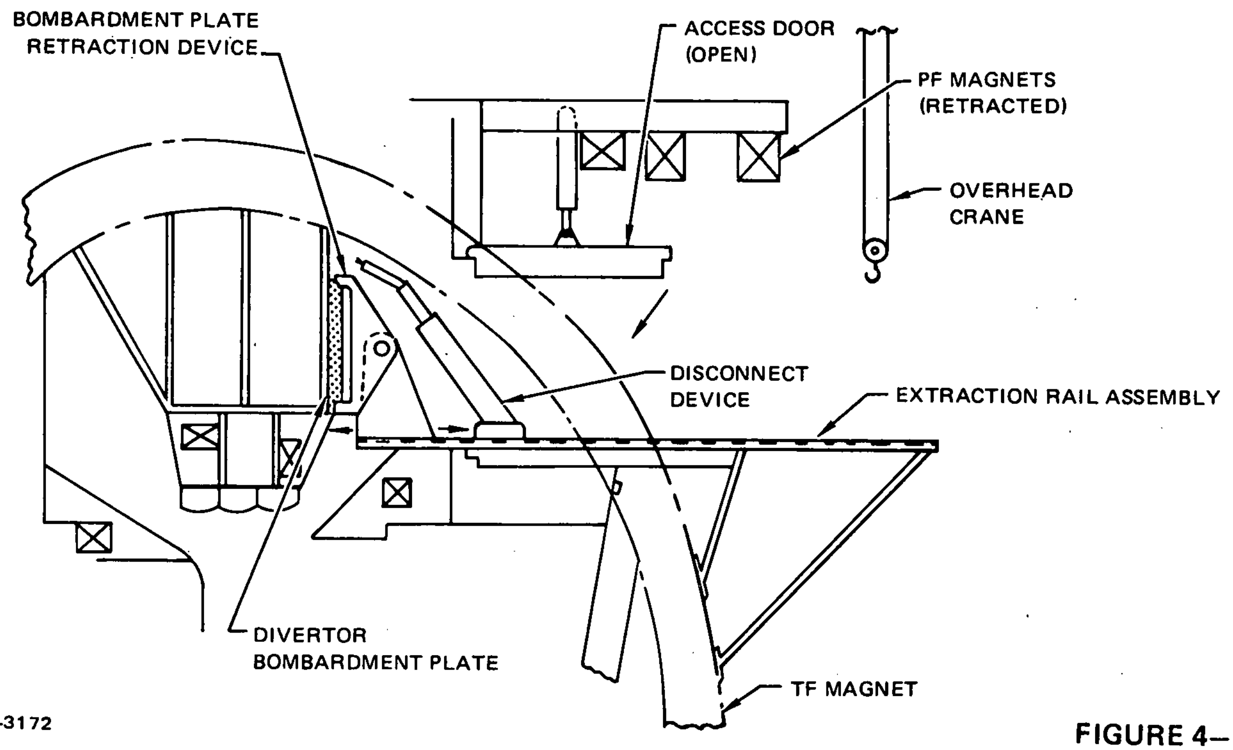
**OMITS SHUTDOWN AND STARUP AND WORKHEAD INSTALLATION AND REMOVAL.

Cryopump replacement requires disconnecting both the regeneration duct and the duct to the divertor plenum on the cryopump side of the isolation valves. These ducts are connected by use of ring clamp fasteners of the same type used for the neutral beam injector beam duct described in the previous section. All other services are brought to single attachment points for each service inlet and outlet to reduce the number of connections that must be worked to a minimum. Structural connections are such that, after services and structure are disconnected, the cryopump can be lifted from its support by the overhead crane and placed on a floor dolly for removal from the reactor room. The regeneration duct includes a short bellows section to allow it to be moved laterally to clear the cryopump before lifting the cryopump out of position.

The procedure and downtimes given in Table 4-40 are for fully remote operations since the cryovacuum pumps are expected to be radioactive when removed from the reactor. Sufficient shielding to provide biological protection and permit hands-on maintenance would be very heavy and expensive.

4.3.1.5 Divertor Particle Bombardment Plate Replacement - The replacement of divertor particle bombardment plates uses access through shield doors located in the vacuum plenum wall above the divertor and between toroidal field coils (Figure 4-14). The bombardment plates, both inner and outer, are mounted on structural end

DIVERTOR PARTICLE BOMBARDMENT PLATE REMOVAL



13—3172

FIGURE 4—14

plates located inside the bore of the toroidal field coils. These plates are recessed behind the divertor first wall/blanket module to protect the edges of the plate from direct neutron steaming. The life of plates and the resultant replacement rate when installed in this position is unknown.

The procedure for replacement of the plates is outlined in Table 4-41. The access door is unlatched and a permanently mounted actuator opens the door. The poloidal field coils above the reactor centerline must be fully retracted for this operation. The Bombardment Plate Removal Device (BPRD) is installed by dropping it into locating sockets with the aid of the overhead crane. This device is secured by attaching it to the reactor structure. The plate retraction workhead is attached to the plate and supports it while it is being disconnected by the disconnect

TABLE 4–41
DIVERTOR PARTICLE BOMBARDMENT PLATE REPLACEMENT
IMS TOKAMAK REACTOR (REMOTE OPERATIONS)

LEVEL 1 TASK	LEVEL 2 TASK	DURATION (HRS:MIN)
SHUTDOWN	SHUTDOWN REACTOR	17:00
ACCESS	RAISE POLOIDAL FIELD MAGNETS	5:00
	INSTALL BOMBARDMENT PLATE REMOVAL DEVICE (BPRD)	3:00
	ATTACH REMOVAL WORKHEAD TO BOMBARDMENT PLATE	:30
	DISCONNECT BOMBARDMENT PLATE SERVICES AND STRUCTURE	1:40
REMOVE	RETRACT FROM REACTOR AND PLACE ON DOLLY	1:45
REPLACEMENT	EMPLACE REPLACEMENT MODULE IN REACTOR	2:05
REASSEMBLE	CONNECT BOMBARDMENT PLATE SERVICES AND STRUCTURE	3:25
	DISCONNECT AND REMOVE BPRD FROM REACTOR	1:35
	CLOSE ACCESS DOOR AND LATCH	1:05
	LOWER POLOIDAL FIELD MAGNETS	6:00
STARTUP	STARTUP REACTOR	28:00
	TOTAL:	71:05
	ADDITIONAL TIME FOR INNER PLATE:	9:25
	TIME FOR 2 PLATES IN ADDITIONAL SECTOR:	24:30

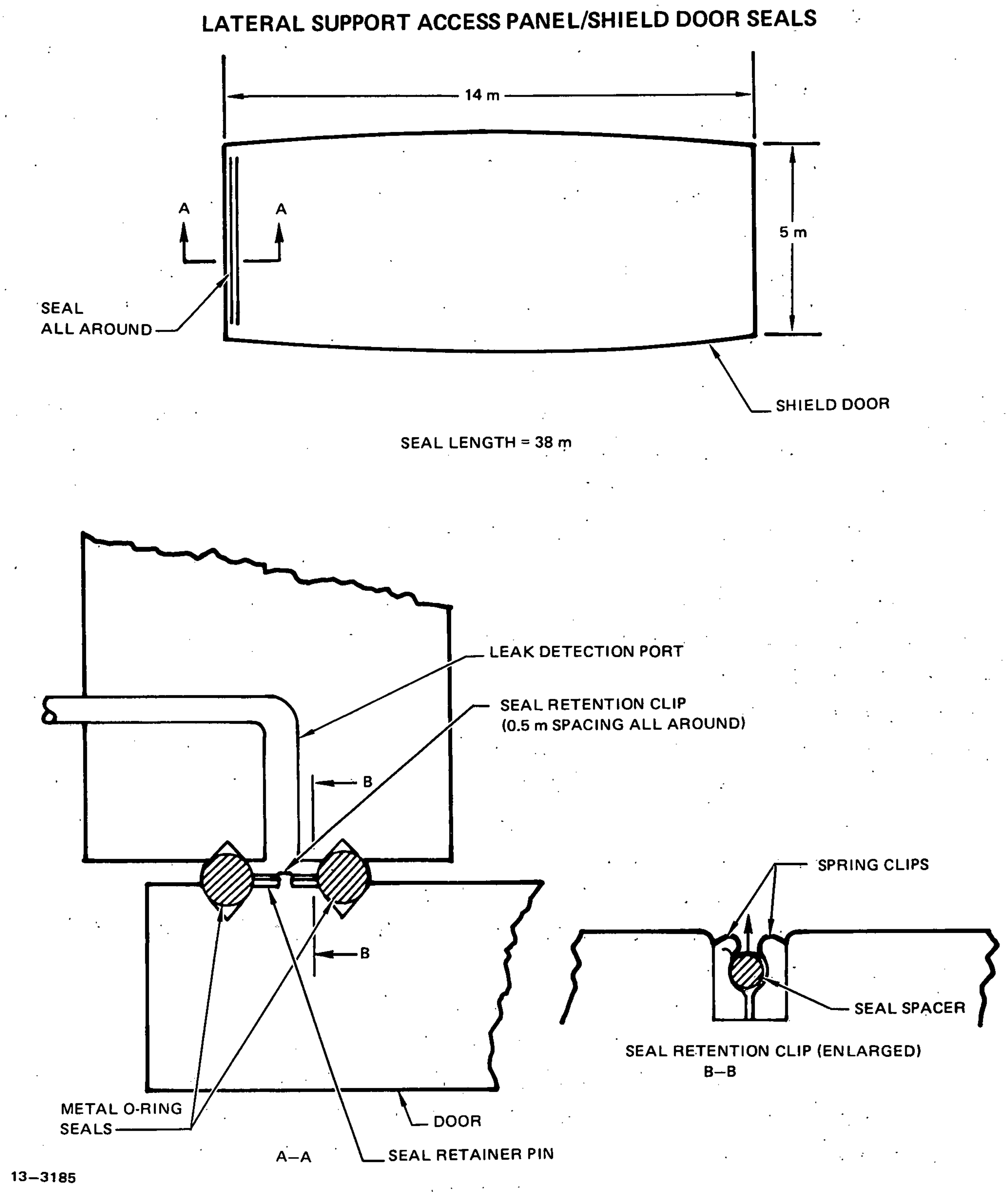
workhead. This disconnect workhead reaches above and behind the plate after removal of a small shield block and disconnects the coolant lines at either side of the plate. The structural fasteners are disconnected. Both workheads are withdrawn from the plenum chamber and the bombardment plate is removed by use of the overhead crane. The inner bombardment plate is detached in a similar manner but to remove it from the chamber the workhead must be canted sideways to allow the plate to pass between its structural supports. The details of this mechanism are not shown in the illustration.

4.3.1.6 Shield Door Seal Replacement - A typical maintenance action for replacing large vacuum wall seals is that of replacing the seal in the outer shield door of each IMS tokamak reactor sector. The seal design uses a double metal seal which is mounted around the periphery of the inside face of the door on a lip of the door. It is assumed that the seal is a continuous, closed and preformed piece so that it is unable to be handled as a small package during installation. The mounting method is illustrated in Figure 4-15.

The procedure for installing this seal is defined in Table 4-42. A special seal workhead is located precisely on the inner face of the door after it is opened and in position as a bridge in the floor of the reactor room. This workhead grips the old seal and pulls it free from the retention clips. The workhead and the old seal are then lifted free of the door. The seal is transported in and out of the reactor room on a transport fixture. The seal workhead is as large as the shield door and, therefore, it must be handled by a hoist or the overhead crane. This workhead is positioned and operated by the General Purpose Maintenance Machine (GPMM). Since the inner surface of the shield door is radioactive, only remote operations are considered for this maintenance.

It is expected that this maintenance action will be conducted after each replacement of a first wall/blanket sector. Therefore, even though Table 4-42 indicates the total procedure, much will already be accomplished and replacement of a door seal will only require an additional 13:30 hours.

4.3.1.7 Coolant Loop Valve Replacement - A typical coolant valve replacement operation is the replacement of a control valve in the plasma chamber shield coolant line. The shield coolant is water and the line to a single sector is assumed to be approximately 6 inches in diameter. The valve is located in the reactor room but outside of the outer shield door/lateral support panel assembly and below the level of the main floor. Access to the valve is achieved by reaching from the main floor beside the pit surrounding the reactor to just below floor level with the



LATERAL SUPPORT ACCESS PANEL/SHIELD DOOR SEALS
14 m
5 m
A
A
SEAL
ALL AROUND
SHIELD DOOR
SEAL LENGTH = 38 m
LEAK DETECTION PORT
SEAL RETENTION CLIP
(0.5 m SPACING ALL AROUND)
B
B
METAL O-RING
SEALS
DOOR
A–A
SEAL RETAINER PIN
SPRING CLIPS
SEAL SPACER
SEAL RETENTION CLIP (ENLARGED)
B–B
13–3185

FIGURE 4–15

TABLE 4-42
SHIELD DOOR SEAL REPLACEMENT
IMS TOKAMAK REACTOR (REMOTE OPERATIONS)

LEVEL 1 TASK	LEVEL 2 TASK	DURATION (HRS:MIN)
SHUTDOWN	SHUTDOWN REACTOR	17:00
ACCESS	RAISE POLOIDAL FIELD COILS	5:00
	OPEN SHIELD DOOR	12:45
	INSTALL SEAL WORKHEAD ON SHIELD DOOR	3:25
	ENGAGE AND FREE SEAL FROM DOOR. INSPECT	1:20
REMOVE	INSTALL SEAL ON TRANSPORT FIXTURE	1:20
REPLACEMENT	PICKUP NEW SEAL FROM TRANSPORT FIXTURE. INSPECT	1:35
	INSTALL SEAL IN SHIELD DOOR SEAL GROOVES. ATTACH	2:50
REASSEMBLE	REMOVE SEAL WORKHEAD AND PLACE ON TRANSPORT DOLLY	3:00
	CLOSE SHIELD DOOR	14:00
	LOWER POLOIDAL FIELD COILS	6:00
STARTUP	STARTUP REACTOR	28:00
	TOTAL:	96:15
	TIME REQUIRED FOR COMPLETE ADDITIONAL SECTOR:	40:15
	TIME REQUIRED FOR SEAL REPLACEMENT ONLY:	13:30

General Purpose Maintenance Machine (GPMM). The hoist on the machine is used to handle the valve. The valve is assembled in the coolant line with bolted flanges since replacement of a valve is generally not a life limited item that requires frequent servicing. A valve located in this region was chosen because the reactor will have to be shut down when the coolant flow is shut off in order to replace the valve. A redundant loop is not available at this point.

The operation is outlined in Table 4-43. The procedure is described for a fully remote operation even though the radioactivity level in this region may be low. While a hands-on operation may be feasible, a remotely conducted maintenance action will be required if the operation occurs when other parts of the reactor are open, for example, during a scheduled outage, or if the reactor room or coolant radioactivity level exceeds the allowable limits for hands-on work.

TABLE 4–43
COOLANT LOOP VALVE REPLACEMENT
IMS TOKAMAK REACTOR (REMOTE OPERATIONS)

LEVEL 1 TASK	LEVEL 2 TASK	DURATION (HRS:MIN)
SHUTDOWN	SHUTDOWN REACTOR	17:00
	DRAIN AND PURGE COOLANT LOOP LINE	3:00*
ACCESS	ATTACH GENERAL PURPOSE MACHINE HOIST TO VALVE	2:25
	DISCONNECT TWO VALVE FLANGES AND ACTUATOR POWER LEAD	9:00
REMOVE	MOVE VALVE TO DOLLY	:50
REPLACEMENT	POSITION REPLACEMENT VALVE	1:25
REASSEMBLE	CONNECT TWO FLANGES	12:50
	TEST FOR LEAKS	2:00
	REMOVE MAINTENANCE EQUIPMENT	:35
STARTUP	STARTUP REACTOR	28:00
	TOTAL:	74:05
	TIME FOR ADDITIONAL VALVE REPLACEMENT:	29:05

*PARALLEL OPERATION. NOT INCLUDED IN TOTAL.

The time estimated for replacement of this valve is assumed to be typical of a medium difficulty type of valve replacement. Insulation need not be stripped from the valve housing since the shield is at relatively low temperatures and the heat removed is waste heat which may not require completely insulated lines at the valve flanges. The operation described in Table 4-43 assumes that the draining and purging of the shield coolant is accomplished during shutdown or before the line is opened. Therefore, these activities are not included in the total time required to replace the valve.

4.3.1.8 Electrical Power Lead Replacement - Power cables are of many sizes, lengths and access difficulty so the cable selected for this maintenance action can only be considered typical in a very broad sense even though the estimate is used to represent cable replacement times throughout this study. The replacement operation examined is for the cable leading from the neutral beam ion source to the hinge point of the shield door/lateral support panel (Figure 4-16). This cable is relatively large in diameter since it contains the main power cables for the ion sources and several instrumentation/control wires. Therefore, it is basically a rigid bundle. It is held in place by 10 support straps attached to the reactor structure (approximately one every 2 meters) which provide support when the door assembly is rotated to the horizontal position.

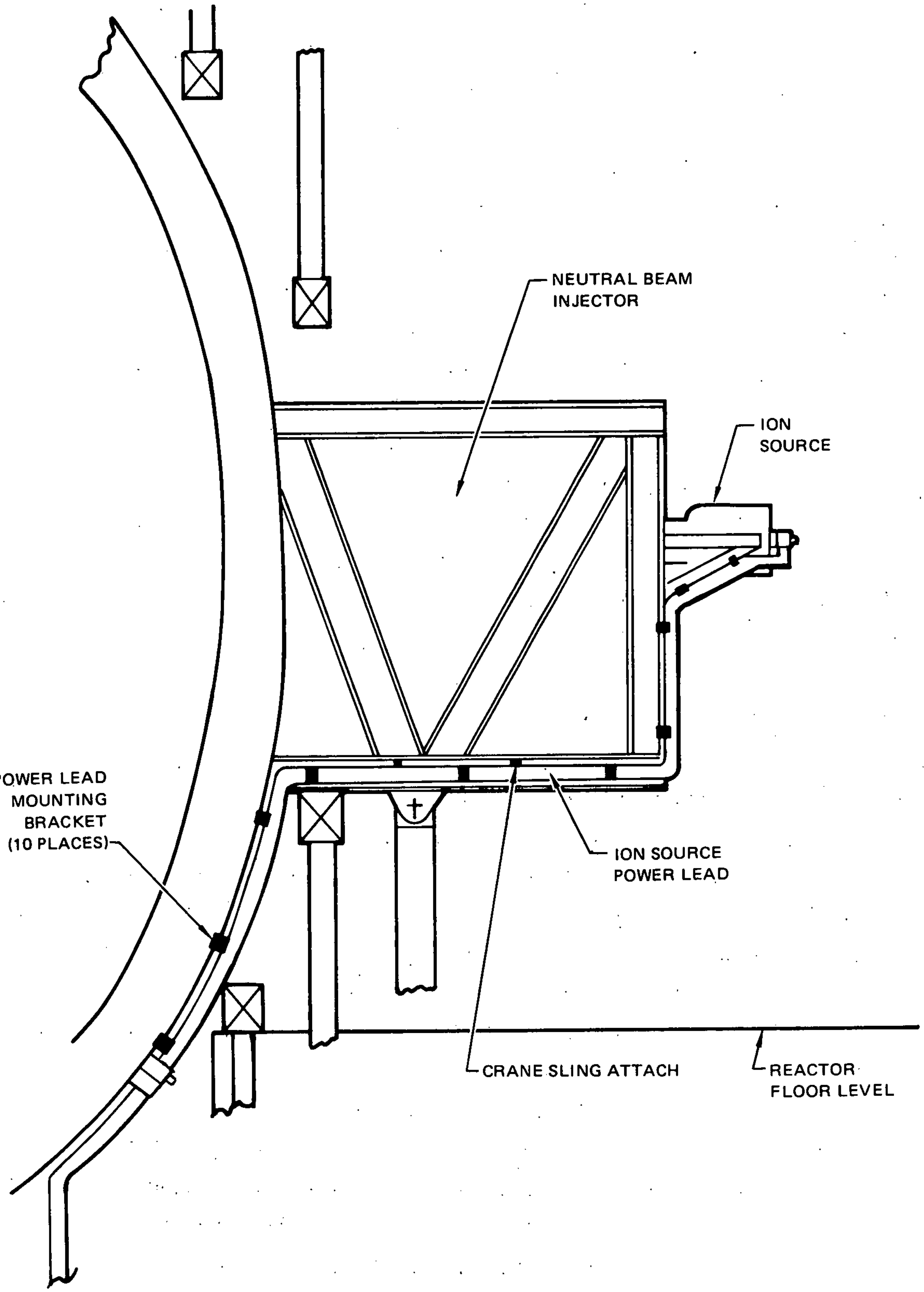
The removal of the cable assembly is assumed to occur when the shield door/lateral support panel assembly is closed. Access is provided from the reactor room floor by the GPMM. For replacement of the cable with the shield door/lateral support panel assembly open, access must be accomplished from below the floor level and different procedures are required.

The procedure for this maintenance action is outlined in Table 4-44. The cable weight is supported by the overhead crane while the support points are being disconnected. The cable is then removed by lifting it with the crane and guiding it around the poloidal coils with the GPMM at the same time. The replacement cable is positioned in the same manner.

This maintenance action, like the valve replacement, could probably be conducted in a hands-on operation. However, since the need for a remote operation may become imperative, the time and equipment requirements are determined for a fully remote operation. Also, if redundant neutral beams are available, this cable may be replaced with the reactor in operation, thereby requiring remote operations. Even for a hands-on operation, handling equipment is required for such a heavy cable.

4.3.1.9 Charge Exchange Analyzer Replacement - The maintenance actions required by the diagnostics system in either the tokamak or the TMR have been given little attention thus far, yet, in power plant operations this system requires more extensive maintenance than many others. The diagnostics system is divided, for convenience in describing maintenance actions, into: (1) those sensors which are inserted as probes that are removable without removing other components, (2) those sensors which are built into components and require removal of the component for their replacement, and (3) those sensors that are external to the reactor and which are usually complex, requiring relatively extensive replacement operations. The

TYPICAL ELECTRICAL CABLE INSTALLATION ON NEUTRAL BEAM INJECTOR



13–3170

FIGURE 4–16

TABLE 4–44
ELECTRICAL POWER LEAD REPLACEMENT
IMS TOKAMAK REACTOR (REMOTE OPERATIONS)

LEVEL 1 TASK	LEVEL 2 TASK	DURATION (HRS:MIN)
SHUTDOWN	SHUTDOWN REACTOR	17:00
ACCESS	ATTACH CRANE AND MAINTNANCE MACHINE	2:25
	DISCONNECT CABLE FROM ION SOURCES AND STRUCTURE	4:30
REMOVE	MOVE CABLE TO DOLLY	:50
REPLACEMENT	POSITION CABLE	1:45
	CONNECT CABLE TO ION SOURCES AND SUPPORTS	6:20
	REMOVE MAINTENANCE EQUIPMENT	:50
STARTUP	STARTUP REACTOR	28:00
	TOTAL:	61:40
	TIME FOR ADDITIONAL CABLE REPLACEMENT:	16:40

sensor examined in this section is typical of the latter type and is considered to be representative of a diagnostic system that requires a significant amount of time for its replacement.

The replacement procedure for the charge exchange neutral beam analyzer is outlined in Table 4-45. This analyzer is assumed to be installed in a manner similar to the installation indicated in preliminary sketches for the Tokamak Fusion Test Reactor (TFTR). A diagrammatic sketch of its installation is shown in Figure 4-17. The system is installed in a shielded vacuum enclosure connected to the plasma chamber directly through a shielded collimating tube. It is capable of being separated from the plasma chamber by a vacuum isolation valve. The installation is somewhat similar to the neutral beam injector installation except that a large cryopump installation is not included in the vacuum enclosure. All disconnects are reduced to a set of 7 common lines within the system. These are four fluid lines, including two for the shield coolant, and three electrical lines. It is assumed that this system is installed near the main floor level and is accessible from above.

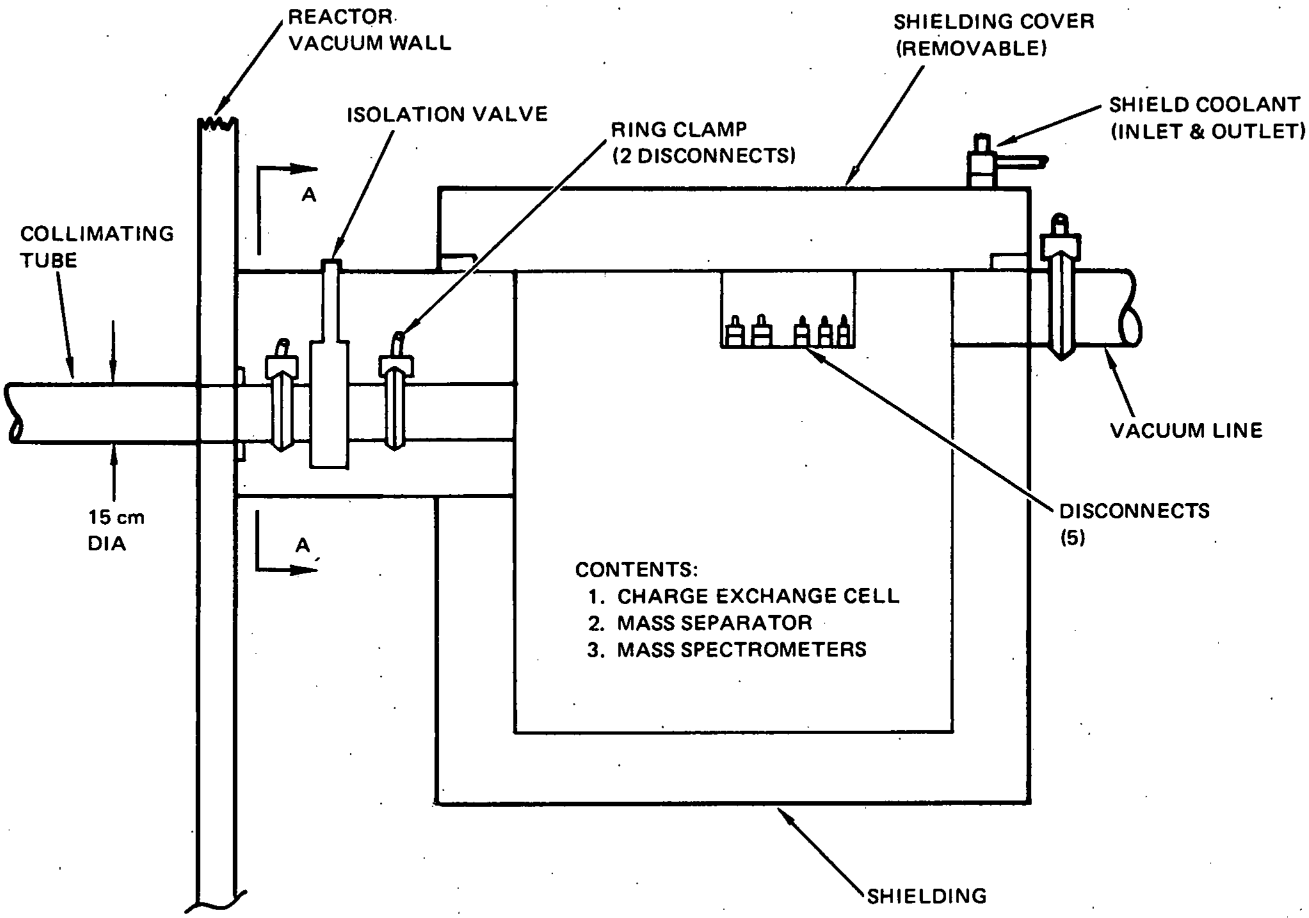
TABLE 4–45
CHARGE EXCHANGE ANALYZER REPLACEMENT
IMS TOKAMAK REACTOR (REMOTE OPERATIONS)

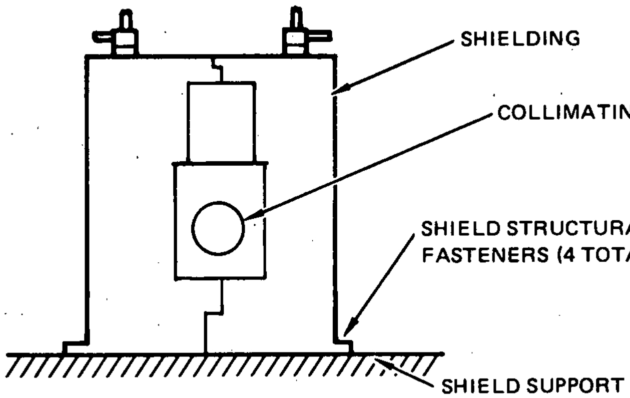
LEVEL 1 TASK	LEVEL 2 TASK	DURATION (HRS:MIN)
SHUTDOWN	SHUTDOWN REACTOR	17:00
	CLOSE ISOLATION VALVE, PURGE ANALYZER	1:05*
ACCESS	POSITION GENERAL PURPOSE MACHINE	1:40
	REMOVE SHIELD COVER	1:50
	DISCONNECT ANALYZER SERVICE LINES	2:30
	REMOVE COLLIMATING TUBE SHIELDING	4:30
	DISCONNECT COLLIMATING TUBE AND SUPPORT STRUCTURE	2:10
REMOVE	MOVE ANALYZER TO FLOOR DOLLY	1:20
REPLACEMENT	POSITION REPLACEMENT ANALYZER UNIT IN CASE	1:25
REASSEMBLY	CONNECT COLLIMATING TUBE AND SUPPORT STRUCTURE	3:20
	CONNECT ANALYZER SERVICE LINES	3:50
	TEST FLUID LINE CONNECTIONS FOR LEAKS	2:00
	INSTALL COLLIMATING TUBE SHIELDING	5:10
	INSTALL SHIELD COVER	1:25
	TEST SHIELD LINES AND REMOVE GP MACHINE	1:05
STARTUP	STARTUP REACTOR	28:00
*PARALLEL OPERATION. NOT INCLUDED IN TOTAL.	TOTAL:	77:15
	TIME REQUIRED TO REPLACE ADDITIONAL DIAGNOSTIC UNIT:	32:15

The procedure first requires removal of the top shield cover and the shielding around the collimating line connecting ring clamp. All disconnects are designed for remote operations using a single screw to release the connection. After disconnecting and clearing all service lines, the analyzer system is lifted from the shielded enclosure as a unit by the hoist of the GPMM. The analyzer unit includes its own vacuum housing.

This unit is expected to be activated by the neutrons streaming through the collimating tube. Therefore, all operations subsequent to removal of the shield cover must be conducted remotely. Replacement of the unit may be conducted while the reactor is operating if redundant analyzer systems are included in the plant and if maintenance equipment and the analyzer unit can be designed for movement in intense magnetic fields. However, in this instance, the replacement procedure is defined for a scheduled outage of the reactor.

CHARGE EXCHANGE NEUTRAL BEAM ANALYZER





A–A
COLLIMATING TUBE SHIELDING ARRANGEMENT

13–3171

FIGURE 4–17

4.3.1.10 Toroidal Field Magnet Replacement - The replacement of a toroidal field magnet is one of the more extensive and difficult maintenance operations that may be required in a tokamak reactor. This maintenance action is expected only rarely, if at all, and, therefore, it has been omitted from any analysis of scheduled maintenance of the tokamak reactor for the same reasons that the replacement of the Yin-Yang coil set is omitted from the scheduled maintenance analysis in the TMR. A brief estimate of the maintenance action required to replace a toroidal field coil was made in the earlier phase of this study but not for the IMS tokamak reactor. While this current estimate is also limited in the depth of detail covered, the order of magnitude of the effort is indicated.

Several critical design assumptions have been made to assist this maintenance action. The poloidal field coils within the base of the toroidal field coils are segmented. The outer vacuum shield wall is designed for removal in flat pieces one sector wide. The toroidal field coil is wound outside of the reactor room and a spare coil is built while the coil to be replaced is being removed. All operations in the reactor room are conducted remotely with equipment designed for other maintenance operations except for special hoist fixtures and workheads.

Table 4-46 and 4-47 outline the procedure for replacing one toroidal field coil. To access one coil requires removal of the first wall/blanket, lateral support panel doors, divertors, cryopumps and outer shield walls from four sectors. This provides access to the segment joints in the poloidal field coils. The removal of one segment of each poloidal field coil requires that the joints between coil segments lie between toroidal field coils. As a minimum, it is necessary to remove the poloidal field coils from four sectors because the overlap in the coil joints interferes with the removal of the center column shield in those sectors that are on either side of the toroidal field coil which is being replaced. Reassembly uses essentially the reverse of the access sequence.

4.3.2 Maintenance Equipment Outage Requirements - The maintenance equipment defined for the IMS tokamak reactor is taken principally from the equipment used for the Culham Mark II reactor as defined in the earlier study phase (Reference 3). The equipment required has been revised to take advanctage of the improved maintenance concept and the reduced requirement for massive transporters. The principal equipment items required are listed in Table 4-48. The maintenance actions defined in the previous sections for which each major item of equipment is used are also listed.

TABLE 4–46
TOROIDAL FIELD MAGNET REMOVAL
IMS TOKAMAK REACTOR (REMOTE OPERATIONS)

ITEM	LEVEL 2 TASK	DURATION (HRS:MIN)	DURATION DAYS
SHUTDOWN	REACTOR SHUTDOWN	17:00[1]	.7[1]
	MAGNET WARMUP	336:00[1]	14.0[1]
ACCESS	GAIN ACCESS-OPEN LATERAL SUPPORT PANEL DOORS (4 SECTORS)	32:00[2]	1.3[2]
	REMOVE 1st WALL/BLANKET MODULES (4)	45:00[2]	1.9[2]
	REMOVE CRYOVACUUM PUMPS (5)	59:00[2]	2.5[2]
	REMOVE DIVERTOR PARTICLE BOMBARDMENT PLATES (4)	80:00[2]	3.3[2]
	RAISE UPPER THREE POLOIDAL FIELD MAGNETS ABOVE TOROIDAL FIELD COILS	320:00	13.3
	REMOVE SHIELD FLOOR (4 SECTORS)	192:00	8.0
	REMOVE LOWER POLOIDAL FIELD MAGNETS SEGMENTS (5)	170:00	7.1
	REMOVE SHIELDING FROM UPPER POLOIDAL FIELD MAGNETS (4)	192:00	8.0
	REMOVE UPPER POLOIDAL FIELD MAGNETS SEGMENTS (4)	136:00	5.7
	REMOVE NBI FROM LATERIAL SUPPORT PANEL DOORS	17:00[3]	.7[3]
	REMOVE ACTUATORS FROM LATERAL SUPPORT PANEL DOORS	25:00[3]	1.0[3]
	REMOVE LATERAL SUPPORT PANEL DOORS	52:00	2.2
	REMOVE VACUUM PUMP PLENUM AND DIVERTOR STRUCTURE	480:00	20.0
	REMOVE CENTER COLUMN SHIELD	144:00	6.0
REMOVE	REMOVE TOROIDAL FIELD MAGNET TENSION RINGS	29:00	1.2
	CUT TOROIDAL FIELD MAGNET INNER DEWAR	96:00	4.0
	DISCONNECT TOROIDAL FIELD MAGNET SUPPORT STRUCTURE	42:00	1.8
	REMOVE TOROIDAL FIELD MAGNET	49:00	2.0
	TOTAL REMOVAL:	2255:00	94

(1) PRODUCTIVITY FACTOR NOT APPLIED TO THESE ITEMS.
(2) PARALLEL WITH MAGNET WARMUP/COOLDOWN. NOT INCLUDED IN TOTAL.
(3) PARALLEL EFFORT. NOT INCLUDED IN TOTAL.

TABLE 4–47
TOROIDAL FIELD MAGNET REPLACEMENT
IMS TOKAMAK REACTOR (REMOTE OPERATIONS)

ITEM	LEVEL 2 TASK	DURATION (HRS:MIN)	DURATION DAYS
REPLACEMENT	REPLACE TOROIDAL FIELD MAGNET	79:00	3.3
	INSTALL TOROIDAL FIELD MAGNET SUPPORT STRUCTURE	126:00	5.3
	INSTALL TOROIDAL FIELD MAGNET INNER DEWAR	108:00	4.5
	INSTALL TOROIDAL FIELD MAGNET TENSION RINGS	39:00	1.6
REASSEMBLE	INSTALL CENTER COLUMN SHIELD	216:00	9.0
	INSTALL VACUUM PUMP PLENUM AND DIVERTOR STRUCTURE	640:00	26.6
	INSTALL LATERAL SUPPORT PANEL DOORS	90:00	3.8
	INSTALL LATERAL SUPPORT PANEL DOOR ACTUATORS	44:00(3)	1.8(3)
	INSTALL NBI ON LATERAL SUPPORT PANEL DOORS	30:00(3)	1.3(3)
	INSTALL UPPER POLOIDAL FIELD MAGNETS (4)	184:00	7.7
	INSTALL SHIELDING ON UPPER POLOIDAL MAGNETS (4)	288:00	12.0
	INSTALL LOWER POLOIDAL FIELD MAGNETS (5)	230:00	9.6
	INSTALL SHIELD FLOOR (ALL SECTORS)	288:00	12.0
	LOWER UPPER THREE POLOIDAL FIELD MAGNETS TO NORMAL POSITION	480:00	20.0
	INSTALL DIVERTOR PARTICLE BOMBARDMENT PLATES (4)	120:00(2)	5.0(2)
	INSTALL CRYOVACUUM PUMPS (5)	91:00(2)	3.8(2)
	INSTALL 1st WALL/BLANKET MODULES (4)	70:00(2)	2.9(2)
	REASSEMBLE, CLOSE LATERAL SUPPORT PANEL DOORS	29:00(2)	1.2(2)
	MAGNET COOLDOWN	336.00(1)	14.0(1)
	REACTOR CHECKOUT AND STARTUP	168:00(1)	7.0(1)
	INSTALLATION SUBTOTAL:	3272:00	136
	TOTAL:	5527:00	230
	TOTAL WITH .625 PRODUCTIVITY FACTOR:	8329:00	347

(1) PRODUCTIVITY FACTOR NOT APPLIED TO THESE ITEMS.
(2) PARALLEL WITH MAGNET COOLDOWN. NOT INCLUDED IN TOTAL.
(3) PARALLEL EFFORT, NOT INCLUDED IN TOTAL.

TABLE 4–48
PRINCIPAL SPECIALIZED MAINTENANCE EQUIPMENT UNITS FOR THE IMS TOKAMAK REACTOR

EQUIPMENT TITLE	CODE	APPLICABLE MAINTENANCE ACTION(S)
OVERHEAD CRANE	OC	TRANSPORT FIRST WALL/BLANKET SECTOR PLASMA CHAMBER CRYOPUMP REPLACEMENT DIVERTOR BOMBARDMENT PLATE REPLACEMENT SHIELD DOOR SEAL REPLACEMENT ELECTRICAL POWER LEAD REPLACEMENT CHARGE EXCHANGE ANALYZER REPLACEMENT TOROIDAL FIELD COIL REPLACEMENT
GENERAL PURPOSE MAINTENANCE MACHINE	GPMM	NEUTRAL BEAM ION SOURCE REPLACEMENT NEUTRAL BEAM ISOLATION VALVE REPLACEMENT SHIELD DOOR SEAL REPLACEMENT COOLANT VALVE REPLACEMENT ELECTRICAL POWER LEAD REPLACEMENT CHARGE EXCHANGE ANALYZER REPLACEMENT TOROIDAL FIELD COIL REPLACEMENT
OVERHEAD BRIDGE MANIPULATOR	OM	PLASMA CHAMBER CRYOPUMP REPLACEMENT ELECTRICAL POWER LEAD REPLACEMENT
OPERATIONAL MAINTENANCE UNIT	OMU	NBI ION SOURCE REPLACEMENT FIRST WALL/BLANKET SECTOR REPLACEMENT
REACTOR SECTOR REMOVAL MACHINE	RSRM	FIRST WALL/BLANKET SECTOR REPLACEMENT
CENTRAL CORE MAINTENANCE DEVICE	CCMD	PLASMA CHAMBER CRYOPUMP REPLACEMENT
BOMBARDMENT PLATE REMOVAL DEVICES	BPRD	DIVERTOR BOMBARDMENT PLATE REPLACEMENT
TUG	-	ALL
POLOIDAL MAGNET RETRACTION SYSTEM	PFMRS	FIRST WALL/BLANKET SECTOR REPLACEMENT DIVERTOR BOMBARDMENT PLATE REPLACEMENT SHIELD DOOR SEAL REPLACEMENT TOROIDAL FIELD COIL REPLACEMENT

The impact of the failure of these equipment items on the downtimes experienced has been examined in the earlier study phase and is summarized in Table 4-49. The maintenance scenarios previously defined are similar to those encountered with the

IMS reactor and the failure reaction time and failure recovery time are approximately the same. Therefore, the impact on the downtime resulting from the time estimates summarized in Table 4-49 is representative of the impact of maintenance equipment failures for the IMS tokamak reactor.

TABLE 4–49
MAINTENANCE EQUIPMENT FAILURE MODE SCENARIOS

FAILURE MODE SCENARIO	FAILURE RESPONSE	MAINTENANCE EQUIPMENT REQUIRED	FAILURE RECOVERY DOWNTIME (HRS:MIN)	REMARK
REACTOR SECTOR REMOVAL MACHINE (RSRM) - FAILS WITH SECTOR PARTIALLY RETRACTED	o DISCONNECT RSRM FROM SECTOR o REPLACE WITH SPARE	o SPARE RSRM o OPERATIONAL MAINTENANCE UNIT o DOLLIES	98.00	o SAME PROCEDURE AS FOR CULHAM CONCEPT
CUTTING/WELDING WORKHEAD - FAILS DURING COOLANT MANIFOLD WELDING	o EXCHANGE CUTTING/WELDING WORKHEAD	o SPARE WORKHEAD o OPERATIONAL MAINTENANCE UNIT	25:15	o ASSUMES WELDMENT DAMAGE BY FAILURE. REQUIRES 8:00 HOURS TO REPAIR
OPERATIONAL MAINTENANCE UNIT - FAILS TO RETRACT WHEN REMOVING DIVERTOR FIRST WALL/BLANKET CANISTER	o RETRACT MANUALLY WITH SECOND OMU MANIPULATOR o DISCONNECT CANISTER WITH SPARE OMU o REPLACE WITH SPARE OMU	o OMU o SPARE OMU o SPECIAL RETRACTION AND DISMANTLING TOOLS	98:00	o SIMILAR TO REACTOR SECTOR REMOVAL MACHINE
CENTRAL CORE MAINTENANCE DEVICE (CCMD) - FAILS WHILE ATTACHED TO VACUUM ISOLATION VALVE	o RELEASE CCMD FROM VALVE WITH OVERHEAD MANIPULATOR o REPLACE CCMD WORKHEAD	o OVERHEAD MANIPULATOR o CCMD SPARE WORKHEAD	18:00	o SIMILAR TO GPMM REPLACEMENT
GENERAL PURPOSE MAINTENANCE MACHINE (GPMM) - FAILS WHEN DISCONNECTING ION SOURCE SERVICES	o RELEASE GPMM FROM ION SOURCE WITH OMU o REPLACE GPMM WITH SPARE	o OPERATIONAL MAINTENANCE UNIT o SPARE GPMM	18:00	o ASSUME GPMM IS ATTACHED TO ION SOURCE AT THE TIME OF FAILURE
OVERHEAD MANIPULATOR - TROLLEY FAILS WHEN EMPLACING CENTRAL CORE WORKHEAD	o REPLACE TROLLEY WITH SECOND MANIPULATOR o REPLACE TROLLEY USING CRANE	o SECOND MANIPULATOR o OVERHEAD CRANE o SPARE MANIPULATOR SYSTEM	45:00	o SIMILAR TO TMR OVERHEAD CRANE TROLLEY FAILURE
OPERATIONAL MAINTENANCE UNIT - CREW ENVIRONMENT CONTROL UNIT (ECU) FAILS DURING FIRST WALL/BLANKET COOLANT MANIFOLD WELDING OPERATION	o TUG WITH CREW TRANSFER UNIT EVACUATES CREW o CREW WITH SELF-CONTAINED ECU RELEASES OMU FROM MANIFOLD WORK o REPLACE OMU WITH SPARE UNIT	o SPARE OMU o TUG WITH TRANSFER UNIT o CREW SUITS	33:30	o SCENARIO DIFFERS BUT REMEDIAL ACTION SIMILAR TO ORNL CONCEPT
POLOIDAL FIELD MAGNET RETRACTION SYSTEM - FAILS TO RAISE ONE POLOIDAL FIELD MAGNET TO CLEAR LATERAL SUPPORT PANEL DOOR	o ISOLATE FAILURE TO ONE RETRACTION MECHANISM o REMOVE MECHANISM o REPLACE WITH SPARE OR REPAIR	o SPARE MECHANISM o OPERATIONAL MAINTENANCE UNIT (OMU) o SUPPORT JACKS o DOLLIES	34:00	o SAME SYSTEM AS FOR UWMAK-III BUT OUTSIDE LATERAL SUPPORT PANEL DOOR

The design of the Reactor Sector Removal Machine (RSRM) for the IMS varies from that used for the Culham reactor concept for which this scenario was defined but the operations are similar. The principal time requirements for securing the first wall/blanket sector and then disconnecting, replacing and connecting the actuator used for withdrawal of the sector remain the same and are equally appropriate for the IMS tokamak reactor.

The failure of the cutting/welding workhead during the reconnection of the first wall/blanket sector helium coolant line manifold is a straightforward replacement of a workhead. For recovery from this failure the assumption is made that the workhead, which is of the type that travels around the pipe it is welding, is accessible at the point where it failed. Insufficient space for access and withdrawal requires additional design features to allow the workhead to be maneuvered to a point where it is accessible.

The IMS concept uses the Operational Maintenance Unit (OMU) to remove the individual first wall/blanket canisters from the divertor. A failure of the OMU arm that holds the cannister is rectified by using the second OMU manipulator arm to activate a manual system for moving the cannister and OMU arm from the reactor. This is a time consuming operation and is assumed to require special tools. If the manipulator arm failed so that it could not be retracted, space is available to move another OMU close by and use its manipulator. The time allowed is the same as for recovery from the RSRM failure.

The Central Core Maintenance Device (CCMD) used with the IMS is assumed to fail while operating a cryopump isolation valve. Removing this workhead from the valve and replacing the workhead by use of the overhead bridge mounted manipulator is a task similar to the replacement of the GPMM discussed below.

The failure of the General Purpose Maintenance Machine (GPMM) while disconnecting services to the neutral beam injector ion source is typical of a short downtime failure recovery. The estimated time is that required to use another manipulator to first extricate the GPMM from the ion source it is replacing and then to exchange maintenance equipment. Access is available without disassembly of other equipment.

Failure of the overhead bridge mounted manipulator trolley presents a situation similar to that of the overhead crane failure described for the TMR. The trolley may be disengaged either by another manipulator or by the OMU. An overhead crane is then used to lift the trolley free of the bridge and lower it to the reactor room floor. The manipulator is replaced in a similar manner.

The failure of the self-contained environmental control system in the Operational Maintenance Unit (OMU) uses different equipment for recovery than was used in the previous study phase for the ORNL reactor concept. However, the principal functions are the same and the downtime is estimated to be the same. This type of failure points up the need for a rescue system wherever a manned system is inserted into a remote operation environment.

The failure recovery time estimate for the poloidal field magnet retraction system indicated in Table 4-49 assumes that the system automatically stops if one actuator fails to move. This system must then be made operative before the lateral support panel door can be opened to give access to the first wall/blanket sector. This failure mode and system is similar to that postulated for the UWMAK-III reactor from which this data is taken. The major variation is that the system can be repaired for the IMS concept without opening the lateral support panel doors.

While several more difficult and lengthy maintenance equipment failure modes and recovery actions have been investigated in the earlier study phase for other reactor concepts, those discussed above are representative for the IMS concept even though other "worst case" failure modes might be defined.

4.3.3 Total Scheduled Outage Plan - The scheduled outage plan for the TMR includes consideration of all subsystems in the reactor. This is required to achieve a better comparison of the maintainability of the TMR and the tokamak reactors. Therefore, the scheduled outage plan for the IMS tokamak reactor must also consider the same scope of subsystem maintenance actions. The principal maintenance actions used in defining this plan are those defined in Section 4.3.1. Additional scheduled outage maintenance actions are derived from some of the components and subsystems listed in Table 4-4. The downtime estimates for these additional subsystems are based on typical component replacement downtimes also defined in Section 4.3.1. Table 4-50 lists the downtime required for each maintenance action included in the maintenance plan, both those defined in detail and those estimated as similar to others defined in detail. For these estimates a productivity factor of .625 is used to increase the downtime estimate to a total expected time for each maintenance action. Reactor shutdown and startup require time in addition to that shown.

The number of maintenance actions selected for each component in the total scheduled maintenance plan are listed in Table 4-51. The quantities selected for the major maintenance actions are for a replacement fraction of 0.5 for the first wall/blanket sectors and a replacement fraction of 1.0 for the neutral beam ion sources and the divertor cryopump replacement. Since the replacement of the first wall/blanket sectors is a driver in determining the total scheduled outage time, the replacement fraction for this maintenance action is used as the identifying fraction for the total outage. This replacement fraction resulted in the minimum cost of electricity in the earlier study phase analyses.

The additional maintenance actions included in the listing shown in Table 4-51 are similar to the additional maintenance actions selected for the TMR. Some of these maintenance actions, such as replacement of the divertor door seals, are associated with the maintenance actions estimated in detail. Others are nominal preventative maintenance, such as inspection and adjustment of the six poloidal field coil magnet retraction systems. Still others are replacement of failed units in redundant systems, such as replacement of 10 percent of the valves in the cryogen system or in the vacuum system. All components in this list are located in the reactor room

TABLE 4–50
IMS TOKAMAK SCHEDULED MAINTENANCE ACTION DOWNTIMES

MAINTENANCE ACTION	DOWNTIME PER UNIT, DAYS(1)
BASED ON DETAILED ESTIMATES	
FIRST WALL/BLANKET REPLACEMENT	
EACH SECTOR	11.0
NEUTRAL BEAM ION SOURCE REPLACEMENT	
FIRST ION SOURCE/NBI	1.5
ALL ION SOURCES (3)/NBI	3.5
NEUTRAL BEAM INJECTOR ISOLATION VALVE REPLACEMENT	1.7
DIVERTOR CRYOPUMP REPLACEMENT	2.0
DIVERTOR BOMBARDMENT PLATE REPLACEMENT	
EACH SECTOR, BOTH PLATES	1.6(2)
SHIELD DOOR SEAL REPLACEMENT	
FIRST SECTOR	3.4(3)
ADDITIONAL SECTORS	2.7(2)
COOLANT LOOP VALVE REPLACEMENT	1.9(4)
ELECTRICAL POWER LEAD REPLACEMENT	1.1(4)
CHARGE EXCHANGE ANALYZER REPLACEMENT	2.2(4)
TOROIDAL FIELD COIL REPLACEMENT	347(5)
ADDITIONAL COMPONENT ESTIMATES BASED ON SIMILARITY	
MAGNET RETRACTION SYSTEM ADJUSTMENT	.8
CRYOGEN VALVE REPLACEMENT	1.9
CONTROL VALVE INSPECTION	1.5
DIVERTOR ACCESS DOOR SEAL REPLACEMENT	.9
NEUTRAL BEAM INJECTOR CRYOPUMP REPLACEMENT (HALF OF TOTAL/NBI)	3.9
VACUUM ISOLATION VALVE REPLACEMENT	1.7
DIVERTOR SLOT LINER REPLACEMENT	2.0
SHIELD COOLANT VALVE REPLACEMENT	1.9
NEUTRAL BEAM INJECTOR COOLANT CONTROL VALVE REPLACEMENT	1.9
INSTRUMENTATION REPLACEMENT	.5
PLASMA CONTROL SENSOR ASSEMBLY REPLACEMENT	2.2

(1) 24 HOUR, 3 SHIFT DAYS, SHUTDOWN AND STARTUP EXCLUDED, PRODUCTIVITY OF .625 INCLUDED
(2) ASSUMES POLOIDAL MAGNET MOVEMENT ACCOMPLISHED FOR OTHER MAINTENANCE ACTION
(3) INCLUDES POLOIDAL MAGNET MOVEMENT
(4) TYPICAL DOWNTIMES FOR SIMILAR MAINTENANCE ACTIONS ON TMR.
(5) NOT INCLUDED IN TOTAL SCHEDULED OUTAGE, FORCED OUTAGE ONLY.

and, therefore, the total number is restricted. This is the case with the vacuum isolation valves between the plenum chamber and the cryopump or in the regeneration vacuum line. Other valves in the vacuum system which are redundant and external to the reactor room are maintained during reactor operation. The quantities of those components which are similar to or the same as components selected for the TMR are made the same as the quantity selected for the TMR. For example, this consideration determined the number of diagnostic units replaced.

TABLE 4–51
MAINTENANCE ACTIONS INCLUDED IN TOKAMAK SCHEDULED OUTAGE

MAINTENANCE ACTION	NUMBER OF UNITS WORKED	PERCENT OF TOTAL
DOWNTIME BASED ON DETAILED ESTIMATES	RF = .5	RF = .5
REPLACE FIRST WALL/BLANKET SECTORS	8	50
REPLACE NEUTRAL BEAM ION SOURCES	36	100
REPLACE NEUTRAL BEAM INJECTOR ISOLATION VALVES	8	67
REPLACE DIVERTOR CRYOPUMPS	20	100
REPLACE DIVERTOR BOMBARDMENT PLATES	16	100
REPLACE SHIELD DOOR SEALS	8	50
REPLACE MAIN COOLANT VALVES	2	13
REPLACE ELECTRICAL POWER LEADS	1	1
REPLACE CHARGE EXCHANGE ANALYZER	2	67
ADDITIONAL COMPONENTS IN SCHEDULED OUTAGE		
INSPECT/ADJUST MAGNET RETRACTION SYSTEM	6	100
INSPECT CRYOGEN CONTROL VALVES	38	100
REPLACE CRYOGEN VALVES	15	10
REPLACE DIVERTOR DOOR SEALS	16	100
REPLACE NEUTRAL BEAM INJECTOR CRYOPUMPS	12	100
REPLACE VACUUM VALVES	4	10
REPLACE DIVERTOR SLOT LINES	2	13
REPLACE SHIELD COOLANT VALVES	2	10
REPLACE NEUTRAL BEAM COOLANT CONTROL VALVES	2	10
REPLACE INSTRUMENTATION	40	20
REPLACE PLASMA CONTROL SENSOR ASSEMBLIES	1	10
TOTAL MAINTENANCE ACTIONS	239	

RF = REPLACEMENT FRACTION

The maintenance actions required to replace life limited items include the first wall/blanket sectors, the neutral beam ion sources, the neutral beam injector isolation valves, the cryovacuum pumps and the divertor bombardment plates. The first wall/blanket replacement uses a fluence limit life of 16 MW Yrs/m^2 for the first wall/blanket. This is the same value used for the TMR. The life of the other life limited components is assumed to be compatible with the annual scheduled outage planned for the balance of plant requirements. The toroidal field magnet replacement is not included in the scheduled outage plan because of the expected long life of these magnets.

Critical Path Selection - The list of maintenance actions defined in Table 4-51 has been examined to determine the probable critical path when conducting as many maintenance actions in parallel as possible in the IMS tokamak reactor. This is the same approach used for determining the critical path for scheduled maintenance in the baseline TMR reactor. The selected combinations of events for the IMS tokamak reactor critical path operations are outlined in Tables 4-52 and 4-53. The down-

TABLE 4–52
TOKAMAK SCHEDULED MAINTENANCE CRITICAL PATH DEVELOPMENT

PATH #1 - FIRST WALL/BLANKET SECTOR REPLACEMENT		
MAINTENANCE ACTION	Δ TIME HRS	SUMMATION (.625 PRODUCTIVITY)
REPLACE: 8 FIRST WALL/BLANKET SECTORS 8 LATERAL SUPPORT PANEL DOOR SEALS DIVERTOR PLATE REPLACEMENT MAGNET RETRACTION SYSTEM MAINTENANCE		
REACTOR SHUTDOWN	17.00*	17.00
INITIAL FIRST WALL/BLANKET SECTOR	252.25	403.60
REMAINING 7 SECTORS OFFSET FOR CRANE MOVEMENT OF SECTORS (18:30 + 19:20) x 7	264.83	423.73
ADD DOOR SEAL REPLACEMENT (IN SERIES)	13.50	21.60
DIVERTOR PLATE REPLACEMENT INCLUDING DOOR SEALS (13.50 + 15.08) x 16 = 457.50 457.50 < (197.25 + 264.83) ALL IN PARALLEL WITH SECTORS	0.00	-
MAGNETS RETRACTION SYSTEM INSP. AND ADJ. 12.25/MAGNET (6 IN PARALLEL)	12.25	19.60
REACTOR STARTUP	28.00*	28.00
TOTAL:	587.83	913.53 38.1 DAYS

*PRODUCTIVITY FACTOR NOT APPLIED TO SHUTDOWN AND STARTUP TIMES.

TABLE 4–53
TOKAMAK SCHEDULED MAINTENANCE CRITICAL PATH DEVELOPMENT

PATH #2 - DIVERTOR CRYOPUMP ASSEMBLY REPLACEMENT		
MAINTENANCE ACTION	Δ TIME HRS	SUMMATION (.625 PRODUCTIVITY)
REPLACE: 20 DIVERTOR CRYOPUMP ASSEMBLIES 20 VACUUM ISOLATION VALVES		
REACTOR SHUTDOWN	17.00*	17.00
FIRST CRYOPUMP AND VALVE ASSEMBLY	30.00	48.00
2nd THROUGH 10th CRYOPUMP AND VALVE ASSEMBLY (ASSUME 2 BOOMS USED ON CCMD) 25.33 x 9 =	228.00	364.80
ADD OFFSET TO INSTALL 2nd BOOM ON CCMD	4.67	7.47
11th THROUGH 20th CRYOPUMP AND VALVE ASSEMBLY (PARALLEL WITH FIRST 10 ASSEMBLIES)	0.00	-
REACTOR STARTUP	28.00*	28.00
TOTAL:	307.67	465.27 19.4 DAYS

*PRODUCTIVITY FACTOR NOT APPLIED TO SHUTDOWN AND STARTUP TIMES.

time buildup for these cases is indicated in each table. Based on these critical path estimates, the scheduled downtime for the IMS tokamak of 39 days when replacing one half of the first wall/blanket sectors is the driving downtime requirement.

The 8 first wall/blanket sectors are replaced in parallel with each other except that the overhead crane can handle only one at a time in the removal sequence. Therefore each sector must wait on the crane availability which results in a time offset of 37:50 hours for each sector. The divertor plates are replaced in parallel with the sector replacement maintenance actions. These plates are replaced by operations which access the plates from above the reactor. Since the total time required for all 16 sets of divertor bombardment plates is less than the time required for 8 first wall/blanket sectors, the latter will determine the length of the scheduled outage. Also, the door seal replacement time is less than the offset time required by overhead crane availability so the time required for replacement of only one door seal need be added for the overlapping replacement of all 8 door seals. Similarly, the inspection and adjustment of the magnet retraction system for all six poloidal field magnets is accomplished concurrently since all other maintenance actions in the critical path are completed before this begins and access is then available to all actuators at the same time.

The second critical path examined replaces both the divertor cryopumps and the isolation valves. Since these can be removed and installed as a single unit, as well as separately, without disconnecting more major connections than for the cryopumps alone, the downtime for cryopump replacement is used. Also, when replacing all 20 cryopump and valve assemblies the use of two workheads on the central core maintenance device (CCMD), with each working on the opposite side of the reactor, appears possible. This allows two cryopumps to be replaced in parallel operations with the only delay being that required to install the second workhead on the CCMD.

If interference exists between the critical path maintenance actions, such as between the divertor bombardment panel replacement and the cryopump replacement then the maximum downtime will be extended. Investigation of all potential interference is beyond the scope of this study. Another type of interference which can be significant is the unavailability of critical maintenance equipment, such as the overhead cranes, or the unavailability of floor space or entry ports for the maintenance equipment and components that are being handled during the scheduled outage. A brief examination of this latter effect is discussed in Section 5.

4.3.4 <u>Resources Required for Tokamak Scheduled Outages</u> - The resources required for maintenance actions include the maintenance equipment, maintenance facilities and direct operating personnel. The equipment required for each individual maintenance action and also that required for the total operations conducted during a scheduled outage have been defined. The quantity of each equipment item and of the direct personnel required are estimated for the varying replacement fractions feasible for each component in the IMS tokamak reactor. Facility requirements have been briefly investigated for tokamak reactors and included in the TOCOMO cost code in earlier studies (Reference 3).

4.3.4.1 Maintenance Equipment Requirements - The maintenance equipment required for the varying replacement fractions in the tokamak reactor systems is delineated in Table 4-54. The total quantity for each equipment item is derived by assuming that the replacement fractions for all components requiring that item are the same. The total quantity required for each item is then approximated by summing the quantity required for each component at a particular replacement fraction, with certain adjustments. To make such a summation inherently implies that each component replaced requires its own equipment and that a minimum of series operations on different components will be performed by each piece of equipment.

TABLE 4–54
EQUIPMENT SUMMARY LIST FOR TOKAMAK MAINTENANCE OPERATIONS

ITEM DESIGNATION	LIFTING CAPABILITY	SIZE L X W X H	WEIGHT/UNIT	QUANTITY/1ST W/B RF SPARES	1/8	1/4	1/2	1
o OVERHEAD CRANE	300 TONNES	40 m x 6 m x 7.7 m	430 TONNES	0	2	2	2	2
o GENERAL PURPOSE MAINTENANCE MACHINE (GPMM)	10 TONNES	5 m x 3 m x 4 m	10 TONNES	1	4	6	10	10
o OVERHEAD BRIDGE MANIPULATOR	4 TONNES	40 m x 4 m 5 m	1660 TONNES	0	1	2	2	2
o OPERATIONAL MAINT. UNIT	1.25 TONNES	14 m x 6.5 m x 4.5 m	78 TONNES	1	2	4	8	8
o REACTOR SECTOR REMOVAL MACHINE	PULLS/PUSHES AT 100 TONNES MAX.	20 m EXTENDED x .5 m x .5 m	5 TONNES	2	2	4	8	16
o TUG	TOW BAR PULL 5 TONNES	4 m x 4 m x 1.5 m	8 TONNES	1	4	8	10	10
o CENTRAL CABLE MAINTENANCE DEVICE (CCMD)	10 TONNES	15 m x 2 m x 16 m	18 TONNES	1	2	2	4	4
o BOMBARDMENT PLATE REMOVAL DEVICE	SUPPORTS 2 TONNES	9 m x 2.5 m x 8 m	8 TONNES	1	2	4	8	8
o IMPACT WRENCH	N/A	70 cm x 24 cm x 33 cm	2 TONNES	3	9	14	24	24
o MODULE REMOVAL TRACK SEGMENT	N/A	1 m x 4 m x .5 m	8 TONNES	2	2	4	8	16
o TRACK SEGMENT DOLLY	SUPPORTS 8 TONNES	10 m x 4 m x 1.0 m	16 TONNES	1	1	1	1	2
o AUXILIARY SERVICES WORKHEAD	10 TONNES	4 m x 3.7 m x 3 m	8 TONNES	1	2	4	8	8
o AUXILIARY SERVICES WORKHEAD DOLLY	SUPPORTS 8 TONNES	4 m x 4 m x 1.0 m	2 TONNES	1	2	4	8	8
o HELIUM COOLANT MANIFOLD COVER	N/A	1.5 m DIA x .25 m THICK	3.5 TONNES	2	2	4	8	16
o HELIUM MANIFOLD COVER DOLLY	SUPPORTS 3.5 TONNES	2 m x 2 m x 1 m	1 TONNE	2	2	4	8	16
o DIVERTOR CANISTER WORKHEAD	1 TONNE	8 m x 2.5 m x 4 m (RETRACTED)	9 TONNES	1	2	4	8	8
o DIVERTOR CANISTER WORKHEAD DOLLY	SUPPORTS 9 TONNES	9 m x 3 m x 1.0 m	3 TONNES	1	2	4	8	8
o DIVERTOR CANISTER TRANSPORT DOLLY	SUPPORTS 6 TONNES	4 m x 2 m x 1.0 m	2 TONNES	2	2	4	8	16
o INSPECTION WORKHEAD	N/A	8 m x 2.5 m x 6.0 m	60 TONNES	1	1	2	4	8
o INSPECTION WORKHEAD DOLLY	SUPPORTS 60 TONNES	9 m x 5.0 m x 1.0 m	20 TONNES	1	1	2	4	8
o LEAK TEST WORKHEAD	N/A	.5 m x .3 m x .3 m	.3 TONNE	8	9	17	21	21
o ION SOURCE DOLLY	SUPPORTS 1.8 TONNES	1 m x 3 m x 1 m	1 TONNE	1	2	4	6	6
o NBI ISOLATION VALVE AND SHIELD DOLLY	SUPPORTS 12 TONNES	2 m x 4 m x 1 m	3 TONNES	1	2	6	6	6
o CCMD DOLLY	SUPPORTS 18 TONNES	15 m x 2 m x 1 m	5 TONNES	1	-	2	2	2
o REACTOR CRYOPUMP DOLLY	SUPPORTS 5 TONNES	4 m x 4 m x 1 m	2 TONNES	1	-	5	10	10
o BOMBARDMENT PLATE REMOVAL DEVICE DOLLY	SUPPORTS 8 TONNES	9 m x 3 m x 1 m	2 TONNES	1	2	4	8	8
o BOMBARDMENT PLATE DOLLY	SUPPORTS 2 TONNES	3 m x 2 m x 1 m	1 TONNE	1	2	4	8	8
o SHIELD DOOR SEAL HANDLING WORKHEAD	N/A	14 m x 5 m x 1 m	14 TONNES	1	1	2	4	4
o HANDLING WORKHEAD DOLLY	SUPPORTS 14 TONNES	14 m x 5 m x 1 m	4 TONNES	1	1	2	4	4
o SHIELD TRANSPORT FIXTURE AND DOLLY	N/A	14 m x 5 m x 1 m	2 TONNES	1	1	2	4	4
o GENERAL PURPOSE VALVE DOLLY	SUPPORTS 1 TONNE	1 m x 1 m x 1 m	.3 TONNES	1	10	10	10	10
o GENERAL PURPOSE CABLE DOLLY	SUPPORTS 5 TONNES	4 m x 4 m x 1 m	1 TONNE	1	1	2	2	2
o GENERAL PURPOSE INSTRUMENT DOLLY	SUPPORTS 5 TONNES	4 m x 4 m x 1 m	1 TONNE	1	1	2	2	2
o MISC. JACKS	5 TONNES	.5 m x .5 m x 10 m (MAX.)	1 TONNE (AVG.)	10	10	10	10	10
o JACK AND ACTUATOR DOLLY	SUPPORTS 5 TONNES	1 m x 10 m x 1 m	2 TONNES	1	2	2	2	2
o CRYOGEN LINE PURGE/MAINT. UNITS	N/A	-	2 TONNES	1	2	2	2	2
o LINE CUTTING/WELDING TOOLS	N/A	-	1 TONNE	1	2	2	2	2
o MISC. TOOLS	N/A	-	5 TONNES/SET	1	2	2	2	2
TOTAL WEIGHT (TONNES)		(W/O OVERHEAD CRANE):	1969.1	343.7	2208.7	4324.1	5177.3	5669.3
		1 SET = 1969.1 + 343.7 = 2312.8 TONNES	NUMBER OF SETS:		1.104	2.018	2.387	2.600

NOTE: SPECIAL EQUIPMENT REQUIRED FOR TOROIDAL FIELD OR POLOIDAL FIELD COIL REPLACEMENT IS ASSUMED PART OF CONSTRUCTION EQUIPMENT AND FIXTURES WHICH MAY BE STORED AND COSTED ELSEWHERE.

While this may be desirable to achieve a minimum downtime, it is relatively impractical. Therefore, the total quantities are adjusted downward at each replacement fraction to represent a gradual increase to the maximum number of a given equipment item that can conceivably be used at one time. This is, at best, an approximate value since an accurate determination of this quantity requires development of a detailed scheduled outage and resource allocation network. Table 4-54 indicates the trends and potential quantities that are anticipated.

The detailed list of equipment required by each maintenance action discussed in Section 4.3.1 is compiled in Table 4-55. This list also includes the equipment required for the additional maintenance actions included in Table 4-50. When assigning quantities for each item, it is assumed that as many parallel maintenance actions as possible are conducted for that item.

Through use of the forgoing procedure the total equipment complement required for a given replacement fraction is defined and the maximum equipment availability considered reasonable is established. For costing purposes, a single unit set of equipment is determined by summing the weight of one equipment item of each kind and adding the nominal spares set indicated in Table 4-54. Then the equivalent number of equipment sets is computed for cost of electricity optimization studies using the TOCOMO CODE. Equivalent equipment sets are computed as defined in Section 4.2.4 for the TMR.

4.3.4.2 Direct Operating Personnel Requiremetns - The direct operating personnel required to conduct the maintenance actions listed in Table 4-50 are indicated in Table 4-56. The number of these personnel required is determined by applying same groundrules used to determine the personnel requirements for the TMR. Operators are provided only for major equipment units that operate independently or control other equipment. The listing in Table 4-56 is restricted to this type of equipment. Each major item of unmanned equipment requires at least one operator while tugs and other manned equipment require two to assure clearance from obstructions when moving. The operators are assumed to function from a control room or rooms located strategically around the reactor room or from a shielded cab on the manned equipment. Operators are provided for each piece of operational equipment (not spares) required for the replacement fraction being conducted during a scheduled outage.

Additional support personnel are provided as permanent staff from the power plant. Costs for direct operating personnel are computed over and above those of the normal plant permanent staff. These costs are based on the use of these direct operating personnel as a contractor furnished team who are only charged to the annual plant operating cost during the period of the scheduled shutdown.

TABLE 4–55
TOKAMAK MAINTENANCE EQUIPMENT REQUIREMENTS BY MAINTENANCE ACTION

MAINTENANCE ACTION	ITEM DESIGNATION	MAJOR FUNCTION	QUANTITY/REPLACEMENT FRACTION					
			SPARES	1/12-1/10	1/8-1/6	1/4-1/3	1/2	1
1ST WALL/BLANKET REPLACEMENT	o OVERHEAD CRANE	REMOVE/INSTALL REACTOR MAJOR COMPONENTS DURING MAINTENANCE AND ASSEMBLY.	0	-	1	1	2	2
	o OPERATIONAL MAINT. UNIT	DISCONNECTS NBI REGENERATION DUCT, INSTALLS TRACK SEGMENT, DISCONNECTS COOLANT MANIFOLD, INSTALLS MANIFOLD COVERS, REMOVES DIVERTOR CANNISTERS, MOUNTS INSPECTION DEVICES. HAS REACH FOR HIGH COMPONENTS.	1	-	2	4	8	8
	o REACTOR SECTOR REMOVAL MACHINE	WITHDRAWS REACTOR SECTORS FROM REACTOR. PROVIDES MOTIVE POWER AND ADDS STABILITY, IF REQUIRED. INSTALLED IN FLOOR.	2 1	- -	2 2	4 4	8 8	16 8
	o TUG	PROVIDES MOTIVE POWER TO MOVE SMALL EQUIPMENT SUCH AS MANIFOLD COVERS, DIVERTOR MODULES, FIXTURES, TRACK SEGMENTS, ETC.	1	-	2	4	8	8
	o IMPACT WRENCH	AUTOMATED DEVICE TO REMOVE/INSTALL LARGE FASTENERS, USED WITH OMU.	1	-	2	4	8	8
	o MODULE REMOVAL TRACK SEGMENT	PROVIDES TRACK FOR MOVEMENT OF REACTOR MODULE FROM REACTOR ACROSS FLOOR GAP.	1	-	2	4	8	16
	o TRACK SEGMENT DOLLY	TRANSPORTS TRACK SECTIONS (8) TO/FROM POSITION IN REACTOR ROOM.	1	-	1	1	1	2
	o AUXILIARY SERVICES WORKHEAD	INSTALLS/REMOVES He MANIFOLD AND He MANIFOLD DUCT COVER.	1	-	2	4	8	8
	o AUXILIARY SERVICES WORKHEAD DOLLY	TRANSPORTS AUXILLIARY WORKHEAD TO/FROM POSITION IN REACTOR ROOM.	1	-	2	4	8	8
	o HELIUM COOLANT MANIFOLD COVER	COVERS THE HELIUM COOLANT DUCT RECESS IN REACTOR FLOOR DURING MOVEMENT OF REACTOR SECTOR. SUPPORTS SECTOR FRONT SUPPORT.	1	-	2	4	8	16
	o HELIUM MANIFOLD COVER DOLLY	TRANSPORTS MANIFOLD COVERS TO/FROM REACTOR.	1	-	2	4	8	16
	o DIVERTOR CANISTER WORKHEAD	INSTALL/REMOVES DIVERTOR CANISTERS. PERFORMS ALL FUNCTIONS DURING REMOVAL.	1	-	2	4	8	8
	o DIVERTOR CANISTER WORKHEAD DOLLY	TRANSPORTS DIVERTOR CANISTER WORKHEAD TO/FROM POSITION IN REACTOR ROOM.	1	-	2	4	8	8
	o DIVERTOR CANISTER TRANSPORT DOLLY	TRANSPORTS DIVERTOR CANISTERS TO/FROM HOT CELL AND STORES CANISTERS.	1	-	2	4	8	16
	o INSPECTION WORKHEAD	INSPECTS REACTOR SECTORS ADJACENT TO REMOVED SECTOR.	1	-	1	2	4	8
	o INSPECTION WORKHEAD DOLLY	TRANSPORTS INSPECTION WORKHEAD TO/FROM POSITION IN REACTOR ROOM.	1	-	1	2	4	8
	o LEAK TEST WORKHEAD	TEST FOR LEAKS AROUND He COOLANT MANIFOLD.	1	-	2	4	8	8
NEUTRAL BEAM INJECTOR ION SOURCE REPLACEMENT	o GENERAL PURPOSE MAINTENANCE MACHINE (GPMM)	DISCONNECT ION SOURCE FLUID AND POWER SERVICES AND DETACH SOURCE FROM NBI; INSTALL ION SOURCES AND CONNECT SERVICES.	1	1	2	4	6	6
	o IMPACT WRENCH	AUTOMATED DEVICE FOR REMOVING/INSTALLING FASTENERS. USE WITH GPMM.	1	1	2	4	6	6
	o LEAK TEST WORKHEAD	TEST FOR LEAKS OF SF_6 AND VACUUM LEAKS IN NBI.	1	1	1	2	3	3
	o ION SOURCE DOLLY	TRANSPORT ION SOURCES TO/FROM NBI.	1	1	2	4	6	6
	o TUG	MOVE ION SOURCES TO/FROM NBI.	1	1	1	1	1	2
NEUTRAL BEAM INJECTOR ISOLATION VALVE REPLACEMENT	o GENERAL PURPOSE MAINTENANCE MACHINE (GPMM)	DISCONNECT/CONNECT SHIELDING AND VALVE. HOIST SHIELDING AND VALVE.	1	1	2	4	6	6
	o IMPACT WRENCH	AUTOMATED DEVICE FOR REMOVING/INSTALLING FASTENERS. USE WITH GPMM.	1	1	2	4	6	6
	o LEAK TEST WORKHEAD	TEST FOR VACUUM LEAKS AT VALVE.	1	1	1	2	3	3
	o ISOLATION VALVE DOLLY	TRANSPORT VALVE AND/OR SHIELD BLOCKS TO/FROM NBI REGION.	1	1	2	4	6	6
	o TUG	MOVE ISOLATION VALVES TO/FROM NBI.	1	1	1	1	1	2

TABLE 4–55
TOKAMAK MAINTENANCE EQUIPMENT REQUIREMENTS BY MAINTENANCE ACTION (CONT.)

MAINTENANCE ACTION	ITEM DESIGNATION	MAJOR FUNCTION	QUANTITY/REPLACEMENT FRACTION					
			SPARES	1/12-1/10	1/8-1/6	1/4-1/3	1/2	1
REACTOR CRYOPUMP REPLACEMENT	o CENTRAL CELL MAINTENANCE DEVICE (CCMD)	DISCONNECT/CONNECT PUMP AND PUMP SERVICES WHILE MOUNTED ABOVE CENTER OF REACTOR.	1	1	-	2	4	4
	o IMPACT WRENCH	AUTOMATED DEVICE FOR REMOVING/INSTALLING FASTENERS. USE WITH CCMD.	1	1	-	2	4	4
	o LEAK TEST WORKHEAD	TEST FOR VACUUM LEAKS AT PUMP.	1	1	-	2	4	4
	o OVERHEAD MANIPULATOR	USE WITH CCMD TO DISCONNECT/CONNECT PUMPS.	0	1	-	2	2	2
	o OVERHEAD CRANE	HOIST PUMPS FROM DOLLY TO REACTOR.	0	1	-	1	2	2
	o CCMD DOLLY	TRANSPORT CCMD AND WORKHEAD TO/FROM REACTOR POSITION.	1	1	-	2	4	4
	o TUG	MOVE CRYOPUMPS AND EQUIPMENT TO/FROM REACTOR.	1	1	-	2	2	4
	o REACTOR CRYOPUMP DOLLY	TRANSPORT CRYOPUMPS TO/FROM REACTOR.	1	2	-	5	10	10
DIVERTOR PARTICLE BOMBARDMENT PLATE REPLACEMENT	o BOMBARDMENT PLATE REMOVAL DEVICE (BPRD)	DISCONNECT/CONNECT AND REMOVE/EMPLACE BOMBARDMENT PLATES ABOVE DIVERTORS.	1	-	2	4	8	8
	o OVERHEAD CRANE	HOIST BOMBARDMENT PLATES AND BPRD INTO AND OUT OF POSITION, PLACE ON DOLLY.	0	-	1	1	2	2
	o BPRD DOLLY	TRANSPORT BPRD TO/FROM REACTOR.	1	-	2	4	8	8
	o BOMBARDMENT PLATE DOLLY	TRANSPORT BOMBARDMENT PLATES TO/FROM REACTOR.	1	-	2	4	8	8
	o TUG	MOVE BPRD AND PLATES TO/FROM REACTOR.	1	-	1	2	4	4
	o LEAK TEST WORKHEAD	TEST FOR VACUUM LEAKS AT UPPER DOOR.	1	-	1	2	4	4
SHIELD DOOR SEAL REPLACEMENT	o GENERAL PURPOSE MAINTENANCE MACHINE (GPMM)	EMPLACES SEAL WORKHEAD.	1	-	2	4	8	8
	o SEAL HANDLING WORKHEAD	PICKS UP AND INSTALLS/DEMOUNTS SEAL.	1	-	2	4	8	8
	o SEAL TRANSPORT FIXTURE AND DOLLY	TRANSPORTS SEALS TO/FROM REACTOR.	1	-	1	2	4	4
	o OVERHEAD CRANE	LIFT SEAL WORKHEAD.	1	-	1	1	1	1
	o HANDLING WORKHEAD DOLLY	TRANSPORTS HANDLING WORKHEAD TO/FROM REACTOR.	1	-	2	4	8	8
	o TUG	MOVE SEALS AND EQUIPMENT TO/FROM REACTOR.	1	-	1	2	4	4
	o LEAK TEST WORKHEAD	TEST FOR VACUUM LEAKS AT SHIELD DOOR.	1	-	1	2	4	4
COOLANT VALVE REPLACEMENT[1] (NOT LIFE LIMITED COMPONENT)	o GENERAL PURPOSE MAINTENANCE MACHINE	DISCONNECT/CONNECT AND REMOVE/EMPLACE COOLANT VALVES.	1	2	2	2	2	2
	o IMPACT WRENCH	REMOVE/INSTALL FASTENERS.	1	2	2	2	2	2
	o LEAK TEST WORKHEAD	TEST FOR LEAKS AT HELIUM COOLANT VALVE.	1	2	2	2	2	2
	o TUG	MOVE VALVES TO/FROM POSITION IN RR.	1	1	1	1	1	1
	o GENERAL PURPOSE VALVE DOLLY	TRANSPORT VALVES TO/FROM REACTOR.	1	2	2	2	2	2
ELECTRICAL CABLE REPLACEMENT[1] (NOT LIFE LIMITED COMPONENT)	o GENERAL PURPOSE MAINTENANCE MACHINE (GPMM)	DISCONNECT/CONNECT ELECTRICAL CABLE.	1	1	1	1	1	1
	o OVERHEAD MANIPULATOR	DISCONNECT/CONNECT CABLES BEYOND REACH OF GPMM.	0	1	1	1	1	1
	o GENERAL PURPOSE CABLE DOLLY	TRANSPORT CABLES TO/FROM POSITION IN RR.	1	1	1	2	2	2
	o OVERHEAD CRANE	HOIST CABLES WORKED BY OVERHEAD MANIPULATOR.	1	1	1	1	1	1
	o TUG	MOVE CABLES TO/FROM POSITION IN RR.	1	1	1	1	1	1
CHARGE EXCHANGE ANALYZER REPLACEMENT[1] (NOT LIFE LIMITED COMPONENT)	o GENERAL PURPOSE MAINTENANCE MACHINE	DISCONNECT/CONNECT SERVICES TO SHIELD AND ANALYZER AND ALSO STRUCTURAL CONNECTIONS.	1	1	1	1	1	1
	o OVERHEAD CRANE	LIFT SHIELD COVER AND SHIELD BLOCKS.	1	1	1	1	1	1
	o IMPACT WRENCH	REMOVE/INSTALL FASTENERS. USE WITH GPMM.	1	1	1	1	1	1
	o GENERAL PURPOSE INSTRUMENT DOLLY	TRANSPORT ANALYZER AND SHIELD BLOCKS.	1	1	1	2	2	2
	o LEAK TEST WORKHEAD	TEST FOR VACUUM LEAKS AT ANALYZER CONNECTION.	1	1	1	1	1	1

TABLE 4–55
TOKAMAK MAINTENANCE EQUIPMENT REQUIREMENTS BY MAINTENANCE ACTION (CONT.)

MAINTENANCE ACTION	ITEM DESIGNATION	MAJOR FUNCTION	QUANTITY/REPLACEMENT FRACTION					
			SPARES	1/12-1/10	1/8-1/6	1/4-1/3	1/2	1
MISCELLANEOUS[1] (NO LIFE LIMITED COMPONENTS)	o OPERATIONAL MAINTENANCE UNIT (OMU)	REACH AND DISCONNECT/CONNECT WHERE OTHER EQUIPMENT IS RESTRICTED.	1	1	1	1	1	1
	o OVERHEAD MANIPULATOR	CONNECT/DISCONNECT UPPER SHIELD DOOR ACTUATOR.	0	1	1	1	1	1
	o GENERAL PURPOSE (GPMM) MAINTENANCE MACHINE	CONNECT/DISCONNECT VALVES, INSTRUMENTS.	1	1	1	1	1	1
	o JACKS	RAISE/LOWER POLOIDAL MAGNETS FOR ACTUATOR REMOVAL.	10	10	10	10	10	10
	o JACK AND ACTUATOR DOLLY	TRANSPORT JACKS AND ACTUATORS TO/FROM POSITION IN REACTOR ROOM.	1	1	2	2	2	2
	o IMPACT WRENCH	DISCONNECT/CONNECT FASTENERS.	1	3	3	3	3	3
	o GENERAL PURPOSE VALVE DOLLY	TRANSPORT VALVES (VALVES ARE FREQUENT MAINTENANCE ITEMS).	-	10	10	10	10	10
	o TUG	MOVE MATERIAL, ETC., IN/OUT OF RR.	1	1	1	1	1	1
	o OVERHEAD CRANE	HOIST HEAVY COMPONENTS/ OPERATION.	1	2	2	2	2	2
	o CRYOGENLINE UNITS	PREPARE LINES FOR MAINTENANCE/ OPERATION.	1	2	2	2	2	2
	o LINE CUTTING/WELDING TOOLS	REPAIR FLUID LINES.	1	2	2	2	2	2
	o MISC. TOOLS	PERFORM SPECIALIZED FUNCTIONS.	-	-	-	-	-	-

(1) THESE MAINTENANCE ACTIONS ARE NOT A FUNCTION OF REPLACEMENT FRACTION BUT THEIR FREQUENCY DEPENDS ON RELIABILITY OF THE COMPONENTS.

TABLE 4–56
TOKAMAK DIRECT OPERATING PERSONNEL REQUIRED

	REPLACEMENT FRACTION			
	1/8	1/4	1/2	1
NUMBER OF FIRST WALL/BLANKET SECTORS REPLACED	2	4	8	16
NUMBER OF PERSONNEL REQUIRED ASSUME: 1 OPERATOR/UNMANNED EQUIPMENT 2 OPERATORS/MANNED - MOBILE EQUIPMENT 2 OPERATORS FOR MAINTENANCE CONTROL				
EQUIPMENT REQUIRING OPERATORS				
OVERHEAD CRANE	4	4	4	4
GENERAL PURPOSE MAINTENANCE MACHINE	4	6	10	10
OVERHEAD MANIPULATOR	2	4	4	4
OPERATIONAL MAINTENANCE UNIT	4	8	16	16
REACTOR SECTOR REMOVAL MACHINE	2	4	8	16
TUGS	8	16	20	20
CENTRAL CORE MAINTENANCE DEVICE	2	2	4	4
BOMBARDMENT PLATE REMOVAL DEVICE	2	4	8	8
CONTROL ROOM OPERATORS	2	2	2	2
TOTAL NUMBER OF PERSONNEL REQUIRED	30	50	76	84

The list of operators shown in Table 4-56 differs from the estimated requirements for the Culham concept in the earlier study phase principally because the number of maintenance actions being considered has increased significantly and, therefore, the equipment required has increased in quantity during a scheduled outage. The number of personnel required appears to be relatively large but the maintenance equipment units must be controlled remotely not only while in the reactor room but also during operations outside of the reactor room. In addition, other remote operations are expected so it is anticipated that the number of personnel estimated for direct operations will not be excessive.

4.3.5 Total Tokamak Forced Outage Plan Composition - Forced outages occur for those components which cannot be replaced during reactor operation, where no redundancy is feasible or where redundancy is insufficient to reduce the system failure rate to a negligible value. The components which are potential causes for forced outages in the IMS tokamak reactor have been examined and are listed in Table 4-4. These components are located primarily in the reactor room because most of the exterior components are assumed to be redundant and can be maintained while the reactor is operating. Thus, they have no impact on reactor downtime estimates.

The forced outage downtime requirements for the tokamak reactor components have been estimated in the same manner as for the TMR analysis and are shown in Table 4-57. Since only a few of these forced outage maintenance action downtimes have been estimated in detail, as discussed in Section 4.3.1, the estimates for the remaining maintenance actions are based on their similarity to other maintenance actions. For brevity, a number of maintenance actions, such as piping connections, are grouped without regard to detailed locations, thereby assuming that the access for each item is the same when making a downtime estimate. These approximations are sufficiently valid to indicate trends.

The relative impact of forced outages for each component listed in Table 4-57 is indicated in Table 4-58. The components estimated to contribute the most downtime to forced outages are listed in the descending order of influence on the total forced outage downtime. The percentages of allowable downtime shown in Table 4-58 have been computed in the same manner as the percentages for the TMR components listed in Table 4-33.

The most critical component for the tokamak reactor is found to be the seals in the primary vacuum wall doors. This occurs both because of the large number of doors that must be sealed and the relatively long time to replace a door seal in comparison with other maintenance actions on the tokamak. Many seal designs exist

TABLE 4–57
IMS TOKAMAK REACTOR FORCED OUTAGE MAINTENANCE ACTIONS

COST ACCOUNT NUMBER	MAINTENANCE COMPONENT (SUBASSEMBLY)	PROBABLE DOMINANT FAILURE MODE	UNSCHEDULED FAILURE IMPACT** (SEE CODE)	NO. OF UNITS REQUIRED	NO. OF UNITS REDUNDANT	ESTIMATED DOWNTIME PER MAINTENANCE ACTION, DAYS*	PERCENT OF FORCED OUTAGE DOWNTIME
22	REACTOR PLANT EQUIPMENT						
22.01	REACTOR EQUIPMENT						
22.01.01	BLANKET AND FIRST WALL						
	FIRST WALL AND STRUCTURE, CELLS	CRACK PROPAGATION AND LEAK	1,2	2800	0	10.0	13.5
	WALL MODIFIERS (COATINGS)	BURN OFF	1,3	1	-	.3	1.0
22.01.02	SHIELD						
	PRIMARY	COOLANT CONNECTOR LEAK	1	16	0	6.8	1.0
	SECONDARY	COOLANT CONNECTOR LEAK	1	16	0	3.7	.6
22.01.03	MAGNETS						
	TOROIDAL FIELD MAGNETS	CONDUCTOR SHORT	1,2	16	0	347	2.7
	POLOIDAL FIELD MAGNETS	CONDUCTOR SHORT	1,2	15	0	288	16.6
	ONMIC HEATING COILS	CONDUCTOR SHORT	1,2	14	0	121	6.5
	POWER LEADS	BURNED LEAD	1	90	0	8.4	.7
22.01.04	SUPPLEMENTAL HEATING						
22.01.04.01	NEUTRAL BEAM HEATING						
	ION SOURCES	FILAMENT BURNOUT	1,2	24	12	3.4	7.2
	ION BEAM DUMP PLATES	COOLANT LEAK	1	12	0	4.0	.3
	ION DUMP/MAGNETS	CONDUCTOR SHORT	1	12	0	4.0	.2
	NBI ISOLATION VALVE	ACTUATOR STUCK OPEN	1,2	12	12	3.6	4.0
22.01.05	STRUCTURE AND SUPPORT						
	MAGNET RETRACTIUN SYSTEM	ACTUATOR JAMMED	1,2	48	0	4.9	.7
22.01.06	VACUUM SYSTEMS						
22.01.06.01	PLASMA CHAMBER VACUUM	(AT DIVERTORS)					
	CRYOPUMPS	VALVE ACTUATORS	1,2	16	4	3.9	2.0
	MECHANICAL PUMPS	SEAL LEAK	3	4	1	-	-
	CRYOGEN PIPING, CONNECT.	CONNECTOR LEAK	1,3	160	0	3.0	1.4
	CRYOGEN VALVES, CONTROL	FAIL OPEN OR CLOSED	1,2	20	20	3.8	.9
	VACUUM PIPING, CONNECT.	CONNECTOR LEAK	1,3	64	16	3.0	nil
	VACUUM VALVES	VALVE SEAL LEAK	1,2	32	8	3.8	nil
	CRYOGEN VALVES, ISOLATE	VALVE SEAL LEAK	3	48	12	3.8	-
22.01.06.02	MAGNET DEWAR VACUUM						
	PUMPS/COMPRESSORS	BEARING FAILURE	3	1 SET	1 SET	-	-
	PIPING, CONNECTIONS	CONNECTOR LEAK	3	188	0	3.0	-
	VALVES, EXTERNAL	VALVE SEAL LEAK	3	94	0	3.8	-
22.01.06.03	SUPPLEMENTAL HEATING VAC						
	CRYOPUMPS	VALVE ACTUATORS	1,2	12	6	6.1	1.9
	MECHANICAL PUMPS	(USE PLASMA CHAMBER PUMPS)					
	CRYOGEN PIPING, CONNECT	CONNECTOR LEAK	1,3	144	0	3.0	1.2
	CRYOGEN VALVES, CONTROL	FAIL OPEN	1,2	18	18	3.8	.9
	VACUUM PIPING, CONNECT	CONNECTOR LEAK	1,3	4	0	3.0	nil
	VACUUM VALVES, REGEN.	VALVE SEAL LEAK	1,2	12	0	3.8	nil
	CRYOGEN VALVES, ISOLATE	VALVE SEAL LEAK	3	54	0	3.8	-
22.01.06.04	DIRECT CONVERTER VACUUM	(NOT APPLICABLE)					
22.01.06.05	REACTOR VACUUM SYSTEMS	(SECONDARY VACUUM ZONE)					
	PUMPS/COMPRESSORS	BEAING FAILURE	3	2 SETS	1 SET	-	-
	PIPING, CONNECTIONS	CONNECTOR LEAK	3	12	0	3.0	-
	VALVES	VALVE SEAL LEAK	3	6	0	3.8	-
22.01.06.06	REACTOR VACUUM WALL PENETRATIONS (DOORS)	SEAL LEAK	1,2	32	0	5.3	20.4

TABLE 4–57
IMS TOKAMAK REACTOR FORCED OUTAGE MAINTENANCE ACTIONS (CONTINUED)

COST ACCOUNT NUMBER	MAINTENANCE COMPONENT (SUBASSEMBLY)	PROBABLE DOMINANT FAILURE MODE	UNSCHEDULED FAILURE IMPACT** (SEE CODE)	NO. OF UNITS		ESTIMATED DOWNTIME PER MAINTENANCE ACTION, DAYS*	PERCENT OF FORCED OUTAGE DOWNTIME
				REQUIRED	REDUNDANT		
22.01.07	POWER SUPPLY, ENERGY STORAGE						
	DIESEL GENERATORS	FAIL TO START	3	2	1	-	-
	CABLES, METERS	CONNECTOR INTERRUPT	1,2,3	5000	1000	1.8	.3
	POWER CONDITIONING EQUIP.						
	POWER SUPPLIES	BEARING FAILURE	3	57	14	-	-
	ENERGY STORAGE EQUIP.	CONDUCTOR SHORT	3	2	1	-	-
	SUPPLEMENTAL HEATING POWER	POWER DISRUPTION	3	4	1		
22.01.08	IMMUNITY CONTROL						
	DIVERTORS						
	SLOT LINERS, SETS	STRUCTURAL FAILURE	1,2	16	0	4.3	.1
	BOMBARDMENT PLATES	COOLANT LEAK	1,2	32	0	3.6	.4
	PLATE COOLANT SYSTEM	SERVO VALVE FAILURES	1,3	1 SYS.	0	3.8	2.6
22.01.09	DIRECT ENERGY CONVERTER	(NOT APPLICABLE)					
22.02	MAIN HEAT TRANSPORT SYSTEMS						
22.02.01	PRIMARY COOLANT SYSTEM						
22.02.01.01	PUMPS AND DRIVES	SEAL LEAK	3	8	1	-	-
22.02.01.02	PIPING, CONNECTIONS	CONNECTOR LEAK	1,3	352	44	3.0	1.6
	ISOLATION VALVES	VALVE SEAL LEAK	1,3	144	18	3.8	1.1
	CONTROL VALVES	ACTUATOR FAILURE	1,2	18	18	3.8	.9
22.02.01.03	HEAT EXCHANGER (INTERMEDIATE)	TUBE LEAK	3	16	2	-	-
22.02.01.04	TANKS	CONNECTION LEAK	3	8	1	-	-
22.02.01.05	CLEAN-UP SYSTEM	CONTROL FAILURE	3	8	1	-	-
22.02.01.06	THERMAL INSULATION	(SEE PIPING, ABOVE)					
22.02.01.07	TRITIUM EXTRACTION	(SEE TRITIUM RECOVERY)					
22.02.02	INTERMEDIATE COOLANT SYSTEM						
22.02.02.01	PUMPS AND DRIVES	SEAL LEAK	3	8	1	-	-
22.02.02.02	PIPING, CONNECTIONS	CONNECTOR LEAK	1,3	112	14	3.0	.8
	ISOLATION VALVES	VALVE SEAL LEAK	1,3	16	2	3.8	nil
	CONTROL VALVES	ACTUATOR FAILURE	1,2	18	18	3.8	3.1
22.02.02.03	STEAM GENERATOR	TUBE LEAK	3	8	1	-	-
22.02.02.04	TANKS	CONNECTION LEAK	3	8	1	-	-
22.02.02.05	CLEAN UP SYSTEM	CONTROL FAILURE	3	8	1	-	-
22.03	AUXILIARY COOLING SYSTEMS						
22.03.01	MAGNET COOLING SYSTEM						
	Ha REFRIGERATION SYSTEM	VALVE SEAL	3	90	0	-	-
	N_2 REFRIGERATION SYSTEM	VALVE SEAL	3	90	0	-	-
	PIPING CONNECTIONS	CONNECTOR LEAK	1,3	360	0	3.0	3.1
	TANKS/CONTAINERS		3	92	0	-	-
22.03.02	SHIELD COOLING						
	INNER SHIELD	(SEE PRIMARY COOLANT)					
	OUTER SHIELD (WATER COOLANT)						
	PIPING, CONNECTIONS	CONNECTOR LEAK	1,3	76	0	3.0	.7
	CONTROL VALVES	VALVE SEAL LEAK	1,2	38	0	3.8	nil
	HEAT EXCHANGER	TUBE LEAK	3	2	1	3.8	-
	PUMPS AND DRIVES	SEAL LEAK	3	1	1	-	-
22.03.03	SUPPLEMENTAL HEATING COOLING						
	Ha REFRIGERATION SYSTEM	VALVE SEAL	3	24	0	-	-
	N_2 REFRIGERATION SYSTEM	VALVE SEAL	3	24	0	-	-
	PIPING CONNECTIONS	CONNECTOR LEAK	1,3	144	0	3.0	1.2
	VALVES, CONTROL	VALVE SEAL LEAK	1,2	24	0	3.8	nil
	HEAT EXCHANGER	(INCLUDED WITH SHIELD COOLING)					
	PUMPS AND DRIVES (WATER)	(INCLUDED WITH SHIELD COOLING)					

TABLE 4-57
IMS TOKAMAK REACTOR FORCED OUTAGE MAINTENANCE ACTIONS (CONTINUED)

COST ACCOUNT NUMBER	MAINTENANCE COMPONENT (SUBASSEMBLY)	PROBABLE DOMINANT FAILURE MODE	UNSCHEDULED FAILURE IMPACT** (SEE CODE)	NO. OF UNITS		ESTIMATED DOWNTIME PER MAINTENANCE ACTION, DAYS*	PERCENT OF FORCED OUTAGE DOWNTIME
				REQUIRED	REDUNDANT		
22.03.04	POWER SUPPLY COOLING						
	Ha REFRIGERATION SYSTEM	(WITH SUPPLEMENTAL HEATING, COOLING)					
	N_2 REFRIGERATION SYSTEM	(WITH SUPPLEMENTAL HEATING, COOLING)					
	PIPING CONNECTIONS	CONNECTOR LEAK	1,3	27	0	3.0	.2
	VALVES	SEAL LEAK	1,3	15	0	3.8	nil
22.04	RADIOACTIVE WATER TREATMENT	(NOT INCLUDED)					
22.05	FUEL HANDLING AND STORAGE						
22.05.01	FUEL PURIFICATION	CONTROL FAILURE	3	NOT DEFINED		-	-
22.05.02	LIQUIDATION	NOT DEFINED	1,2			-	-
22.05.03	FUEL PREPARATION	SEAL LEAK	1,2			-	-
22.05.04	FUEL INJECTION	DRIVE FAILURE	1,2			-	-
22.05.05	FUEL STORAGE/PIPING	CONNECTOR LEAK	1,3			-	-
22.05.06	TRITIUM RECOVERY	CONTROL FAILURE	3			-	-
22.05.07	EMERGENCY AIR DETITRIATION	NOT DEFINED	3			-	-
22.06	OTHER REACTOR EQUIPMENT						
22.06.01	MAINTENANCE EQUIPMENT						
	CRANES	MECHANICAL SEIZURE	2	SEE DETAILED LIST		-	-
	OVERHEAD MANIP.	MECHANICAL SEIZURE	2			-	-
	FLOOR MTD. MANIP.	MECHANICAL SEIZURE	2,3			-	-
	HEAVY FLOOR MTD. HOISTS/MANIP.	MECHANICAL SEIZURE	2,3			-	-
	SHIELD DOOR RETRACTION	MECHANICAL SEIZURE	2			-	-
	COOLANT LINE RETRACTORS	MECHANICAL SEIZURE	2			-	-
	TUGS AND DOLLIES	STRIPPED FITTING	2,3			-	-
	ENTRANCE AND EGRESS LOCKS	MECHANICAL SEIZURE	2			-	-
22.06.02	SPECIAL HEATING SYSTEMS	(NOT INCLUDED)					
22.06.03	COOLANT STORAGE AND MAKEUP	(NOT INCLUDED)					
22.06.04	GAS SYSTEMS	(NOT INCLUDED)					
22.06.05	BUILDING VENTILATION SYSTEM						
	FANS	DRIVE FAILURE	3	NOT DEFINED		-	-
	FILTERS AND SCRUBBERS	CONTROL FAILURE	3			-	-
22.07	INSTRUMENTATION AND CONTROL						
22.07.01	REACTOR I&C EQUIPMENT						
	PROBES (PERFORMANCE MONITORING SYSTEM)	INSTRUMENT FAILURE	2	NOT DEFINED		-	-
	INTERNAL INSTRUMENTS (REACTOR STATUS SYSTEM)	INSTRUMENT FAILURE	2			-	-
	EXTERNAL INSTRUMENTS (PLASMA CONTROL SYSTEM)	INSTRUMENT FAILURE	2			-	-
	CONTROL ROOM EQUIPMENT	INDICATOR FAILURE	3			-	-
	COMPUTERS	POWER SUPPLY FAILURE	3			-	-
22.07.02	RADIATION MONITORING SYSTEM	SENSOR FAILURE	3			-	-
22.07.03	ISOLATED GAUGES	(NOT INCLUDED)					

*REMOTE OPERATION, ADJUSTED FOR .625 PRODUCTIVITY FACTOR

**FAILURE IMPACT CODE:
1 IMMEDIATE SHUTDOWN
2 REPAIR DURING SCHEDULED SHUTDOWN
3 REPAIR DURING OPERATION

TABLE 4-58
TOKAMAK FORCED OUTAGE CONTRIBUTIONS

COMPONENT[2]	UNSCHEDULED DOWNTIME[1] (PERCENT OF TOTAL ALLOWABLE)
VACUUM WALL DOOR SEAL LEAKS	20.4
POLOIDAL FIELD MAGNETS	16.6
FIRST WALL/BLANKET	13.5
NEUTRAL BEAM INJECTOR ION SOURCES	7.2
OHMIC HEATING COILS	6.5
NEUTRAL BEAM INJECTOR VACUUM VALVES	4.0
INTERMEDIATE COOLANT SYSTEM CONTROL VALVES	3.1
MAGNET CRYOGEN SYSTEM PIPING CONNECTIONS	3.1
TOROIDAL FIELD MAGNETS	2.7
DIVERTOR BOMBARDMENT PLATE COOLING SYSTEM	2.6
PLASMA CHAMBER CRYOPUMP VALVES	2.0
NEUTRAL BEAM CRYOPUMP SHUTTERS	1.9
PRIMARY COOLANT SYSTEM PIPING CONNECTIONS	1.6
PLASMA CHAMBER CRYOPUMP CRYOGEN PIPING CONNECTIONS	1.4
NEUTRAL BEAM CRYOPUMP CRYOGEN PIPING CONNECTIONS	1.2
NEUTRAL BEAM COOLING SYSTEM PIPING CONNECTIONS	1.2
PRIMARY COOLANT SYSTEM VALVES	1.1
OTHER COMPONENTS (< 1 PERCENT EACH)	9.9
	100.0

[1] VARIATIONS IN PRELIMINARY ESTIMATES CAN ALTER RESULTS SIGNIFICANTLY.

and it is quite possible that both this downtime and the relative frequency of occurrence can be reduced.

The first wall/blanket is also likely to be a significant cause of forced outages. Again, the relatively long downtime required to make repairs and the large first wall area involved are the principal factors that make this subsystem a major forced outage factor.

In addition, redundancy is infeasible with the first wall/blanket and any malfunction will result in a forced outage. The frequency of a forced outage resulting from a first wall/blanket malfunction is expected to be low and the large percentage of the total downtime is primarily caused by the longer MTTR.

In a similar vein, the poloidal field coils contribute significantly to the forced outage downtime primarily because of the extremely long estimated MTTR. These coils are more highly stressed than the toroidal field coils and are likely to be down more frequently, even though fewer in number. Ohmic heating coils are similar to the poloidal field coils in that they are expected to have a similar forced outage frequency, but, since they are smaller and more accessible from above the reactor, the downtime for replacement is much less.

The neutral beam injector ion sources are a significant cause of forced outages in the tokamak reactor but the arrangement is such that redundancy is feasible. Therefore, while the relative outage frequency of individual ion sources is the same as assumed for the TMR, the reactor forced outage frequency from this cause is much less, thereby reducing the impact on forced outage downtime below that defined for the TMR.

The remaining items in the component list of Table 4-58, with a few exceptions, are in the category of plumbing. Cumulatively, valves and piping connections account for a total of 27.6% of forced outage downtime with 23.2% reported in Table 4-58. This forced outage impact includes the effect of utilizing redundant control valves for all fluid flow lines. Since valves and piping connections are widely used and the individual frequency of forced outages is known to be low, the major cause for their contribution to the total forced outage downtime is the large number of valves and connections required. In estimating the number of valves, only those fluid loops designated as a reactor system in Table 4-57 are considered. Also, piping connections are assumed to exist only where components are connected to the line. For high capacity coolant systems, such as the primary coolant loops, a redundant loop is assumed available to prevent a forced outage from a single point failure in one of the loops. A more detailed design is required to determine which valves and connections in each fluid system will cause a forced outage.

In evaluating the importance of forced outages for reactor componetns in this manner, the preliminary nature of estimates of relative forced outage frequency and of MTTR for each component must be considered. Any variation in the assumptions can significantly alter the results of this listing. The principal benefit of the results shown in Table 4-58 is to indicate the types of systems and components that must be investigated further and the design concept arrangement and composition that must be considered to reduce forced outages to a minimum.

5.0 TMR AND TOKAMAK MAINTAINABILITY ASSESSMENT

The scheduled and forced outage requirements for the TMR and the tokamak reactor concepts are assessed in this section. The influence on scheduled outage requirements of different replacement fractions for critical components, of different redundancy for subsystems and components, of maintenance equipment failures and of limiting equipment and other resources is examined. The influence of specific components and subassemblies on forced outage requirements and the impact of both forced and scheduled outages on availability and cost of electricity are also assessed. All costs are calculated using the TOCOMO and MICOMO cost models.

In addition to the foregoing studies the trends in maintainability and cost of electricity resulting from a more advanced TMR design study are evaluated. This advanced TMR design study is being conducted at the Lawrence Livermore Laboratory and its pertinent features are defined in Reference 6.

5.1 SELECTED SUBSYSTEM REPLACEMENT FRACTION IMPACTS - The examination of the TMR maintenance and critical path estimates in Section 4.2.3 indicated that the direct converter cryopump panels, the end plugs and the central cell sectors have major impacts on scheduled downtime. Both the direct converter cryopump panels and the central cell sectors consist of many units, i.e., 50 cryopump panels in each direct converter and 36 central cell sectors. Replacement of end plug first wall and shield modules is not included in this discussion of replacement fraction sensitivities because it is conducted by discreet sections and does not lend itself to a replacement fraction concept for maintenance. Replacement of the cryopump panels is assumed to be frequent because of wearout of the shutter and valve actuators resulting from frequent regeneration.

The replacement fractions selected for the cryopump panels and the first wall/blanket subsystems are dependent on the relative life of the subsystems. The life of the first wall/blanket is approximately 7.8 operating years based on a fluence limit of 16 MW-yrs/m^2. Thus, if a replacement fraction of 0.5 is used, a scheduled outage for replacement of the central cell sectors is 3.9 years. However, the life of the valve assemblies on the cryopumps in the direct converter region may be much shorter. While this is not known, a minimum life of approximately four operating years is assumed. From the critical path estimates given in Tables 4-25 through 4-27 the dominant life limited component for determining scheduled outage is a cryopump panel. The effect of two different life assumptions for those panels is considered and the results are summarized in Table 5-1. For a cryopump panel life of 3.9 years with an 7.8 year central cell first wall/blanket life, replacement fractions of 1/4, 1/2 and 1.0 are assumed for the cryopump panels. The central cell first wall/blanket replacement fractions that would be replaced during these scheduled outages would be 1/9, 1/4 and 1/2, respectively. The corresponding required scheduled outage downtimes are 24, 38 and 40 days as determined by the cryopump panel critical path. Replacement fractions up to 100% for the central cell sectors can be used when replacing 50% or more of the cryopump panels since the longest downtime required for these sectors is only 30 days when replacing the entire 36 sectors.

TABLE 5–1

SENSITIVITY OF TMR SCHEDULED MAINTENANCE REQUIREMENTS TO REPLACEMENT FRACTION (1)

COMPONENT LIFE, YRS						
CRYOPUMP PANELS	←	≈ 3.9	→	←	≈ 7.8	→
FIRST WALL/BLANKET, ET.AL.	←	≈ 7.8	→	←	≈ 7.8	→
MAINTENANCE INTERVAL, APPROX. YRS	1	2	4	1	2	4
REPLACEMENT FRACTION						
CRYOPUMP PANELS	.25	.50	1.0	.12	.25	.50
FIRST WALL/BLANKET, ET.AL.	.111	.25	.50	.111	.25	.50
NUMBER OF UNITS REPLACED						
CRYOPUMP PANELS	12	25	50	6	12	25
CENTRAL CELL SECTORS	4	9	18	4	9	18
MAINTENANCE EQUIPMENT, EQUIVALENT SETS	1.8	2.03	2.98	1.77	1.92	2.97
DIRECT OPERATING MANPOWER	41	67	96	37	57	96
SCHEDULED OUTAGE, DAYS	24	38	40	18	28	38
AVAILABILITY	.7940	.7886	.7918	.7942	.7969	.7926

(1) DOWNTIME FOR BOP MAINTENANCE=28 DAYS AND FOR FORCED OUTAGES=65 DAYS/OPERATING YEAR

Similarly, the scheduled outage downtimes and the number of modules exchanged are derived when the life of the cryopump panels and the first wall/blanket are assumed to be equal at 7.8 years. In this case, however, if 12 cryopump panels are replaced with a central cell replacement fraction of 1/4 (9 sectors) the downtime for central cell sector replacement determines the outage downtime. Such a change in critical path components is likely to occur when the downtimes for two components are close. This example also illustrates the influence of component life when determining the critical path scheduled downtimes.

Figure 5-1 indicates the sensitivity of the cost of electricity and availability of these two cases. For this analysis a balance of plant scheduled annual outage of 28 days and a forced outage downtime of 65 days per operating year were used in both cases. Also, in both cases the downtime required for cryopump panel replacement determined the scheduled outage duration with only the one exception mentioned above. However, since a greater percentage of the cryopump panels are being replaced at a given wall fraction when the cryopump life is 1/2 of the wall life, the additional downtime results in lower availabilities and higher cost of electricity at the intermediate replacement fractions.

COE AND AVAILABILITY FOR TMR

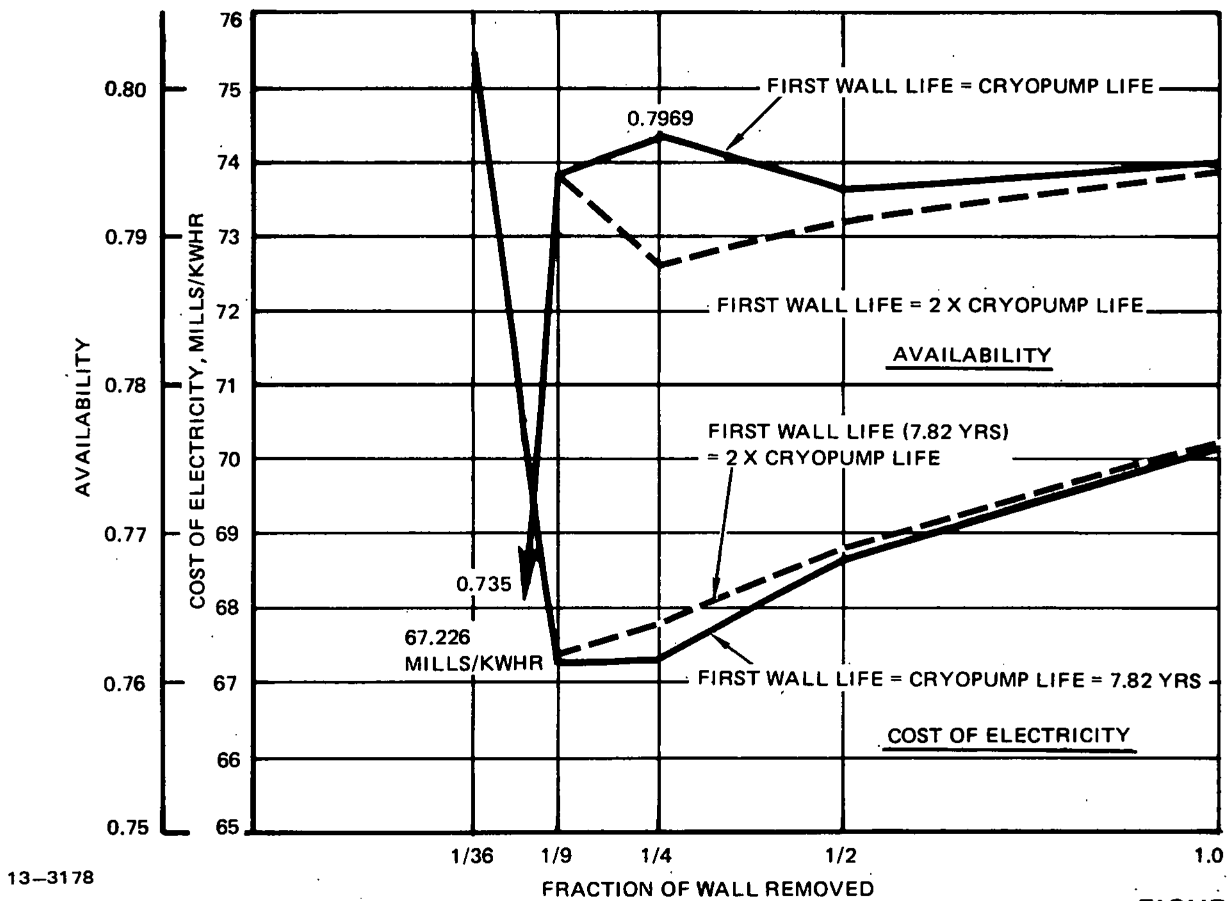


FIGURE 5–1

At the limiting first wall replacement fractions, i.e., RF = 1/36 or 1.0, the difference in life of these two systems has little effect on either availability or cost of electricity. When only one first wall sector is removed (RF = 1/36) the outage duration required for the few cryopumps to be replaced is also short and both are less than required by the balance of plant scheduled maintenance. However, at this low replacement fraction the scheduled outage frequency is higher than required for balance of plant operations. The effect of this frequent outage is evidenced by the low availability and the high cost of electricity. The scheduled outage duration required at this low replacement fraction is increased only a few hours by the shorter cryopump life case. Therefore, availability differences are negligible. Equipment and personnel requirements are a minimum for both cases. Therefore, cost differences are negligible. At the other extreme, when all sectors are removed during a scheduled outage (RF = 1.0) then all cryopump panels are also replaced in either of the two cases and the downtime, equipment and personnel required are the same. Therefore, the cost of electricity and availability are also unchanged.

This analysis is very abbreviated since it considers the impact of only two of the subsystem components which are scheduled outage drivers. Its principal purpose is to illustrate the need for considering multiple subsystems in a maintainability analysis when more than one subsystem in a reactor is a driver for unscheduled downtime, equipment or personnel. This is the situation in the tandem mirror reactor concept under study. Advanced versions may not have this characteristic. However, as the maintainability improves, the subsystems tend to have increasingly similar impacts and multiple decisions of replacement fractions must be made to establish an optimum maintenance plan. At this time the conceptual designs are insufficiently defined to warrant a much more extensive investigation.

In comparison, the tokamak reactor analysis of replacement fraction impacts is much simpler than for the TMR because the first wall/blanket maintenance is clearly the major driver for scheduled outage duration. This is shown by the critical path estimates defined in Section 4.3.3. Earlier studies (Reference 3) indicate that, for the tokamak reactors, the optimum replacement fraction occurs at approximately 1/2 for the replacement of 8 of the 16 sectors. These analyses assumed a fluence limit of the first wall of 5 MW-yrs/m^2 which resulted in an optimum scheduled outage occurring approximately once a year. For the current study, which uses a fluence limit of 16 MW-yrs/m^2 for both the tokamak reactor and the TMR, it is expected that the optimum replacement fraction will be reduced.

This trend is indicated in Figure 5-1 where the wall life of 7.82 years gives an optimum COE at a replacement fraction of 1/9 to 1/4. These replacement fractions result in scheduled outage intervals of 1.10 and 2.45 years, respectively.

5.2 REDUNDANCY IMPACTS - The effectiveness of using redundancy to reduce forced outages is readily determined by assuming that all redundant components and subsystems listed in the system descriptions defined in Tables 4-31, 4-32 and 4-57 are installed without redundancy and that the same relative component outage frequency applies. The principle effect of this loss of redundancy is that a failure in many of the components which could formerly have been repaired while the reactor is operating will now result in forced outages.

Two types of components are repairable while the reactor is operating. One type are those components that are always repairable when the reactor is operating whether they are redundant or not. The other type require redundancy to be repairable when the reactor is operating and if redundancy is lost a reactor shutdown is required. Both types are listed in the system description tables cited above but only the latter is included in this analysis. This restriction is relatively severe and results in a worst case situation for some of these subsystems since, when designing without redundancy, some excess capacity is usually available to allow operation with a faulty component. Such is the case with cooling loop, neutral beam and vacuum subsystems.

Omission of all redundancy is not feasible where safety of personnel and equipment are involved. A more detailed examination to determine the most appropriate components and subsystems for redundant operation is warranted when more detailed designs are available. However, the relative trends and effectiveness for the TMR and the tokamak reactors are indicated in this section.

5.2.1 TMR Component Redundancy Impacts - The principal subsystems assumed to include redundant components are defined in Section 3.4.1 as well as in Tables 4-31 and 4-32. These include the central cell primary cooling loops (incorporating an intermediate loop also), the vacuum roughing/regeneration pumps, the power supply system, fuel injection ion sources, and the main and neutral beam cryopumps. When these redundant components and subsystems are included the relative forced outage downtime decreases to approximately 60% of the downtime when no redundancy is included.

Table 5-2 summarizes the redistribution of forced outage downtime when redundancy is included in the selected subsystem designs. The vacuum system down-

TABLE 5–2
TMR REDUNDANCY EFFECTS ON FORCED OUTAGES

SUBSYSTEM [1] [2]	SUBSYSTEM PERCENTAGE CONTRIBUTION TO TOTAL FORCED OUTAGE DOWNTIME	
	WITHOUT REDUNDANT COMPONENTS [3]	WITH REDUNDANT COMPONENTS
CENTRAL CELL		
FIRST WALL/BLANKET/SHIELD	3	4
MAGNETS	NIL	1
VACUUM SYSTEMS	6	7
POWER SUPPLY	7	NIL
PRIMARY COOLING SYSTEM	11	4 [4]
AUXILIARY COOLING SYSTEMS	3	5
FUELING SYSTEM	8	3 [4]
END PLUG AND DIRECT CONVERTERS		
FIRST WALL/SHIELD	NIL	1
MAGNETS	NIL	NIL
NEUTRAL BEAM INJECTORS	24	40
VACUUM SYSTEMS	25	18 [4]
POWER SUPPLY	1	NIL
DIRECT CONVERTER	10	16
COOLING SYSTEMS	2	2
	100	100

(1) SUBSYSTEM DATA IS SUM OF COMPONENT PERCENTAGES.

(2) I&C SYSTEMS NOT INCLUDED IN ANALYSIS.

(3) SOME COMPONENTS ASSUMED REPAIRABLE DURING REACTOR OPERATION.

(4) REDUNDANCY INCORPORATED PRIMARILY IN THESE SUBSYSTEMS

time, for example, reduces from 31% to 25% of the total forced outage downtime. Because the neutral beam injectors and the direct converters have no redundancy in either assumed configuration, their forced outage impact increases markedly when redundancy is added to other subsystems.

The summary in Table 5-2 also indicates that the central cell first wall/ blanket/shield and magnets are unlikely to be significant contributors to forced outages. Neutral beam injectors, cryopumps and direct converters show the largest effect on forced outages. Very little data exists to determine the reliability of these advanced state-of-the-art systems and a variation in assumptions can significantly affect these results. For other systems where reliability data exists, such as cooling systems and vacuum pumps, even the relatively low impact of these redundant designs on forced outage downtime can be improved when the designs are optimized for redundancy.

The effect of adding redundancy to the end plug neutral beam injector or its forced outage contribution was briefly examined. By adding four ion sources to the four already in the neutral beam injectors and assuming any four of the total of eight will be sufficient (this simplifies the analysis) the downtime will be reduced by approximately 72%, making the impact on forced outage downtime for the neutral beam system approximately 29% instead of the 40% indicated in Table 5-2. Other redundancies in the neutral beam system would increase this effect.

5.2.2 Tokamak Component Redundancy Impacts - The tokamak reactor conceptual design includes redundancy in the neutral beam injectors, the plasma chamber cryopumps and other vacuum system components, the power supplies, and in the cooling systems. The redundancy in these systems is described in Section 3.4.2 as well as in Table 4-57. Incorporating redundancy in these subsystems reduces the forced outage downtime to approximately 30% of the estimated time without redundancy.

Table 5-3 is a summary at subsystem level of the forced outage downtime variation with and without the redundancies. The addition of redundancy is particularly effective for the neutral beam injectors, reducing their contribution to forced outage downtimes from 46% to 12%. The forced outage downtimes caused by power supplies and cooling systems are also reduced by adding redundancy. It should be noted that a large improvement in one major contributor to downtime, such as the neutral beam injectors, can overshadow a significant improvement in other systems, such as in the vacuum systems. In the analysis summarized in Table 5-3, the vacuum system downtime with redundancy is actually estimated at approximately 62% of that for the design which uses no redundancy but the relative impact on downtime has increased from 14% to 29%.

The relative impact of varying redundancy on a particular component's contribution to forced outage downtime has also been briefly examined for the tokamak reactor. By increasing the redundancy of the neutral beam ion sources from 50% (24 required of 36 units) to 100% (24 required of 48 units) a decrease in forced outage downtime of only 37% is realized. Therefore, increasing the redundancy

TABLE 5–3
TOKAMAK REDUNDANCY IMPACTS ON FORCED OUTAGES

SUBSYSTEM(1)(2)	SUBSYSTEM PERCENTAGE CONTRIBUTION TO TOTAL FORCED OUTAGE DOWNTIME	
	WITHOUT REDUNANT COMPONENTS(3)	WITH REDUNDANT COMPONENTS
FIRST WALL/BLANKET/SHIELD	5	16
MAGNETS	8	27
NEUTRAL BEAM INJECTORS	46	12(4)
VACUUM SYSTEMS	14	29(4)
POWER SUPPLY	14	NIL(4)
DIVERTORS	1	3
PRIMARY COOLING SYSTEM	10	8(4)
AUXILIARY COOLING SYSTEMS	2	5(4)
	100	100

(1) SUBSYSTEM DATA IS SUM OF COMPONENT PERCENTAGES.

(2) I&C SYSTEMS NOT INCLUDED IN ANALYSIS.

(3) SOME COMPONENTS ASSUMED REPAIRABLE DURING REACTOR OPERATIONS.

(4) REDUNDANCY INCORPORATED PRIMARILY IN THESE SUBSYSTEMS.

above the level selected in this study (50%) is relatively ineffective in reducing the downtime further for this component.

5.2.3 Comparative TMR and Tokamak Evaluation - The results of this abbreviated analysis indicate that redundancy is effective in reducing forced outage downtime in the tokamak design, particularly in the neutral beam injectors which are the major downtime contributor without redundancy. On the other hand, the TMR neutral beam injectors, which are also major downtime contributors, are installed at the end plugs and redundancy does not appear possible with the design given in Reference 2. However, the advanced TMR concept employs a lower energy neutral beam which can possibly employ multiple ion sources and achieve some redundancy.

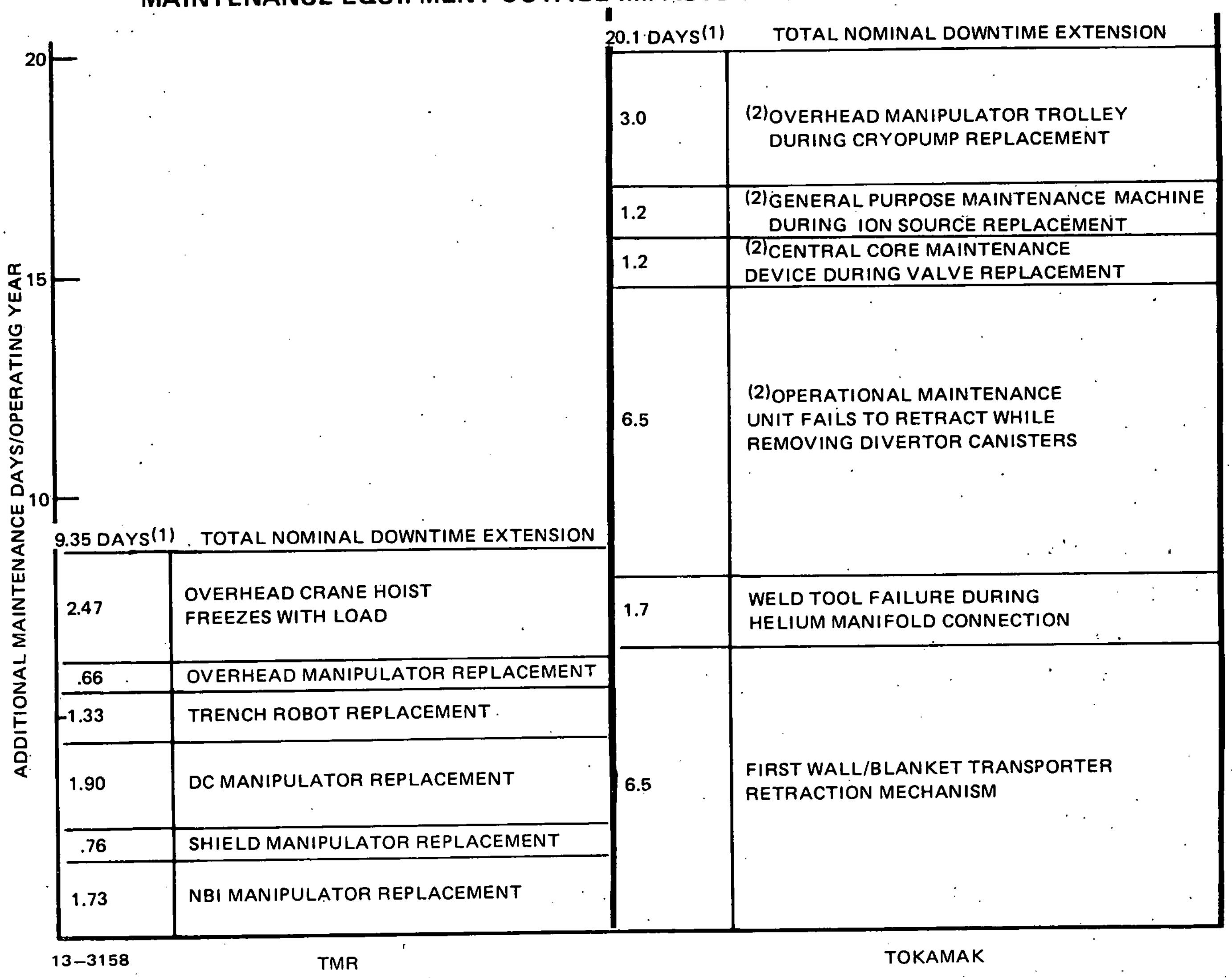
Both the TMR and tokamak employ redundancy effectively in the cryopump systems but the improved access for the tokamak cryopumps (the TMR pumps are inside of the direct converter chamber) results in less total benefit because the downtime requirements per outage are less.

In general, redundancy can be more effectively applied to the tokamak concept but advanced TMR concepts indicate that an increase in redundancy over that used for the baseline TMR is possible. Such improvements will further reduce forced outage downtime.

5.3 IMPACT OF MAINTENANCE EQUIPMENT OUTAGES ON SCHEDULED MAINTENANCE - Earlier studies of tokamak reactors indicated that maintenance equipment failures during an outage could seriously affect the system downtime. This is especially the case if the equipment or the reactor requires that maintenance work be internal to the reactor, such as within the plasma chamber.

Seven typical maintenance equipment failures for the TMR system have been discussed in Section 4.2.2. The six of those that are likely to be encountered during a scheduled outage are summarized in Figure 5-2 and compared with six of the equipment failures examined for the IMS tokamak baseline in Section 4.3.2.

MAINTENANCE EQUIPMENT OUTAGE IMPACTS ON SCHEDULED DOWNTIME



(1) 24 HOUR, 3 SHIFT DAYS ASSUMED
(2) ESTIMATED FROM SIMILAR MAINTENANCE ACTIONS

FIGURE 5–2

The six TMR maintenance equipment outages all require less than three days for recovery, the largest time being required for recovery from an overhead crane failure under load. None of the maintenance equipment failures are assumed to be catastrophic but the more difficult conditions for recovery are included. Since all recovery times are short, the total for the six failures is only 9.4 days. If these represent a nominal set of failures during an optimum scheduled outage of 18 days the total downtime would be increased to only 28 days. This still does not increase the downtime above that required for balance of plant maintenance.

The six maintenance equipment failure modes examined for the tokamak reactor all use maintenance equipment and time estimates devloped in Reference 3 or for the TMR. Some revisions have been made to make them comparable to the TMR maintenance equipment outages. For example, release of the GPMM from the NBI ion source was added since none of the TMR equipment failures required only the exchange of an unattached piece of equipment. This GPMM failure and the other failures which use equipment operating external to the reactor have a maximum recovery time of 3.0 days; the same as for the TMR. However, equipment failures during replacement of divertor canisters or during extraction of a first wall/blanket module require an estimated 6.5 days for recovery. These increase the total recovery time for the six tokamak equipment failures to 20.1 days. If, as for the TMR, these represent a nominal set of failures during an optimum scheduled outage of 23 days the total downtime would be increased to 43 days. This increases the scheduled downtime, thereby reducing availability and increasing the cost of electricity.

One caution must be observed in examining these results. The baseline TMR requires maintenance operations within the direct converter chamber. While recovery from a failure of a direct converter manipulator within the chamber is estimated to require only 1.9 days, other failure modes could possibly occur with much more severe consequences, such as the loss of a wheel on this equipment. These are considered catastrophic and have been omitted from the analysis because the design should take all possible means to prevent these.

The impact of the six representative maintenance equipment failures for both the TMR and the tokamak reactor on availability and cost of electricity (COE) is shown in Table 5-4. The costs used in this table are for minimum COE replacement fractions of 1/8 and 1/9 for the tokamak and TMR, respectively. For both reactors the availability is still acceptable although the COE increase for the tokamak is 1.5 mills/kW-hr with no increase required for the TMR. This represents an annual cost of $10.3 million for the tokamak reactor. At a 15 percent return on invest-

TABLE 5–4

IMPACT OF MAINTENANCE EQUIPMENT OUTAGES ON AVAILABILITY AND COE

	DOWNTIME PER SCHEDULED OUTAGE (DAYS)	AVAILABILITY	COST OF ELECTRICITY (MILLS/KW HR)
TMR			
WITHOUT MAINTENANCE EQUIPMENT OUTAGES	28*	.794	67.226
WITH MAINTENANCE EQUIPMENT OUTAGES	28*	.794	67.226
TOKAMAK			
WITHOUT MAINTENANCE EQUIPMENT OUTAGES	28*	.797	50.110
WITH MAINTENANCE EQUIPMENT OUTAGES	43	.773	51.653

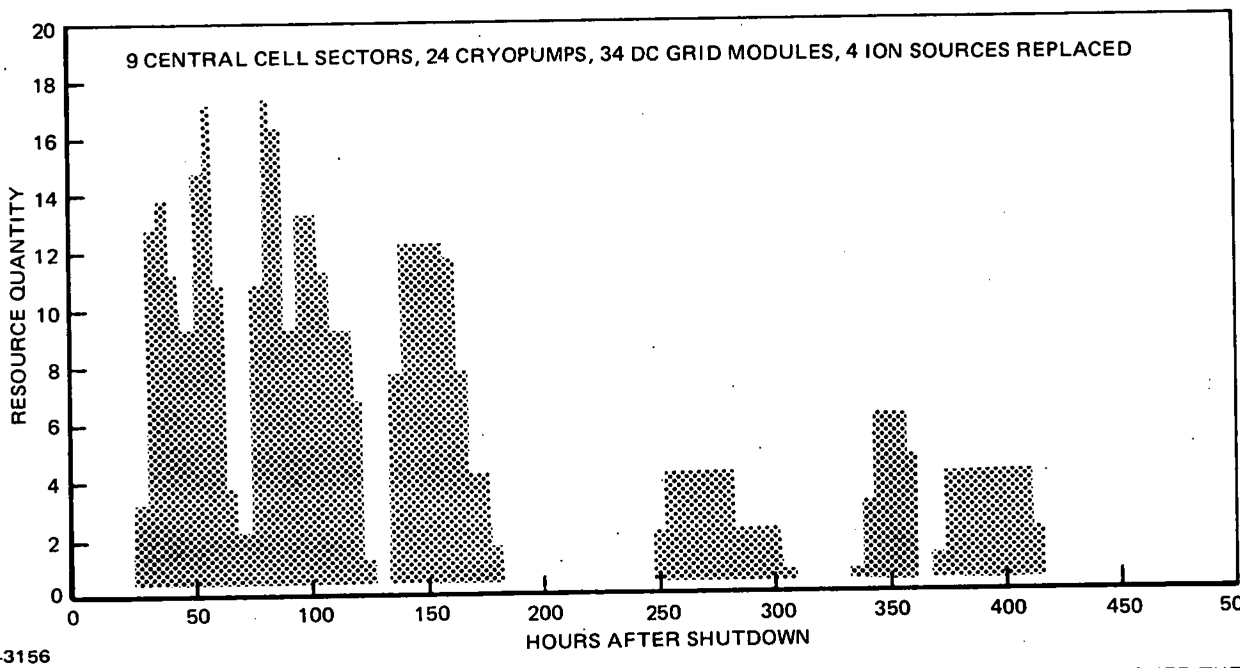
*DETERMINED BY BALANCE OF PLANT REQUIREMENTS

ment this cost could finance capital expenditures of $69 million. However, no additional capital costs are warranted for the TMR because the COE is not increased by maintenance equipment outages during scheduled maintenance, analysis of forced outage impacts was not conducted but could provide a capital expenditure justification also. Comparing these "equivalent capital costs" with the estimated initial maintenance equipment total capital cost of $44.2 million for the TMR equipment and $93.5 million for the tokamak equipment, it is apparent that extensive expenditures can be justified to improve reliability.

5.4 <u>IMPACT OF RESOURCE LIMITS ON SCHEDULED OUTAGE</u> - Parallel maintenance operations are considered in this study for many subsystems. The critical path analysis always allows that other maintenance is being accomplished at the same time. A brief analysis of the equipment requirements for a nominal set of parallel maintenance actions has been conducted. An activity network computer code developed for such scheduling and resource allocation requirements (Reference 7) has been applied to this analysis as discussed in Section 4.1.2.

Although a given scheduled maintenance activity can be accomplished in a reasonably short period of time, the amount of maintenance equipment that can fit into the reactor hall simultaneously is limited. For this reason the actual scheduled maintenance times for a set of parallel maintenance actions can be much longer. For example, the critical path estimate for the nominal set of maintenance actions listed in Table 4-24 and using unlimited resources requires up to 18 central cell cranes at a given time, as indicated in Figure 5-3. Exhorbitant quantities of other maintenance equipment are also required. Estimates indicate that probably only two, and at most four, central cell cranes can be used simultaneously. Hence, the activities that are scheduled simultaneously in the critical path case would actually have to be spread out over a substantially longer period of time (Figure 5-4).

CENTRAL CELL CRANE QUANTITIES REQUIRED FOR MINIMUM DOWNTIME



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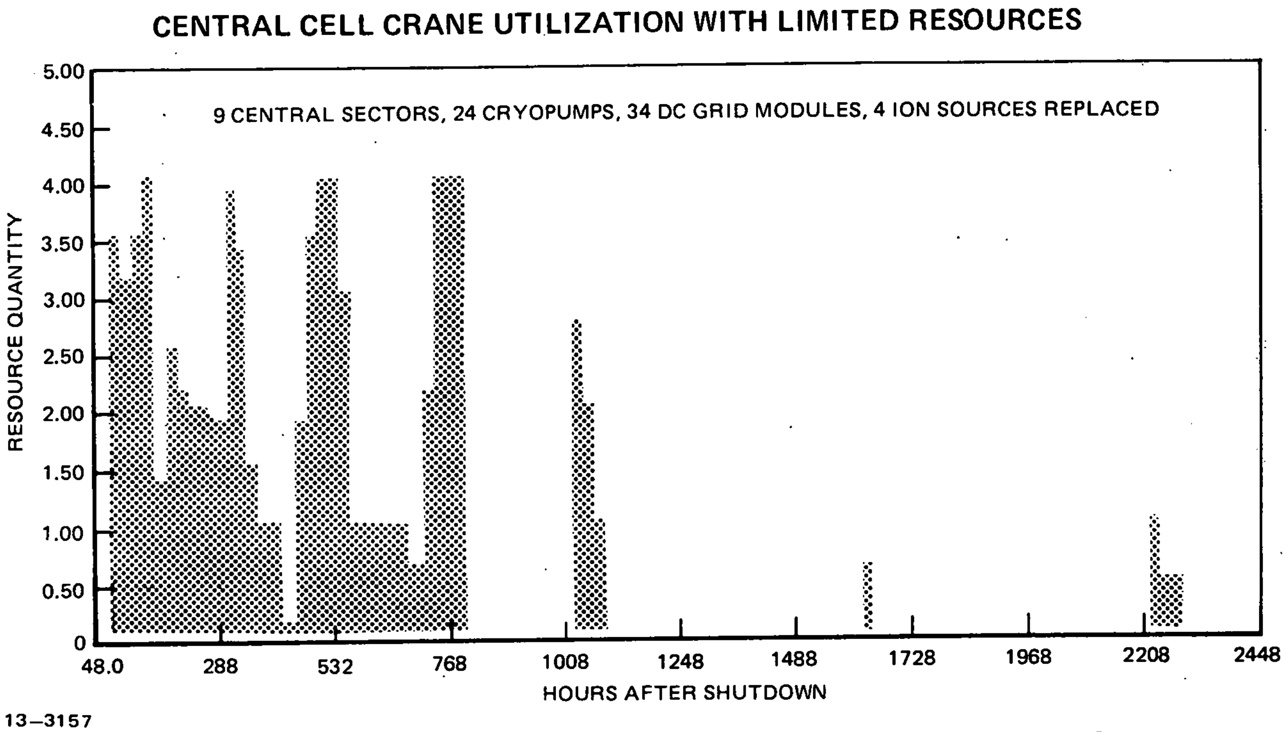
NOTE: FRACTIONAL QUANTITIES OCCUR BECAUSE THE REQUIRED QUANTITY IS AVERAGED OVER THE MINIMUM SCALE TIME INCREMENT (5 HOURS)

FIGURE 5–3

The foregoing example illustrates the results of an investigation conducted to ascertain the severity of restricted resource availability on scheduled downtime duration. Maintenance actions representing all subsystems have been combined for a single scheduled outage. A replacement fraction of 1/4 was used for the central cell sectors and approximately 1/8 for the direct converter cryopump panels. The total number of maintenance actions, i.e., 231, is believed to be within the bounds of the number of maintenance actions expected for a single scheduled outage. Those maintenance actions which have been estimated in detail are scheduled as second level functional sequences and the maintenance equipment is allocated as required by each function. The remaining maintenance actions are shorter in duration and the required maintenance equipment is allocated for the duration of each activity.



NOTE: FRACTIONAL QUANTITIES OCCUR BECAUSE THE REQUIRED QUANTITY IS AVERAGED OVER THE MINIMUM SCALE TIME INCREMENT (24 HOURS).

FIGURE 5–4

Three different maintenance equipment sets are used, each with different quantities of each major equipment item. Minor equipment, such as dollies and tools, are assumed to be available as required by each major equipment item. The three sets include one with unlimited equipment quantities which are made available as required by the schedule. This results in the minimum scheduled downtime and defines the maximum equipment quantities that would be required. The quantities used for the second set of equipment provide the maximum number that can be conceivably operated in the reactor room. These quantities are compiled in Table 5-5. The quantities used for the third set, also included in Table 5-5, provide the number of equipment items for each maintenance action that are required to conduct the critical path activities plus the minimum number required by any other maintenance action. Other resource limits, particularly floor space and personnel, are omitted from this investigation even though they are important in developing a viable schedule.

The results of this analysis are summarized in Figure 5-5. For the critical path, unlimited resource case, the scheduled maintenance requires only 30 days. On the other hand, using the maximum number of resources that will fit into the reactor room the same scheduled maintenance takes 101 days. Using the smallest

TABLE 5–5
TMR RESOURCES ALLOCATED FOR MSCS SCHEDULES

	QUANTITIES	
	NOMINAL	MAXIMUM
HEAVY CENTRAL CELL CRANES	2	4
OVERHEAD MANIPULATORS	2	10
TRENCH ROBOTS	4	12
MAGNET COOLING MODULES	9	18
TUGS	2	10
TRANSFER LOCKS	2	4
LIGHT END PLUG CRANES*	1/1	2/2
LIGHT DIRECT CONVERTER CRANES*	1/1	2/2
DIRECT CONVERTER MANIPULATORS*	1/1	8/8
DIRECT CONVERTER TRANSPORTER*	1/1	2/2
NEUTRAL BEAM INJECTOR MANIPULATORS*	1/1	2/2
END PLUG WALL/SHIELD MANIPULATORS*	1/1	2/2

*DEDICATED TO EACH END OF REACTOR AS INDICATED BY SPLIT

quantity set of equipment the total is 276 days (approximately 9 months). As can be seen from Figure 5-3 and 5-4, the total maintenance time for those activities employing the central cell crane has stretched from approximately 425 hours total (17.7 days) to almost 2300 hrs (95 days) when only four central cell cranes are available. Other equipment utilization profiles show similar results. The downtimes given here are based on the baseline TMR. Use of the latest TMR concept, as described in Section 3.5, should result in reductions in these maintenance times because of the reduced size and complexity of many of the components. A comparison of the minimum scheduled downtime derived in this exercise (30 days) with the 28 days estimated for the similar replacement fraction critical path as shown in Table 5-1 indicates reasonably close correlation. Differences between hand calculations of this type and the activity network estimates are expected because

IMPACT OF LIMITED RESOURCES ON SCHEDULED DOWNTIME

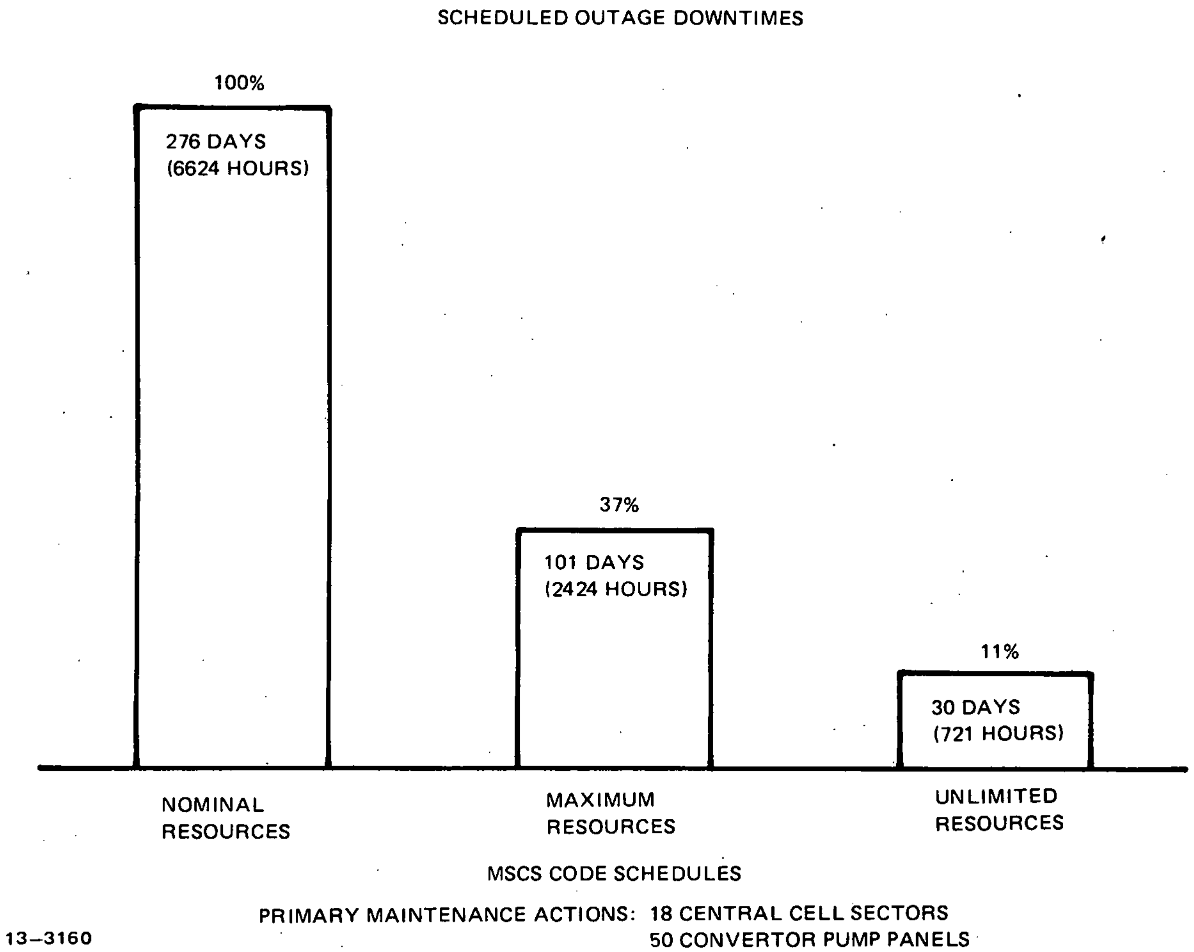


FIGURE 5–5

of changing assumptions in setting up the problem. However, the relative downtimes caused by differences in the amount of equipment available as defined in this example are valid. These results indicate the severe constraints placed on maintenance activities by resources availability limitations.

5.5 IMPACT OF COST OF ELECTRICITY AND AVAILABILITY GOALS ON FORCED OUTAGE REQUIREMENTS - Forced outage requirements imposed on a reactor conceptual design will vary with the cost of electricity which must be achieved to justify acceptance of that reactor design. Conversely, where several reactor concepts are under consideration, a cost of electricity goal or an availability goal can be established for evaluating their relative performance. The relative capability of the TMR and the tokamak reactor concepts to satisfy a common cost of electricity (COE) or availability goal as a function of maintainability parameters is examined in this section.

The optimum, i.e., least COE, maintenance plan for the baseline TMR and the IMS tokamak reactor are selected based on the results shown in Figure 5-1. These maintenance plans use replacement fractions for each scheduled outage of 1/9 for the TMR (replacing four central cell first wall/blanket sectors and 6 cryopump panels in each direct converter) and 1/8 for the tokamak reactor (replacing two first wall/blanket sectors). The TMR replacement fractions assume the wall life of the central cell first wall is twice the life of the cryopump regeneration valve actuators. These maintenance plans also are based on a balance of plant scheduled outage of 28 days per calendar year and a forced outage duration of 65 days per operating year. The theoretical maintenance cycle duration is 13.2 months and 14.2 months for the TMR and the tokamak reactors, respectively, based on a first wall fluence limit of 16 MW-yrs/m^2 for both reactors.

The data presented in Figure 5-6 uses these optimized maintenance plans as a base and the forced outage total allowable downtime is calculated at different COE and availability values. Maintenance capital and operating costs are based on scheduled downtime requirements which have been optimized as previously described.

EFFECT OF UNSCHEDULED MAINTENANCE ON COE AND AVAILABILITY
(Includes Only FW/Blanket & Cryopump Maintenance)

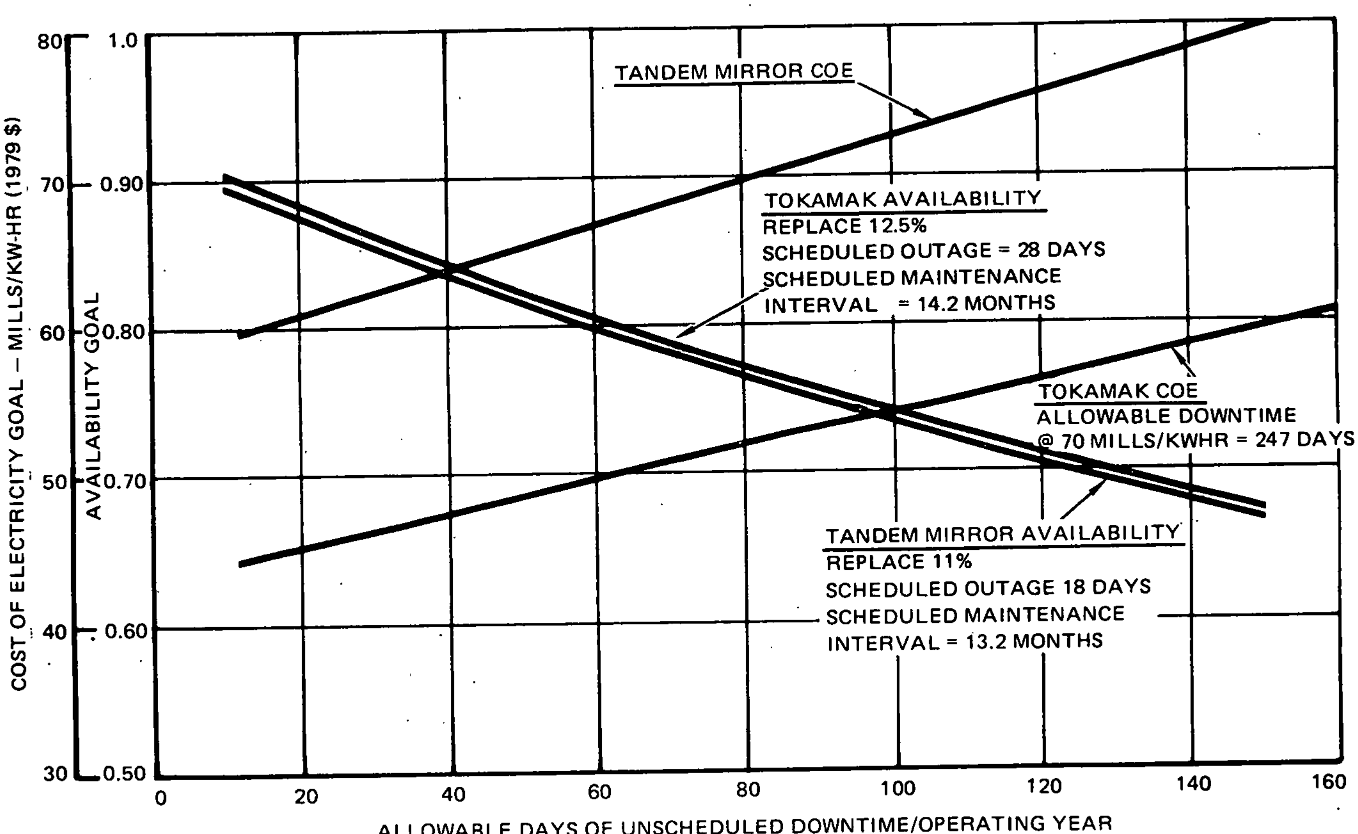


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FIGURE 5–6

Up to this point the unavailability impacts for forced outages have all been based on 65 days per operating year which is an average value taken from current fission power plant experience. Therefore, the forced outage downtime is the most important reactor related parameter yet to be determined.

For an availability goal of 75%, which has been selected for other fusion reactor studies (Reference 12) and which is an acceptable goal for competitive power production (Reference 8), the allowable forced outage downtimes for the TMR and the tokamak are almost the same at 90 and 92 days per operating year, respectively. However, since the cost of electricity is significantly larger for the TMR, the allowable forced outage downtimes at a COE goal of 60 mills/kW-hr is 16 days for the TMR and 156 days for the tokamak reactor. The large variation in COE is primarily caused by a higher estimated capital cost (3.02 $\overline{B}$ in 1979 $ for the TMR compared to 2.18 $\overline{B}$ in 1979 $ for the tokamak) resulting from the larger size of the baseline TMR. The size trends are discussed further in Section 5.8.

The sensitivity of allowable forced outage downtime to variations in capital cost is defined in Figure 5-7 for the TMR. Using the data from Figure 5-6 as a base, the estimated capital cost of the TMR must be reduced to approximately 2.24 $\overline{B}$ in 1979 $ to allow the same number of days for forced outages as are allowed for the baseline tokamak reactor. This is a 26 percent reduction from the current cost estimate for the TMR baseline reactor. This desired capital cost reduction is computed at both 60 and 70 mills/kW hr COE goals to illustrate that the required reduction in capital cost is almost independent of the selected COE goal at these COE levels.

The slope of the curves in Figure 5-7 also indicates the additional capital cost that can be expended to reduce the forced outage downtime for the TMR without increasing the COE. At an initial capital cost of $3.02 $\overline{B}$, approximately $8 $\overline{M}$ can be expended to reduce the forced outage downtime by one day at a COE of 60 mills/kW hr. At 70 mills/kW hr these values decrease to approximately $3 $\overline{M}$ and $6 $\overline{M}$, respectively.

In comparison with forced outage downtime, the allowable expenditures for reduction of scheduled outage downtime will be significantly less. This occurs because the present scheduled outage downtime estimates are less than the assumed balance of plant scheduled downtime requirement and, therefore, further reduction in the reactor scheduled downtime has a very small effect on the COE. However, if the combined scheduled outage requirements exceed the balance of plant scheduled outage then additional expenditures of the order of magnitude described above are justified to reduce this downtime.

IMPACT OF CAPITAL COST ON TMR ALLOWABLE UNSCHEDULED DOWNTIME

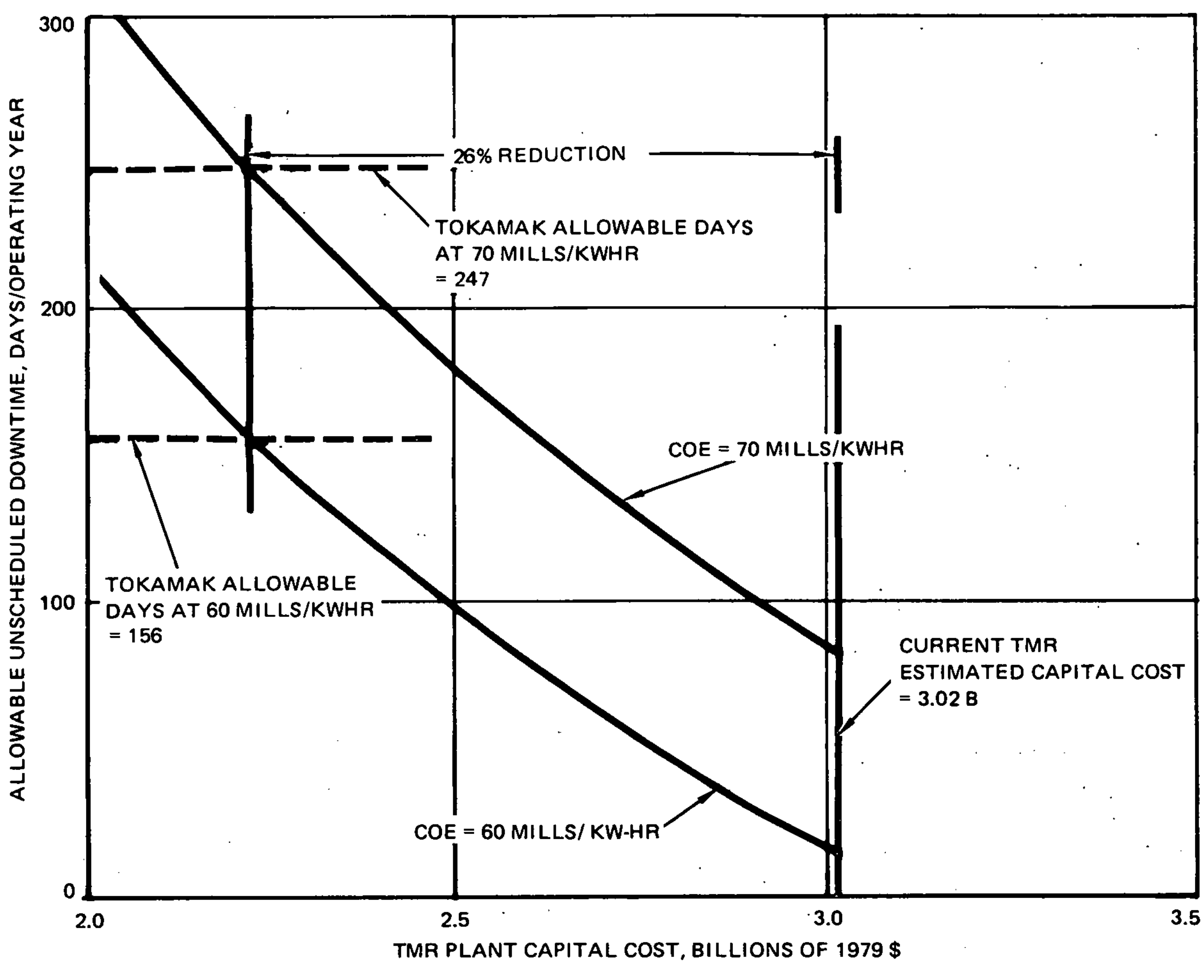

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FIGURE 5–7

5.6 FORCED OUTAGE AVAILABILITY ALLOCATIONS - Selection of a total allowable downtime for forced outages is useful in comparing reactors. However, it provides little guidance in identifying the subsystems and components that influence the expected forced outages most seriously. Also, the total allowable downtime is of little assistance in establishing goals that can be reasonably imposed on the more important subsystems and components. The estimated COE goals and the resultant total allowable forced outage downtimes presented in the preceeding section (5.5) are combined with the forced outage contributions presented in Sections 4.2.5 and 4.3.5 in this discussion in order to define relative failure rate goals. This estimate of goals is based on the relative forced outage rates estimated for the components making up the system. For an actual design, forced outage rate goals will be determined by the reliability criteria employed. At this time, these goals only serve to indicate which components are the more severe forced outage downtime contributors.

The relative percentages of forced outage downtimes estimated for the principal components of the TMR and the tokamak reactor systems are listed in Tables 5-6 and 5-7, respectively. These relative percentages are extracted from Tables 4-31, 4-32, and 4-57 in Section 4.0. By using the total number of units and redundancy for each component indicated in the tables, the approximate relative failure rate goals per unit are determined. The total allowable days of forced outage used for constructing these goals is based on an availability of 75% which allows 90 days for the TMR and 92 days for the tokamak reactor. All outage durations include reactor shutdown and startup times when necessary.

TABLE 5–6

TMR SIGNIFICANT COMPONENT FORCED OUTAGE FREQUENCY GOALS

COMPONENT	AVERAGE ALLOWABLE DOWNTIME FOR FORCED OUTAGES		NUMBER OF UNITS		OUTAGE DURATION PER FAILURE	ALLOWABLE FORCED OUTAGE FREQUENCY
	PERCENT	DAYS/OPER YR	TOTAL	REDUNDANT	DAYS	OUTAGES/OPER. YR/UNIT
END PLUG NEUTRAL BEAM ION SOURCES	22.[illegible]	21	4	0	9.4	.56
END PLUG NEUTRAL BEAM STRIPPING CELLS	14.8	13	4	0	6.1	.53
DIRECT CONVERTER GRID MODULES	11.1	10	34	0	7.1	.04
END PLUG AND DIRECT CONVERTER VACUUM WALL SEALS	10.0	9	2 SETS	0	4.1	1.1
CENTRAL CELL VACUUM WALL SEALS	5.0	5	1 SET	0	4.1	1.2
CENTRAL CELL MAGNET COOLING PIPING CONNECTIONS	4.4	4	566	0	4.3	.002
CENTRAL CELL FIRST WALL/BLANKET SECTORS	3.5	3	36	0	8.4	.01
DIRECT CONVERTER THERMAL PANELS	3.3	3	640	0	8.4	.0006
FUEL INJECTION NEUTRAL BEAM ION SOURCES	2.7	3	12	6	3.7	.66
DIRECT CONVERTER CRYOPUMP CONTROL VALVES	2.3	2	200	100	5.1	.006
CENTRAL CELL PRIMARY COOLING PIPING CONNECTIONS	1.9	2	518	74	4.3	.002
END PLUG NEUTRAL BEAM VACUUM PIPING CONNECTIONS	1.4	1	240	0	3.3	.002
END PLUG ION SOURCE VACUUM PUMPS	1.4	1	8	0	4.2	.04
END PLUG NEUTRAL BEAM CRYOPUMP SHUTTERS	1.3	1	30	10	6.1	.08
DIRECT CONVERTER CRYOPUMP SHUTTERS	1.2	1	100	50	8.9	.08
FUEL INJECTION NEUTRAL BEAM PIPING CONNECTIONS	1.1	1	144	0	4.3	.002
END PLUG MAGNET COOLING PIPING CONNECTIONS	1.0	1	10	0	3.3	.03
OTHER COMPONENTS (< 1 PERCENT EACH)	10.1	9	-	-	-	-
	100.0	90.0 (1)				

(1) ALLOWABLE DOWNTIME FOR AVAILABILITY GOAL OF .75 IS 90 DAYS.

A comparison of Tables 5-6 and 5-7 indicates the relationship between similar kinds of components for the two reactors. For example, piping connection allowable forced outage frequencies in the two reactors are .001 and .002 outages/unit operating year for the TMR and tokamak, respectively. Reasons for this difference include the larger number of connections required in the TMR, the greater redundancy provided for other subsystems in the tokamak, and the fewer total replaceable subassemblies in the tokamak. The neutral beam ion sources for the TMR also require

TABLE 5–7
TOKAMAK SIGNIFICANT COMPONENT FORCED OUTAGE FREQUENCY GOALS

COMPONENT	AVERAGE ALLOWABLE DOWNTIME FOR FORCED OUTAGES		NUMBER OF UNITS		OUTAGE DURATION PER FAILURE	ALLOWABLE FORCED OUTAGE FREQUENCY
	PERCENT	DAYS/OPER. YR	TOTAL	REDUNDANT	DAYS	OUTAGES/OPER. YR/UNIT
VACUUM WALL DOOR SEALS	20.4	19	32	0	5.3	.11
POLOIDAL FIELD MAGNETS	16.6	15	15	0	288	.004
FIRST WALL/BLANKET SECTORS	13.5	12	16	0	10.0	.08
NEUTRAL BEAM INJECTOR ION SOURCES	7.2	7	36	12	3.4	.89
OHMIC HEATING COILS	6.5	6	14	0	121	.004
NEUTRAL BEAM INJECTOR VACUUM VALVES	4.0	4	36	18	3.8	.04
INTERMEDIATE COOLING SYSTEM CONTROL VALVES	3.1	3	36	18	3.8	.01
MAGNET CRYOGEN SYSTEM PIPING CONNECTIONS	3.1	3	360	0	3.0	.003
TOROIDAL FIELD MAGNETS	2.7	3	16	0	347	.0004
DIVERTOR BOMBARDMENT PLATE COOLING SYSTEM	2.6	2	1 SYSTEM	0	3.8	.63
PLASMA CHAMBER CRYOPUMP ASSEMBLIES	2.0	2	20	4	3.9	.1
NEUTRAL BEAM CRYOPUMP ASSEMBLIES	1.9	2	18	6	6.1	.1
PRIMARY COOLANT SYSTEM PIPING CONNECTIONS	1.6	1	396	44	3.0	.003
PLASMA CHAMBER CRYOPUMP PIPING CONNECTIONS	1.4	1	160	0	3.0	.003
NEUTRAL BEAM CRYOPUMP PIPING CONNECTIONS	1.2	1	144	0	3.0	.003
NEUTRAL BEAM COOLING PIPING CONNECTIONS	1.2	1	144	0	3.0	.003
PRIMARY COOLANT SYSTEM VALVES	1.1	1	162	18	3.8	.003
OTHER COMPONENTS (< 1 PERCENT EACH)	9.9	9	-	-	-	-
	100.0	92 (1)				

(1) ALLOWABLE DOWNTIME FOR AVAILABILITY GOAL OF .75 IS 92 DAYS.

relatively lower forced outage rates than for the tokamak. This occurs primarily because the TMR requires a longer forced outage duration and redundant design is not used in the TMR.

While the preliminary nature of the relative forced outage evaluations precludes specific recommendations, the approach taken here has integrated all aspects of design, i.e., the number of units, redundancy, outage duration and reliability, in order to define the maintenance impact of forced outage downtimes.

5.7 IMPACT OF SCHEDULED MAINTENANCE ON COE - Maintenance costs for the optimized maintenance plans associated with both the TMR and the tokamak reactor are summarized in Table 5-8. These costs include the total maintenance costs for the forced and scheduled outages for both the balance of plant and reactor. The impact of only the reactor scheduled outages are considered in this section.

A base cost of electricity is first computed which includes the maintenance costs for the plant permanent maintenance staff and for downtime caused by balance of plant outages (28 days) and by forced outages (65 days). These outages result in a base COE defined at an availability of .797. The remaining maintenance costs

TABLE 5–8
MAINTENANCE COST SUMMARY

	TMR	TOKAMAK
PLANT OPERATION		
AVAILABILITY	.794	.795
SCHEDULED DOWNTIME, DAYS		
REACTOR	18	23
BALANCE OF PLANT	28	28
UNSCHEDULED DOWNTIME, DAYS	65	65
POWER PRODUCTION, MW-HRS	6.88×10^6	6.70×10^6
PLANT COSTS, MILLIONS (1979 $)(1)		
CAPITAL COST W/O MAINTENANCE	2919	2065
MAINTENANCE CAPITAL	98	111
ANNUAL COSTS, MILLIONS (1979 $)		
PLANT CAPITAL ROI	437.82	309.72
MAINTENANCE CAPITAL ROI	14.76	16.67
OPERATIONS AND MAINTENANCE	8.64	9.26
COST OF ELECTRICITY, MILLS/KW HR		
W/O SCHEDULED REACTOR MAINTENANCE	64.19	47.01
TOTAL COE	67.01	50.11
SCHEDULED ANNUAL MAINTENANCE COST, M $(2)	19.4	20.8

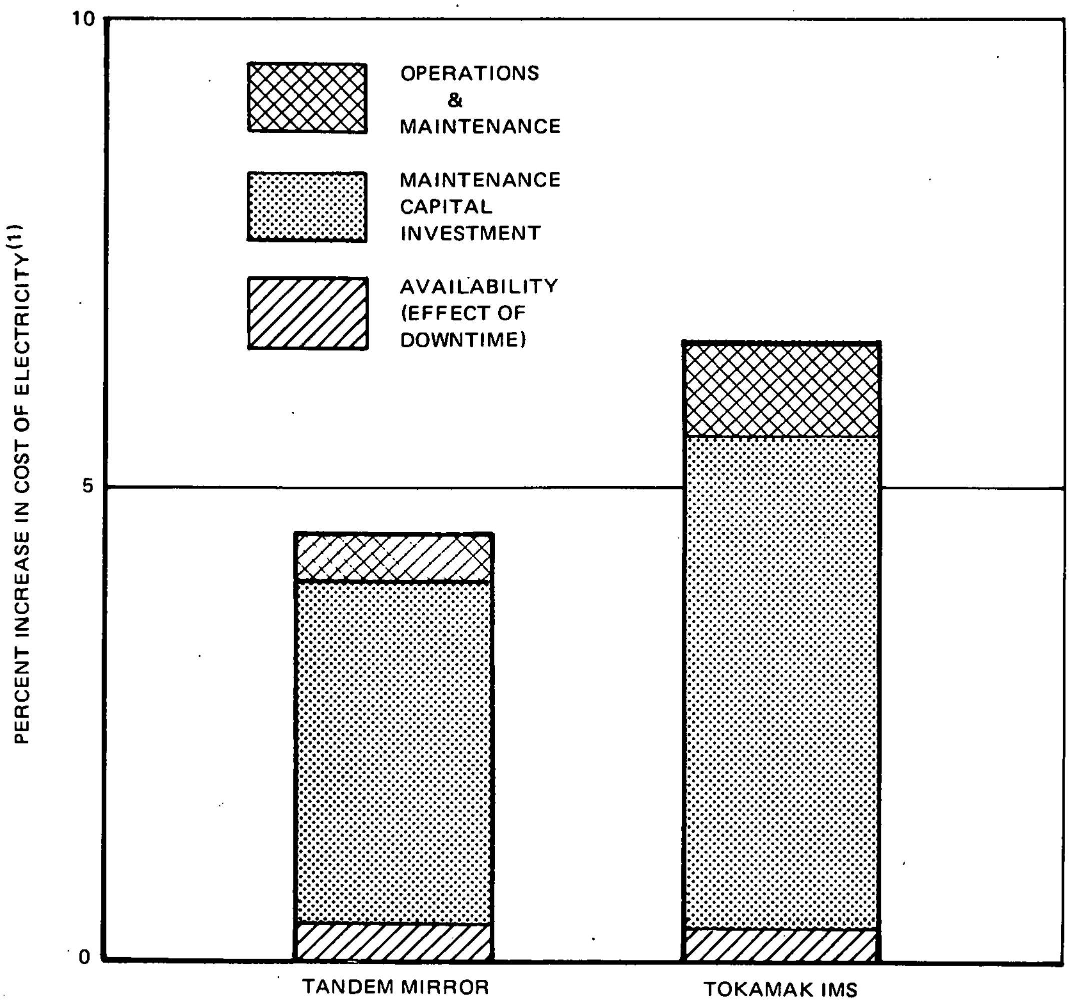
(1) INCLUDES INDIRECT COSTS

(2) CALCULATED FROM Δ COE AND ELECTRICITY PRODUCED/YEAR

are a function of scheduled maintenance. These include: (1) all of the maintenance capital costs (maintenance equipment, maintenance facilities and initial spares); (2) operations costs for replacement hardware and direct operating personnel; and (3) the cost increase caused by the effect of the scheduled outage downtime on availability. Availability costs are computed by averaging annual costs over the net power production. Adding the scheduled maintenance costs causes the COE for the TMR to increase by 2.83 mills/kW hr and for the tokamak reactor the increase is 3.10 mills/kW hr. These represent an increase in the COE caused by scheduled maintenance of 4.4% and 6.6%, respectively. These values are plotted in Figure 5-8 which also shows the three major cost elements that make up the total cost of scheduled maintenance.

The lower percent of cost required for scheduled maintenance of the TMR is principally caused by the higher total plant capital cost as indicated in Table 5-8.

TMR MAINTENANCE IMPACT COMPARES FAVORABLY WITH TOKAMAK



13–3159

(1) RESULTING FROM SCHEDULED MAINTENANCE
(2) REACTORS HAVE THE SAME NET POWER OUTPUT

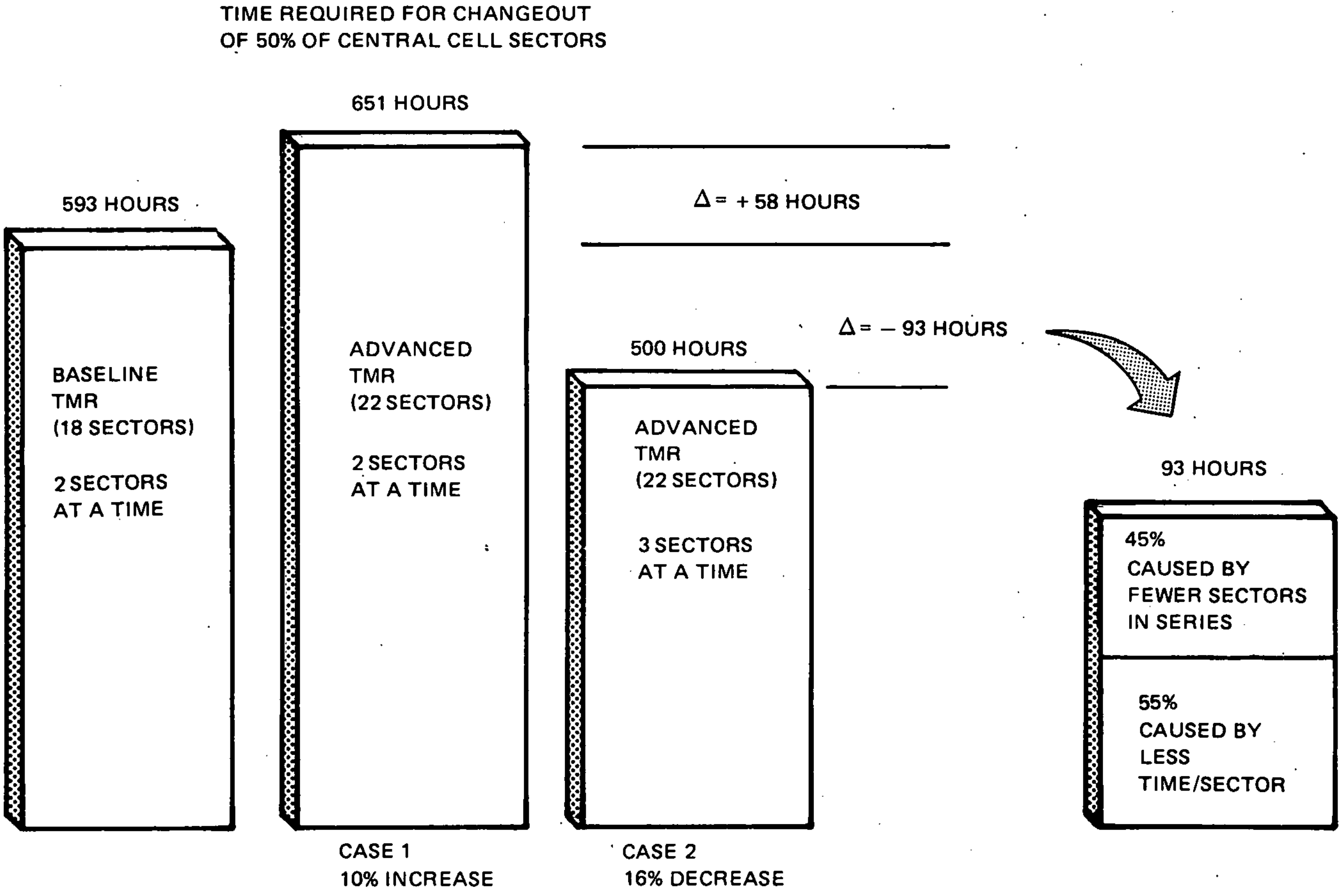
FIGURE 5–8

However, the cost of maintenance equipment and facilities is much less for the TMR. This is because of the better access and the reduced requirement for sophisticated, advanced state-of-art maintenance systems. Figure 5-8 shows that the percentage impact of personnel and replacement costs are also slightly less for the TMR. This is caused by the simpler operations involved.

5.8 ADVANCED TMR TRENDS - The advanced TMR design currently under study at Lawrence Livermore Laboratory will significantly influence some of the findings of this study. This advanced reactor concept is described in Reference 6 and some design elaboration which has been conducted during this study is described in Section 3.5. Two maintenance actions have been discussed in Section 4.2.6. The probable influence of these maintenance actions on the TMR conceptual design maintainability is presented here.

The comparison of the central cell replacement downtime requirements for the baseline and advanced TMR concepts is illustrated in Figure 5-9. When replacing 50% of the sectors in a TMR, several can be worked on in parallel to decrease the overall time. The baseline TMR allows working on two sectors simultaneously since two cranes are available. Each crane and the associated maintenance equipment, i.e., overhead manipulator and pair of trench robots, will handle nine central cell sectors. All of the 18 central cell sectors are in one end of the central cell region to reduce the overall downtime by requiring the

ADVANCED TMR IMPACT ON CENTRAL CELL SECTOR REPLACEMENT



- ADVANCED TMR SECTORS LOCATED UNDER 3 TRENCH COVERS
- BASELINE TMR SECTORS LOCATED UNDER 2 TRENCH COVERS
- REACTOR SHUTDOWN AND STARTUP TIME EXCLUDED

13–3155

FIGURE 5–9

removal of a minimum number of trench covers. These sectors are large and handling more than two at a time is expected to result in interference.

On the other hand, the advanced TMR requires replacement of 22 sectors for 50% of the reactor length. These sectors are smaller, being only 2.0 meters long instead of 2.8 meters and weighing only 500 tonnes compared to the 620 tonnes for the baseline TMR. The joint between sectors is also redesigned to aid in reducing the replacement time. For the advanced TMR, three maintenance plans are investigated to illustrate the effect of alternate approaches to handling these smaller sectors.

The first plan uses two overhead cranes and associated equipment sets and only two sectors are replaced at one time. While the replacement time for each sector is reduced by 10 percent below the replacement time for each of the baseline TMR sectors, the overall time to replace 50 percent of the advanced TMR sectors increases 10 percent because of the increased number of sectors. The additional sectors actually require an increase of 20 percent in the downtime, but the shorter time for each of the smaller sectors reduces the total to the net increase of 10 percent.

The second plan utilizes a third crane so that three sectors in the advanced TMR are worked at one time. Figure 5-9 illustrates that this plan results in a reduction of 16 percent in the total downtime compared with the baseline TMR. About 45 percent of this time reduction is achieved because fewer sectors are worked in series and the remaining 55 percent is accomplished because of the shorter time for the smaller sectors. Working on three sectors at a time in the advanced TMR compared with two larger sectors at a time in the baseline TMR may be feasible because the proportionate length of the reactor per sector is less for the smaller sectors and interference is less likely to occur. However, crane scheduling become more important.

The third plan is to revise the sector length to be equal to the length of the baseline reactor sectors. For this configuration, only 32 central cell sectors are required. By working on only two of these longer sectors at a time and assuming the time per sector is decreased as for the advanced TMR, the total downtime is reduced by 19 percent to 483 hours. This time is approximately equivalent to working on three sectors at a time. This approach can be continued to determine an optimum sector length by comparing the sum of the replacement, repair and spares costs, and of the availability impacts over a range of sector lengths.

In a similar manner the replacement of cryopump panels located in the direct convertor chamber has been compared. The results are illustrated in Figure 5-10. For these panels both the time per panel is less and fewer panels are required by

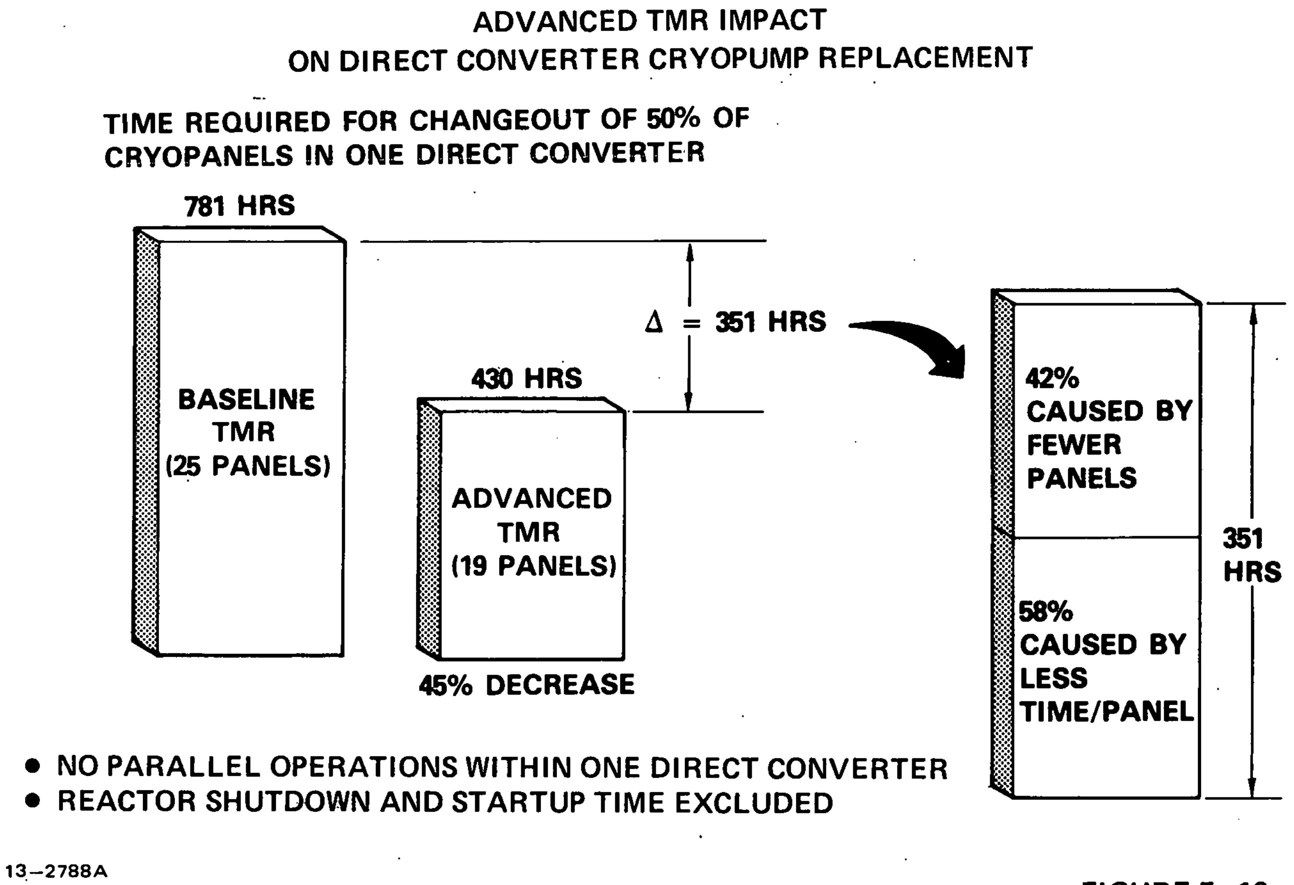


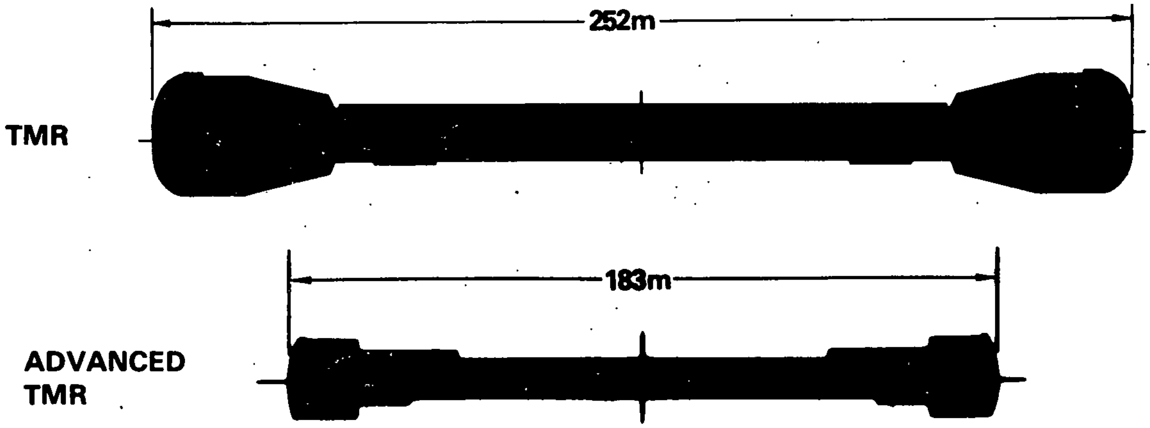
FIGURE 5–10

the advanced TMR. The increased access allows the use of larger panels so that an estimated 38 panels will suffice. The 45 percent time reduction for this subsystem is much greater than for the central cells. Since this subsystem is considered a scheduled downtime critical path driver for the baseline TMR, this reduction should substantially improve maintainability.

The neutral beam injectors also appear to be simplified in design. The reduction to 40 KeV results in a design that appears to provide better access to the ion sources than in the case of the 1.2 MeV neutral beam injector defined for the baseline TMR. The magnet system in the end plug appears more accessible and should provide for simpler servicing of the first wall/shield. Direct converter chamber wall cooling panels are eliminated. These and other design changes are expected to continue the trend toward improved maintainability of the advanced TMR.

While the advanced TMR plant capital costs have not been defined in this study, the relative size of the advanced and baseline TMR designs is indicated in Figure 5-11. The difference in the reactor lengths shown represents a reduction in length

ADVANCED TMR SIGNIFICANTLY IMPROVES MAINTAINABILITY



	TMR	ADVANCED TMR
CENTRAL CELL MODULE REPLACEMENT TIME (50%) —	593 HRS	500 HRS
DC CRYOPANEL REPLACEMENT TIME (50%) —	781 HRS	430 HRS

13–2808A

FIGURE 5–11

of 27 percent. The building volumes also decrease and by even a larger percentage than the reactor length. The estimated volume of the baseline TMR hall is 530,000 m^3 while that for the advanced TMR is 350,000 m^3. This is a reduction of 34 percent.

These trends indicate that TMR conceptual designs can be developed which will have a cost of electricity comparable to that expected from a tokamak reactor.

5.9 ALTERNATE DESIGNS - Several alternate designs have been examined in selecting the TMR design elaboration used for developing the maintenance action scenarios. In addition, some additional design features have been conceived but evaluated only qualitatively since their incorporation would require an iteration of the study results already developed. These alternate concepts are discussed in this section. Table 5-9 lists a qualitative evaluation of these alternative designs.

5.9.1 Central Cell Sector Installation Concepts - The design initially considered for installation of these sectors is the arrangement included in the Lawrence Livermore Laboratory report on the baseline TMR (Reference 2). This design installed the reactor at floor level and removed the sectors on tracks to the side. As indicated in Table 5-9, the visibility below the reactor is improved and the reactor room acts as the secondary vacuum zone without additional covers. On the other hand, the access to cranes and other equipment in the reactor room is impractical for maintenance during reactor operation because of potential neutron streaming.

TABLE 5–9
TMR ALTERNATE DESIGNS CONSIDERED

DESIGN	ADVANTAGES	DISADVANTAGES
INSTALL REACTOR AT MAIN FLOOR LEVEL	o IMPROVE LATERAL ACCESS AND VISIBILITY o ELIMINATE TRENCH COVERS	o EVACUATE ENTIRE REACTOR ROOM o CONTACT CRANE MAINTENANCE, POWER LINES, NBI, AND DC MAINTENANCE HINDERED
HINGE TRENCH COVER	o IMPROVE SEAL ACCESS o REDUCE STOWAGE AREA	o ROTATIONAL MANEUVER IS COMPLEX o DEMOUNTABLE HINGE REQUIRED o HORIZONTAL AREA REQUIRED FOR SOME DOOR OPERATIONS
BOLTED (LATCHED) VACUUM DOORS	o REDUCE DOWNTIME FOR REMOVAL	o POTENTIAL LEAK PATH
INTEGRAL CENTRAL CELL SECTOR BETWEEN SECTOR SHIELD	o REDUCES DOWNTIME FOR REMOVAL	o REQUIRES OCCASIONAL REMOVAL OF TWO SECTORS TO GAIN ACCESS TO THE SECTOR BETWEEN THEM
SECTOR LOCATOR PINS ON TRENCH COVER	o ELIMINATES SECTOR SPACER STRUCTURE DISCONNECTS	o ONLY ADVANTAGEOUS WHEN SHIELD SEGMENTS BETWEEN SECTORS ARE INTEGRAL WITH SECTOR
EXTERNAL DIRECT CONVERTOR CRYOPUMP INSTALLATION	o REDUCES CRYOPUMP DOWNTIME	o CONDUCTANCE MAY BE INSUFFICIENT o POTENTIAL SHIELDING PROBLEM
SPLIT END PLUG SOLENOID COILS	o COILS HANDLED BY CRANE o NORMAL HANDLING ROUTE POSSIBLE	o INCREASE COST o POSSIBLY LARGER COIL REQUIRED
HORIZONTAL HATCH TO TRANSFER LOCK	o SIMPLIFY LOCK HATCH SEAL 0 USE CRANE ONLY AND 1 DOLLY FOR LARGE OBJECTS	o OVERLOAD CRANE TRAFFIC o SMALL ITEMS REQUIRE GROUPING AND CRANE HANDLING

In addition, the maintenance of the neutral beams cannot be conducted without bringing the entire reactor room up to ambient pressure, and the startup time will increase because of the larger volume to be evacuated. The selected trench installation provides favorable trends for all of these considerations.

Another alternate arrangement is to rotate the trench cover about a hinge point instead of lifting it from its position and laying if flat on the floor or stacking it. The cover would be rotated to lean against the wall. This reduces the area required for stowage and improves access to the cover seal for maintenance. The cover could be readily removed if desired, by designing the hinge pin housing to release the hinge pin at a predetermined direction and rotational position. The disadvantages arise from (1) the complexity of the rotating door movement which can take additional time over the simple lift and translation selected for the baseline; (2) the requirement for the demountable hinge to release the door when the door must be moved to another location; and (3) the continuing need for floor space that will be required to accomplish other door maintenance.

The most time consuming function when exchanging central cell sectors is the removal of the shield blocks between sectors. These are necessary to reduce neutron streaming to acceptable levels. An improved joint arrangement has been devised which incorporates the staggered shield block between sectors as a part of each sector. This joint requires two sector designs which alternate such that two "male" sectors must be removed before a "female" sector can be removed. For installation the "female" sector would have to be installed first.

With the foregoing joint, or even with shield blocks, it is not necessary to bolt these joints or blocks to control the spacing between sectors. An alternate is to use locator pins both below the sectors in the support saddles and in the trench cover. The trench cover pins engage the top structure of each sector, holding it firmly in place merely by installation of the cover. These revisions to the joint design and the sector location arrangement may reduce the replacement time for each sector by approximately 31:00 hours. They would also reduce the requirements for trench robots.

5.9.2 <u>End Plug and Direct Converter Alternate Arrangements</u> - Three alternate design arrangements in the end plug and direct converter region could improve maintainability in these areas.

The difficulty in accessing the cryopump panels would be relieved if these pumps were installed external to the direct converter chamber in a manner similar to the cryopump installation suggested for the IMS tokamak reactor. Cylindrical pumps using simple isolation valves for recycling which are installed outside of the chamber are much more accessible and should reduce the replacement time significantly. Whether sufficient conductance is available is not known and requires detailed examination.

The sealed vacuum doors on the direct converter may be latched in place rather than bolted. This type of fastener would reduce the required time for door removal even though a welded seal must be employed. Whether sufficient time is saved to justify the more costly design must be resolved.

Finally, the removal of the large end plug solenoid coils would be simplified if these coils could be made up as a sandwich of 3 coils, each weighing approximately 500-600 tonnes, which is within the capacity of the heavy overhead crane. Then they could be removed without removing the side wall of the trench and could be transported to repair or rewind facilities by the usual route.

5.9.3 Facility Alternatives - The movement of all components and equipment to and from the reactor room is assumed to be through a horizontal airlock designed to handle the largest units. More than one airlock is required when the traffic is high.

The alternate design is to use a transfer lock with an entrance hatch in the reactor room floor which can transfer large equipment by use of a crane. This type of transfer obviates the requirement to seal a door around a floor joint through which tracks are run. Such a seal is difficult to design and time consuming to operate. However, a mixture of these two types of transfer locks may be required to handle the smaller components, i.e., tools and the like, without interfering with crane operations. Crane traffic may be sufficient to preclude the use of a crane for such small items with a floor entry transfer lock without unnecessarily extending the scheduled outage time. A traffic study is necessary to determine the number and type of transfer locks required.

6.0 CONCLUSIONS

The conclusions are compiled in three general categories. First a description is given of features which enhance maintainability of a TMR. Secondly, based on these features and on the maintenance problem areas uncovered during the study, a series of design guidelines has been formulated. The last category defines conclusions relating the maintainability of a TMR and of a tokamak reactor concept.

6.1 <u>DESIRABLE TMR DESIGN FEATURES FOR MAINTAINABILITY</u> - Those design features of the TMR which are particularly beneficial to maintainability emphasize the ability to quickly access some of the more important components. However, not all areas in the reactor possess this feature and these areas, notably the direct converter chamber, are the maintenance drivers in the TMR. Therefore, even though internal access to the direct converter chamber tends to drive the maintainability of the TMR, the external access to the central cell and, to a lesser degree the access to the end plug region, produces several desirable maintainability design features. A list of features which facilitate access, and also several other desirable design features are given in Table 6-1.

TABLE 6–1
DESIRABLE TMR MAINTAINABILITY DESIGN FEATURES

- PROVIDES ACCESS TO MOST COMPONENTS FROM ABOVE THE REACTOR FOR EASE IN MOVING COMPONENTS.
- ACCESS TO THE INSIDE OF CHAMBERS IS UNNECESSARY FOR MOST MAINTENANCE EXCEPT IN THE DIRECT CONVERTER CHAMBERS.
- INTERTWINING MAGNET CONFIGURATIONS ARE ELIMINATED.
- MAJOR DISASSEMBLY OF FIXED REACTOR STRUCTURES OR SECTIONS IS NOT REQUIRED FOR ACCESS TO THOSE COMPONENTS REQUIRING MOST FREQUENT MAINTENANCE.
- MANY COMPONENTS AND REACTOR ZONES CAN BE ACCESSED SIMULTANEOUSLY WITHOUT INTERFERENCE.
- THE DOUBLE VACUUM ZONE SIMPLIFIES DISASSEMBLY OF CENTRAL CELL SECTORS AND END PLUG WALL MODULES.
- ALL PERMANENTLY INSTALLED MAINTENANCE EQUIPMENT IS EXTERNAL TO THE REACTOR VACUUM CHAMBER AND SHIELD TO PERMIT MAINTENANCE DURING REACTOR OPERATION.
- REDUNDANT NEUTRAL BEAMS IN THE END PLUGS ARE DESIRED.
- REDUNDANT CRYOPUMPS ARE DESIRED IN DIRECT CONVERTERS.
- VERTICAL HANDLING OF DIRECT CONVERTER COLLECTOR VANES IS FEASIBLE IN MODULES CONTAINING MULTIPLE VANES.
- ALL REACTOR SERVICES CAN BE ROUTED FROM THE REACTOR ROOM WITH LITTLE INTERFERENCE TO MAINTENANCE ACCESS.
- ALL MAJOR REACTOR COMPONENTS CAN BE WITHIN A RELATIVELY SIMPLE SHIELDED ENCLOSURE, POSSIBLY ELIMINATING ACTIVATION OF REACTOR ROOM WALLS, EQUIPMENT, ETC.

The ability to access most components from above allows most of the maintenance actions to use overhead cranes for replacing components and moving them within the reactor room. This is within the state-of-the-art and gives credibility to the procedures and equipment needed for maintenance of the TMR. The dominant use of cranes reduces the need for sophisticated floor mounted maintenance devices and allows simplified positioning. Vertical access is a beneficial feature, however, careful planning is required to avoid interference between cranes, resulting in delays. Therefore, tugs and floor dollies are used for all minor item transport.

Previous studies have revealed that remote maintenance conducted from within a chamber can require excessive time. One cause is the relatively small size of the demountable components required to fit through the access opening. Another cause is the limited number of components that can be replaced simultaneously and a third cause is the extensive delay required to rescue malfunctioning maintenance equipment. The TMR requires internal maintenance operations only in the direct converter chambers. Even this operation is made external in the advanced TMR concept.

The particularly difficult maintainability problem caused by the intertwining toroidal and poloidal field magnets in the tokamak reactor is absent from the TMR concept. The most complex magnet replacement is either replacement of the Yin-Yang coil set or replacement of one end plug solenoid coil. The Yin-Yang coils can be handled by gas bearings to move the set from within the bore of the solenoids. Then they are lifted from the reactor with the overhead crane. The movement of the large plug solenoid coils is constrained only by their large mass, approximately 1700 tonnes each. This requires some trench wall disassembly and the use of gas bearings but no coils must be disassembled in order to remove them.

The need to disassemble fixed structures for removal of components has not been found in the TMR. This is required in the tokamak to replace magnets, inner shield, or components inboard of the shield. Such disassembly and reassembly is time consuming.

Numerous central cell and end plug components can be accessed simply by removing non structural shield covers with overhead cranes. These components include most of the piping, electrical and instrumentation lines in the trench. Other components are accessed by removing the shield covers above the direct converter grids and the shielded side panels on the neutral beam injectors. Maintainability is enhanced because all of these can be open at the same time, thus providing access to most of the reactor without constraining work to flow through a limited number of openings. Therefore, a large number of maintenance actions can be conducted in parallel. For example, 16 work stations for overhead manipulator assemblies can be used simultaneously even when allowing for only four in the central cell region. These give access to all of the systems in the TMR except for the cryopumps and cooling panels in the direct converters. This access is through the openings made by removal of the shield covers.

The use of a double vacuum zone permits the use of high impedance joints between central cell sectors and between end plug wall/shield modules to separate the vacuum zones. Both zones are maintained at 10^{-4} torr and below, thereby making all flow between zones during reactor operation in the molecular flow regime and allowing the use of the high impedance type of joint. With such joints the need for welded seals and the attendant lengthy setup, cleaning, tests, debris collection and the like are eliminated in favor of simple bolts or, possibly, latches. The outer vacuum wall seals are shielded which, together with the use of separate pumping for the outer zone reduces the sealing requirements for both leaks and radiation. Positioning of central cells and end plug modules is not dependant on seal closure tolerances between cells. Locating pins and direct lifting can be employed. On the other hand, shield segments are still located between sectors to reduce neutron streaming. These should be eliminated by improved joint design since their removal and installation is time consuming. Such elimination would even further aid in reducing replacement time. A double vacuum zone for the neutral beam injector housings and the direct converter chambers is deemed impractical at this time because of the additional volume required at these points.

The TMR design is such that it is unnecessary to install movable maintenance equipment in the vacuum zones or within the shielded volume during reactor operation. Such items as tracks and gas bearings are within the shield and exposed to radiation. Bolts, clamps, latches and seals represent the most complex equipment used during maintenance that is within the radiation environment. Therefore, all equipment, particularly including overhead cranes, are available for maintenance during reactor operation. Alternatives which provide for installing movable equipment in the radiation environment are expected to have a high failure rate because the equipment usually cannot be maintained during reactor operation and this restriction is a potential cause of long delays during reactor maintenance.

While the baseline TMR end plug neutral beams apparently cannot be made redundant because of the limited area for entering the plug region, this capability is desired to reduce the estimated forced outage downtimes. The study estimated that these systems would account for more forced outage downtime than any other in the TMR with the ion sources accounting for about 23 percent of the forced outage downtime. The simpler ion sources defined for the advanced TMR improve access and should reduce downtime. In addition, it appears possible to install redundant ion sources within the same housing. Also, the advanced TMR end plug coils appear to be more open than those in the baseline TMR, thus providing more entry into the plug for additional neutral beams and RF heating sources.

The limited access to the cryopumps in the direct converter chambers requires that these cryopumps have excess capacity and redundant operation or the forced outage downtime for these components is expected to be excessive. Since sufficient area is available, the cryopumps are made 100% redundant (400 m^2 installed instead of the 200 m^2 required). The 200 m^2, in itself, provides 100 percent short term excess capacity when the pumping area normally used for regeneration is included. With this redundancy level (100%) the forced outage downtime for these panels became only 1.2 percent of the total forced outage downtime instead of 8.9 percent which would be expected if all redundancy were removed from this subsystem. The capability to readily install this redundancy because of the available space is a desirable feature of the TMR concept.

The direct converter collector vanes are suspended vertically when in operation and span lengths up to approximately 17 meters without intermediate support. The vanes and their suspension system are estimated to be designed to withstand vertical loads but not the horizontal loads experienced if transported in the horizontal position. The ability to design a module which will handle approximately 40 vanes at one time of the 680 total required and move only in the vertical attitude is desirable since it will reduce downtime. Horizontal operation would save building height but requires additional downtime to install auxiliary supports for protection when in the horizontal atitude. Also, the use of a module with an actively cooled backplate allows all components requiring maintenance to be moved at one time and in sections of such a size which will optimize the maintenance cost. The use of 40 vanes per module has been assumed as a reasonable size at this time and can be optimized when the design becomes more stable. Likewise, the saving in forced outage downtime versus the additional building cost for vertical handling should also be optimized.

The TMR arrangement allows all reactor services for cooling, power, instrumentation, and vacuum lines to enter or leave the reactor room from the side of the reactor while all component removal is accomplished by hoisting from above. This results in minimum interference of the service lines with maintenance operations while still allowing these lines to be connected, disconnected and maintained from above also. This type of access is highly desirable and practically eliminates removal of lines solely for the purpose of gaining access for maintenance. Some possible exceptions exist in cryogen connections to magnets with pool type cooling, for example.

The complex shielding required for the tokamak to eliminate neutron streaming to reactor room walls or external reactor structure is reduced to a minimum in the TMR. Except for the neutral beam housings, all fluid, electrical and instrumentation lines penetrating the reactor appear to be relatively simple and from the side of the reactor. This leaves the shield panels used for access free of penetrations, and simple removal operations are possible. The beam ducts for neutral beams present shielding problems in both reactors but are fewer in number in the TMR. Thus, expenditures to resolve the shielding requirements may be justified. Freedom from radiation in the reactor room during operation appears to be a more reasonable objective for the TMR than for the tokamak because of the apparently simpler shielding. This shielding may be made effective enough to permit hands-on maintenance of equipment and instrumentation located in this room. Similar approaches may be feasible for the tokamak reactors but involve larger expenditures because of necessary access from the side of the reactor for maintenance.

6.2 PRINCIPAL MAINTAINABILITY DESIGN GUIDELINES - Several of the guidelines developed from the tokamak studies have been applied to the design elaboration conducted for the baseline TMR. These guidelines are listed in Section 3.2.1 and again in Table 6-2 because they have proven equally appropriate to the TMR as to the tokamak reactor design.

The impact of applying these guidelines to the baseline TMR is as follows:

- o Double vacuum zones are used in the central cell and end plug regions resulting in scheduled outage times of only 6.2 days for a central cell sector and 16.6 days for an entire end plug wall/shield.
- o The use of larger module sizes for replaceable components appears more effective than smaller modules. For example, the central cell sector size varies between the baseline TMR and the advanced TMR resulting in a variation in the number required. The baseline TMR requires 36 and the advanced TMR requires 44. The replacement downtime for 50 percent of the larger sectors is found to be 91 percent of that for the smaller sectors when applying the same maintenance plan constraints. Therefore, the larger sectors provide more efficient maintenance than the smaller even though the smaller sectors have a more quickly demountable joint design.

TABLE 6–2
GENERAL MAINTAINABILITY DESIGN GUIDELINES APPLICABLE TO TMR

* o USE MULTIPLE VACUUM ZONES TO ENHANCE MAINTAINABILITY.
* o DESIGN FOR LARGEST ECONOMICALLY JUSTIFIABLE MODULE SIZE.
* o DESIGN FOR EASE OF ACCESS AND MINIMUM REPLACEMENT DOWNTIME.
* o MINIMIZE SPECIAL PROVISIONS FOR LONG LIFE COMPONENT REPLACEMENT.
* o DESIGN FOR FULLY REMOTE MAINTENANCE OPERATIONS.
* o DESIGN MAINTENANCE EQUIPMENT TO BE ACCESSIBLE DURING MAINTENANCE OPERATIONS.
* o MINIMIZE THE NUMBER OF CONNECTIONS FOR EXCHANGE OF REPLACEABLE COMPONENTS.
* o MINIMIZE INTERFERENCE TO ACCESS BY SERVICES FOR COMPONENTS.
* o DESIGN FOR CONCURRENT (PARALLEL) MAINTENANCE OPERATIONS.
o DESIGN FOR SCHEDULED MAINTENANCE, MINIMIZE FORCED OUTAGES.
o DESIGN FOR ONE YEAR MINIMUM LIFE BEFORE REPLACEMENT.
o MAKE MAINTENANCE OPERATIONS SIMPLE BOTH IN NUMBER AND TYPE.

* DESIGN GUIDELINES USED FOR TMR DESIGN ELABORATION FOR MAINTENANCE.

- Ease of access and a resultant reduction in replacement downtime is achieved by the direct converter chamber cryopump design for the advanced TMR. Improved access alone results in a decrease in downtime of 26 percent for the replacement of 50 percent of the cryopump panels.
- The long life components in the baseline TMR are represented by the end plug magnets. The only provisions made for their replacement are the installation of a gas flotation device under the Yin-Yang and the plug solenoid magnets and structural openings in the trench side walls for removal of the massive solenoid magnets. Even so, the forced outage replacement time for these magnets appears nominal, being only 18 days for the Yin-Yang coil set.
- All maintenance operations in the reactor room that occur when trench covers, NBI side panels or direct converter doors have been removed must be remote. Therefore, all maintenance actions, even those that could use hands-on maintenance, are designed to be accomplished by fully remote operations. This allows for either parallel operations, if they are more effective, or for remote operations in an emergency.

- All maintenance equipment is accessible to an overhead crane for retrieval during remote maintennace operations except the equipment operating within the direct converter chamber. Methods of making this directly accessible for retrieval could not be visualized without adding major disadvantages.
- All component designs utilize only one set of connections, i.e., supply and return, for each required service. For example, NBI connections are reduced to 13 plus structure and each central cell sector requires 10 connections plus shield door connections and mounting structure. These are the minimum that appear to be feasible with the baseline TMR design.
- Minimum interference to maintenance operations by service lines is achieved by locating all service disconnects for each replaceable subassembly or component at the side. All maintenance access is initiated from above to minimize interference with these service lines, although some operations on the side of the reactor may require additional study to prevent interference.
- A high degree of parallelism in maintenance operations is feasible with the TMR. Each direct converter is provided with four doors. Each end plug region has 6 access covers which expose it completely from above and from both sides of each NBI. The entire central cell is exposed from above by 4 covers. The most interference to parallel operations is through interference of the maintenance equipment with other maintenance equipment. The emphasis on crane hoisting operations requires that several cranes be provided. For the optimum replacement fraction where only 4 of 36 central cell sectors per scheduled outage are replaced, a total of 8 cranes has been used.
- To minimize forced outages three approaches are taken. First, all components possible are located outside of the reactor room to permit repair while the reactor is operating. Second, redundancy is provided, where necessary and practical, to allow component repair during reactor operation. Third, redundancy is provided to extend the MTBF of a system to reduce forced outages. The cryogen refrigeration system located outside of the reactor room exemplifies the first approach, redundant primary coolant loops outside of the reactor room is an example of the second approach and excess cryopump capacity is an example of the third approach. If these three approaches cannot be used for a component or subsystem, then forced outages can only be reduced by increasing reliability.

- Scheduled outage intervals are slightly more than one year (1.10 years) when the cost of electricity is optimized at the best replacement fraction for central cell sectors. More frequent outages are seen to increase the cost of electricity as shown in Figure 5-1. Here the COE increased from 67.2 to 75.5 mills/kw hr when the frequency varied from one outage in 1.10 years to one in 0.30 years. The optimum will tend to be close to the scheduled balance of plant outage of one per year. Therefore, all components must be designed to operate at least for this period or multiples thereof.
- Simple mechanical maintenance operations are employed with a minimum number of tool changes and supporting fixtures or equipment. Welding has been avoided except for some door seals. Fitting of joints is minimized by the use of flexible lines or bellows. Single point line connection releases are used and the use of latches instead of bolted attachments for frequently disconnected components is prescribed. Extensive work on such devices is required before they can be considered reliable enough for these applications, however.

Several additional design features became evident which impose specific design guidelines for future TMR commercial system concepts. These guidelines are listed briefly in Table 6-3 and the reasons for selecting them as guidelines are summarized in the following paragraphs.

TABLE 6–3
TMR SPECIFIC MAINTAINABILITY DESIGN GUIDELINES

o	USE MINIMUM NUMBER OF CENTRAL CELL SECTORS CONSISTENT WITH REPAIR AND SPARES COSTS.
o	DESIGN NBI ION SOURCES FOR SIMPLE ACCESS.
o	MAKE NBI CRYOPUMP PANELS REMOVABLE WITH VACUUM WALL.
o	EMPLOY SUBSYSTEM REDUNDANCY, WHERE FEASIBLE, ON SHORT MTBF COMPONENTS.
o	DESIGN SUBSYSTEMS FOR MAINTENANCE WHILE REACTOR IS OPERATING, WHERE POSSIBLE.
o	MAKE PIPING CONNECTIONS OUTSIDE SHIELDED WALL.
o	DESIGN FOR EXTERNAL ACCESS TO COMPONENTS WITHIN DIRECT CONVERTER CHAMBERS.
o	OVERHEAD CRANE OPERATING ENVELOPES SHOULD BE UNRESTRICTED.

Minimize Number of Central Cell Sectors - The maintenance penalties of increasing the number of central cells are evident from two analyses conducted in this study. In comparing the TMR with the tokamak reactor, the scheduled outage per central cell (6.2 days) is much shorter than the outage per tokamak first wall/blanket sector (11.0 days). The total time required for replacement of several sectors which are close to each other cannot be paralleled as much as for the tokamak because the central cell sectors are relatively short and maintenance equipment working on adjacent sectors will interfere. For the minimum COE maintenance plan, the TMR requires replacement of 4 central cell sectors to the two required for the tokamak. Therefore, without parallel sector replacement, the initial advantage of one sector is soon lost as the increased number of smaller sectors required by the TMR requires more operations to replace the same percentage of first wall/blanket. The other comparison illustrating the advantage of a smaller number of sectors is the reduction in downtime defined in section 5.8 for the advanced TMR when the number of sectors is reduced from 44 to 32. The comparison of downtime with the baseline TMR, which uses 36 sectors, goes from a 10 percent increase in downtime to a 19 percent decrease in downtime because of the reduced number of sectors.

Reducing the number of central cell sectors can obviously be carried too far and the optimum number must consider the sector repair costs and time, manpower utilization, the number and size of repair facilities, and the replacement spares costs.

Simplify NBI Ion Source Access - Replacement of non-redundant ion sources is estimated to require almost 23 percent of the forced outage time. The downtime per source replaced is estimated at 7.2 days for a scheduled outage and 9.4 days for a forced outage. However, for the NBI design used on the tokamak reactor the replacement time required for an ion source forced outage is only 3.4 days, including reactor shutdown and startup. These tokamak NBI ion sources are accessible without entering the NBI housing and, thus, the number of operations to exchange such an ion source is reduced significantly. Either the tokamak NBI type of access or better should be the design goal for the higher voltage NBI's required by the TMR.

Simplify NBI Cryopump Panel Removal - A design concept devised for removal of the cryopump panels in the TMR neutral beam injector is possibly appropriate for all NBI designs. Complete NBI internal access and removal of one half of the cryopump panels is achieved by removal of the complete side panel/shield with the cryopump panels attached to the inside surface. All service lines are disconnected outside of the NBI housing. By this arrangement half of the cryopump panels can be replaced during a scheduled outage in only 3.9 days or all can be replaced in 5.7 days when using only one overhead crane.

This approach makes the removable subassemblies as large as possible; it simplifies maintenance operations; and it makes as many connections as possible outside of the reactor chamber.

Employ Subsystem Redundancy Where Feasible - All components in the TMR or in the tokamak reactor which incorporate redundancy are listed in Sections 4.2.5 and 4.3.5, respectively. These redundant installations result in reducing the estimated forced outage downtimes by 40 percent and 70 percent, respectively. A significant percentage of this downtime reduction, 45 percent for the TMR and 32 percent for the tokamak reactor, occurs because components can be replaced while the reactor is operating in many cases where redundancy is employed.

Design for Maintenance with Reactor Operating Whenever Feasible - The survey of replaceable components resulted in selecting a significant number of components which can be replaced when the reactor is operating. The aforementioned impact of redundant components on this capability makes redundancy one technique for use when designing to this guideline. The total impact on forced outage downtime is unavailable from this study because downtime was not estimated for components that are repairable while the reactor is operating other than where redundancy is employed.

Make Connections Outside of Shield Wall - This design arrangement is employed in the neutral beam injectors and should result in decreased leakage when it can be employed. Difficulty is encountered in employing this guideline at the direct converter grid assemblies and in the central cell sectors. While this arrangement is not assumed for the direct converter cryopumps, it is conceivable that external connections could be employed if the cryopumps can be installed outside of the direct converter wall as suggested in Section 5.9.

Design for External Access to Components Within Direct Converter Chamber - This guideline is a direct application of the desire to keep maintenance equipment exposed and to make connections external to the reactor as cited in the foregoing paragraph.

Make Overhead Crane Operating Envelopes Unrestricted - The objective of this guideline is to prevent operations which require placing crane loads on transporters for horizontal movement because fluid or electrical service lines running across the reactor room either prevent lifting the load over them or require excessive lifting to clear these lines. The use of cranes is restricted in many tokamak designs because of the need for vacuum and cooling lines above the reactor in order to remain clear of the side of the tokamak to allow side access for maintenance. This requirement appears to be eliminated completely from the TMR based on the components investigated in this study.

6.3 MAINTAINABILITY COMPARISON OF THE TMR AND TOKAMAK REACTOR CONCEPTS - Throughout this report a number of observations have been made which result in conclusions that are explained in the following paragraphs. A summary of these conclusions is given in Table 6-4.

TABLE 6–4
RESULTS OF TMR AND TOKAMAK REACTOR MAINTAINABILITY COMPARISON

- o THE TMR APPEARS TO HAVE NO SINGLE COMPONENT WHICH DRIVES SCHEDULED DOWNTIME. THE DRIVING COMPONENT FOR THE TOKAMAK REACTOR IS THE FIRST WALL/BLANKET SECTORS.
- o SCHEDULED REPLACEMENT FRACTIONS OPTIMIZED FOR COE ARE BELOW 1/4 WHEN FIRST WALL FLUENCE LIMIT OF 16 MW-YRS/m^2 IS USED.
- o OPTIMUM SCHEDULED DOWNTIMES FOR THE TMR AND THE TOKAMAK REACTORS ARE 18 DAYS AND 23 DAYS, RESPECTIVELY.
- o REDUNDANCY REDUCES FORCED OUTAGE DOWNTIMES FOR THE TMR AND THE TOKAMAK REACTORS BY 40 % AND 70 % RESPECTIVELY.
- o THE ANNUAL COSTS OF SCHEDULED MAINTENANCE FOR THE TMR AND THE TOKAMAK REACTOR ARE APPROXIMATELY $19.4 MILLION AND $20.8 MILLION, RESPECTIVELY.
- o EQUAL FORCED OUTAGE DOWNTIMES FOR BOTH REACTORS CAN BE ALLOWED IF THE ESTIMATED PLANT CAPITAL COST OF THE TMR IS REDUCED APPROXIMATELY 26 PERCENT.
- o MAINTENANCE EQUIPMENT IS MORE ACCESSIBLE FOR THE TMR, REDUCING OUTAGE TIMES FOR MAINTENANCE EQUIPMENT REPAIR FROM A TOTAL OF 20.1 DAYS FOR THE TOKAMAK TO 9.4 DAYS FOR THE TMR.
- o THE TOTAL IMPACT OF SCHEDULED OUTAGE ON COE IS INFLUENCED SIGNIFICANTLY BY THE QUANTITY OF RESOURCES AVAILABLE FOR MAINTENANCE.
- o FORCED OUTAGES IN THE TMR ARE CAUSED PRINCIPALLY BY SYSTEMS LOCATED IN THE END PLUG AND DIRECT CONVERTER REGIONS.
- o THE ADVANCED TMR CONCEPT INDICATES TRENDS WHICH WILL IMPROVE ITS COE RELATIVE TO THE TOKAMAK REACTOR.
  - \- REDUCED CAPITAL COST
  - \- IMPROVED DIRECT CONVERTER ACCESS

<u>TMR Scheduled Outage Downtime Drivers</u> - The TMR incorporates several components which can drive the scheduled downtime. These include:

- o central cell sectors,
- o direct converter cryopumps,
- o direct converter collector grids,
- o neutral beam ion sources, and
- o end plug first walls.

While the replacement life of some can vary widely and the downtime for each unit is relatively small, with all being less than 7.2 days, the large quantity of units being maintained makes many of these components drivers for scheduled outages. By comparison, the tokamak reactor has only one significant driver, the first wall/ blanket sectors. One tokamak sector requires 11.0 days to replace compared to a maximum of 3.9 days for any other unit in the tokamak reactor. A single TMR direct converter chamber cooling or cryopump panel, a central cell sector, an NBI ion source or a Yin-Yang coil shield module all require between 5.4 and 7.2 days to replace.

Optimized Replacement Fractions - Scheduled replacement fractions, i.e., the fraction of identical components replaced during an outage, optimize at 1/9 of the central cell sectors for the TMR and 1/8 of the first wall/blanket sectors for the tokamak reactor. While these fractions yield the minimum COE for both reactors, the TMR does not also have the maximum availability at this point. Contrary to the tokamak, the TMR availability is driven by replacement of the direct converter cryopump panels, of which 6 (approximately 1/8 of the total) are replaced in each direct converter to achieve the optimum COE. Thus, the maximum availability for the TMR of .7969 occurs at a replacement fraction of 1/4 when the maintenance interval for the central cell sectors is almost exactly a multiple of the annual balance of plant maintenance interval and no lost time penalty exists for scheduled reactor maintenance.

In the earlier study phases the tokamak reactors optimized at a replacement fraction of 1/2. However, for this phase of the study the first wall fluence limit was raised from 5 MW yrs/m^2 to conform to current estimates of 16 MW yrs/m^2. This change, as well as the reduced downtime requirements, are the principal causes of the optimization at lower replacement fractions.

Optimum Scheduled Downtimes - The range of downtimes for scheduled outages of the TMR with various replacement fractions of the cryopump panels is from 13 days for one panel, together with the other sequential and parallel maintenance actions included in this critical path, to 40 days for all cryopump panels. For the optimum replacement fraction of 1/9 this maintenance action requires only 18 days. The central cell sector downtime is only 17 days when replacing 1/9 of the sectors in the reactor. The end plug wall can be replaced in parts so that it takes as few as 14 days if the reactor is shutdown almost annually as assumed for the cryopump panel replacement.

The comparable scheduled downtime for the tokamak reactor at an optimum replacement fraction of 1/8 is 23 days for two first wall/blanket sectors and attendant maintenance actions. This reaches a maximum of 59 days when replacing all 16 sectors. It can be seen that the optimum downtimes for the TMR are significantly less than those for the tokamak reactor.

However, the COE for the optimum TMR critical path is 67.2 mills/kw hr while for the tokamak the COE for the optimum critical path is 50.1 mills/kw hr because of the higher capital cost for the TMR.

Redundancy Reduces Forced Outage Downtimes - The relative ineffectiveness of redundancy in the TMR is attributable to the greater difficulty in providing redundant components. This is especially the case in the end plug and direct converter regions where most of the TMR maintenance critical components are installed. Design of the end plug to accept redundant systems would improve this situation significantly. Redundant neutral beams or RF heating systems would be likely candidates.

Annual Cost of Scheduled Maintenance - The scheduled maintenance annual costs discussed in Section 5.7, include the return on investment for maintenance capital, i.e., equipment, facilities and spares, the operating costs and the effect of the availability on cost. When these costs are expressed as the percentage of the total COE for scheduled maintenance, the result is 4.4 percent for the TMR and 6.6 percent for the tokamak. These are percentages of the base annual costs without scheduled maintenance which are defined at availabilities determined by the BOP and forced outages. Since the annual scheduled maintenance costs are close to the same for both reactors, COE variations between reactors must then be caused by capital cost variations.

TMR Plant Capital Cost Requirements - The relative COE analysis discussed in Section 5.5 indicated the need to reduce TMR plant capital costs by approximately 26% in order to allow the same days for forced outage as for the tokamak reactor. Such an objective may be feasible because the relative conceptual design maturity of the TMR lags the tokamak considerably, allowing greater opportunity for improvement. The ongoing study of an advanced commercial TMR conceptual design indicates that the plant capital cost will be significantly less than the cost of the baseline TMR.

Maintenance Equipment Maintainability - Maintainability of maintenance equipment is primarily measured by its operational reliability and the ability to recover from a failure while operating. The total downtime for six of the more difficult maintenance actions caused by maintenance equipment malfunctions was only 9.4 days for the TMR maintenance equipment and 20.1 days for the tokamak. The simpler access to the equipment in the TMR and the use of minimal equipment operating within the reactor are the principal causes for this difference. The longest TMR recovery time is 3.0 days while the longest time for the tokamak is 6.5 days.

Maintenance Resource Availability - Insufficient maintenance equipment will increase a scheduled outage duration significantly. In the test case, a reasonably heavy load of 231 maintenance actions is used. Using downtime derived by use of the maximum possible equipment that can conceivably be used as a base, reduction of this equipment to only a few of each item increased the outage duration by 173%. Conversely, allowing unlimited equipment, with the assumption that it could be used, decreased the scheduled outage duration by approximately 70%. However, the equipment requirements for the latter assumption appear impractical to use in the restricted space of the reactor room. Because of the limited analysis possible in this study these results are only intended to illuminate the nature of the analysis required and the extent to which this parameter can influence the overall results.

Forced Outage Causes - The principal components causing forced outages in the TMR and the percentage of forced outages related to each subsystem include:

- o Neutral Beam Subsystems 40%
- o Vacuum Systems 18%
- o Direct Converter Systems 15%

These are all located in the end plugs and direct converter region. On the other hand, the principal tokamak components causing forced outages are included in the following subsystems:

- o Vacuum Systems 29%
- o First Wall/Blanket/Shield 16%
- o Neutral Beam Subsystems 12%

These are all associated directly with the tokamak plasma chamber. Magnets also are significant in the tokamak reactor, representing 27% of the forced outage total but the cause is the long duration of the outage and not the frequency. Therefore, their failure is considered an unusual forced outage event. The complete outage list is included in Section 5.2.

Advanced TMR Trends - The principal maintainability difficulties encountered in the TMR are the difficult access and high downtime caused by the direct converter and end plug configuration and the low allowable forced outage downtime required to have a competitive cost of electricity with the tokamak reactor concept.

The TMR conceptual design currently under study tends to alleviate both of these concerns. First, it is smaller, being 183 meters in overall length compared with the baseline TMR length of 252 meters, a reduction of 27%. The enclosing building is also estimated to be much smaller both in length and height because the diameter of the revised configuration and the direct converter vertical handling height is less. The building volume is reduced approximately 34 percent. Secondly, the revised TMR is small enough to allow removal of the direct converter chamber end caps providing excellent access to the interior without requiring maintenance equipment to operate inside the reactor. These design features are all trends toward a more maintainable and economical reactor concept.

7.0 REFERENCES

1. "Fusion Reactor Design Studies - Standard Accounts for Cost Estimates", Battelle Memorial Institute, Pacific Northwest Laboratory, Richland, Washington, Report No. PNL-2648, May 1978.
2. "Preliminary Design Study of the Tandem Mirror Reactor (TMR)" by Moir, R. W., et. al., Lawrence Livermore Laboratory, Report No. UCRL-52302, July 1977.
3. "Developing Maintainability for Tokamak Fusion Power Systems - Phase II Report" by Zahn, H. S., et. al., McDonnell Douglas Astronautics Company, St. Louis, prepared for the U.S. Department of Energy, Report No. COO-4184-6, November 1978.
4. Personal Communication, Mitchell, J. T. D., Culham Laboratory, Abingdon, Oxfordshire, England, to Fuller, G. M., McDonnell Douglas Astronautics Company, 10 March 1978, enclosure of drawings from report in preparation.
5. "Tokamak Fusion Test Reactor, Final Design Report", Princeton Plasma Physics Laboratory, Report No. PPPL 1475, PH-R007, August 1978.
6. "Tandem Mirror Reactor with Thermal Barriers" by Carlson, G. A., et. al., Lawrence Livermore Laboratory, Report No. UCRL-52836, September 1979.
7. "MSCS - Management Scheduling and Control System", McDonnell Douglas Automation Company, St. Louis, MO, No. 8-MCAUTO-70221A, March 1979.
8. "Fusion Reactor First Wall/Blanket Systems Analysis Tokamak Concepts, Interim Report", by G. M. Fuller, McDonnell Douglas Astronautics Company - St. Louis, prepared for Electric Power Research Institute, Research Report 472-1, October 1977.
9. "Impact of Confinement Physics on Fusion Power Station Design and Economics and the Utility Interface, Final Report", University of Michigan and McDonnell Douglas Astronautics Company - St. Louis, prepared for Electric Power Research Institute, Report No. EPRI RP547-1, July 1978.
10. "Developing Maintainability for Tokamak Fusion Power Systems, Phase I Report", by Zahn, H. S., et al., McDonnell Douglas Astronautics Company, St. Louis, prepared for the U.S. Department of Energy, Report No. COO-4184-4, October 1977.
11. "Fusion Reactor Remote Maintenance Study", by Sniderman, M., Westinghouse Electric Corporation, Pittsburgh, prepared for Electric Power Research Institute, Report No. ER-1046, April 1979.
12. "Starfire, A Commercial Tokamak Reactor, An Interim Report", prepared by Argonne National Laboratory, McDonnell Douglas Astronautics Company, General Atomic Company, Ralph M. Parsons Company, October 1979 (to be published).

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